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Cognitive, perceptual and motor bases for the acquisition of tool use in infants

PhD Thesis, Developmental Psychology, Université Paris Descartes

Bases cognitives, perceptuelles et motrices de l'utilisation d'outils chez le très jeune enfant

Thèse de Doctorat, Psychologie du Développement, Université Paris Descartes

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À **Pierre Rat** *(1921 – 2010)*
Scientifique et Grand-père
Qui a toujours su attiser notre curiosité sur le monde qui nous entoure.

Extrait de **La chenille et le papillon**

“La chenille marche, si l'on peut dire, d'un pas d'arpenteuse, avec ses trois paires de courtes pattes aidées par des ventouses que porte l'abdomen. Le papillon va, d'un vol léger, d'une fleur à l'autre. **Comment a-t-il appris** ? Sa mémoire de papillon a-t-elle gardé un souvenir de sa vie de chenille ? En tout cas, on ne voit pas comment cela aurait pu lui apprendre à voler ! […] Comment a pu se former cet extraordinaire logiciel, imprimé dans le patrimoine génétique du papillon, pour qu'un scénario si compliqué puisse se dérouler ?”

Pierre Rat - Goutte de Sciences n°37 – 18 mai 1998

Cognitive, perceptual and motor bases for the acquisition of tool use in infants

Abstract

Tool use is the ability to act on an object with another object. In human infants, this ability develops toward the end of the second year of life. Despite a recent resurgence of interest in the study of tool-use learning in infancy, very little is known about the developmental steps in this learning or the underlying mechanisms. The present thesis presents a series of investigations on the age and conditions under which infants learn to use a tool to retrieve an out-of-reach object.

In a first cross-sectional study (**Paper 1**), based on a preliminary study on 5 infants followed longitudinally from 12 to 20 months of age (Appendices 2 and 3), infants aged 14 to 22 months were tested on a task involving the use of a rake-like tool to retrieve an out-of-reach toy. Infants' performance across variations in the spatial relationship between the rake and the toy was explored. The results showed that infants as young as 14 months of age succeeded spontaneously when the toy was initially placed against the rake or at least lay in the shortest trajectory between the rake and the infant. When the toy was placed at some distance from the rake, outside its shortest trajectory, infants only succeeded spontaneously at the task around 18 to 22 months of age. Likewise, when an adult demonstrated how to use the rake in the same spatial conditions, infants showed sensitivity to the demonstration only starting at 18 months of age. In a follow up of this study, a finer analysis of the data was conducted, which yielded insight on the age at which infants start to plan their action when using a tool (**Paper 2**). This analysis showed that before 18 months of age, infants were mostly influenced by their manual preference toward the right hand when grasping the tool. In contrast, starting 18 months, infants were more likely to vary the hand they used for grasping according to the toy's position in relation to the tool (right or left). These results show that infants who are in the phase of acquiring tool use are better able to anticipate the action than younger infants.

One observation from these first cross-sectional and longitudinal studies was of particular interest. When the toy was attached to the rake, all infants were spontaneously able to successfully retrieve the toy starting at 12 months of age. This suggests that at this age, infants have already acquired the notion of composite objects. In a complementary study, a significant change was observed between 6 and 9 months of age in the understanding of the notion of spatial connectedness between objects. Starting at 8 months of age, infants befan to show visual anticipation toward the distal part of the composite object when grasping its proximal part. Thus, 8-month-old infants use the notion of connectedness when acting on composite objects. This is in line with results from previous studies showing that around 10-12 months infants pull a string to which an out-of-reach object is attached before trying to grasp the object. However, in a pilot study where 16-month-old infants were presented a choice of several strings, only one of which was connected to the out-of-reach object, infants did not systematically choose the connected string. This led us to an investigation of why, at 16 months, infants do not use the notion of connectedness between objects in order to solve this task (**Paper 3**). To do so a study was conducted comparing infants' performance on the multiple strings task (action condition) with their looking behaviours at the same multiple-string scene when an adult solved the task in front of them (vision condition). The results showed that only infants who succeeded at the task themselves were able to visually anticipate which string the adult had to pull in order to retrieve the object. Additionally, the results showed that lack of inhibitory control partly explains infants' failure at the task.

A final study investigated why, in the previous studies, infants did not learn to use a tool by observation before 18 months of age. This result is surprising given the fact that infants can learn complex actions by observation before this age. One apparent possibility was that infants did not understand the demonstrator's intention, and thus did not perceive the function of the tool as they were

not able to anticipate the action of the demonstrator. To test this hypothesis, a study was conducted on 16-month-old infants to investigate whether presenting elements indicating the demonstrator's intention would help infants learn to use a tool by observation before 18 months (**Paper 4**). Infants who saw the demonstrator explicitly show her intention to obtain the toy before demonstrating the target action showed enhanced performance after demonstration.

In conclusion, several mechanisms whose development is likely to influence the emergence of infants' capacity to use a tool are proposed, and in particular inhibitory control and action planning processes, as well as observational learning.

Bases cognitives, perceptuelles et motrices de l'utilisation d'outils chez le très jeune enfant

Résumé

(voir Annexe 4 pour un résumé extensif en français)

L'utilisation d'outils est définie comme la capacité d'agir sur un objet par l'intermédiaire d'un autre objet. On sait que cette capacité se met en place vers la fin de la seconde année de vie chez l'enfant. Malgré un intérêt grandissant pour l'étude de l'apprentissage de l'utilisation d'outils, les étapes ainsi que les mécanismes sous-jacents de cet apprentissage restent très peu connus. Dans ce travail de thèse, nous avons cherché à savoir à partir de quel âge et dans quelles conditions le jeune enfant apprend à utiliser un outil pour rapprocher un objet hors de portée.

Dans une première étude transversale, inspirée d'une étude préliminaire longitudinale sur 5 enfants entre 12 et 20 mois (Annexes 2 et 3), nous avons testé des bébés âgés de 14 à 22 mois sur une tâche d'utilisation d'un râteau pour approcher un jouet hors de portée (**Article 1**). Plusieurs conditions de relations spatiales entre le râteau et le jouet ont été comparées. Les résultats ont montré que les premiers succès spontanés apparaissent dès 14 mois lorsque le jouet est initialement placé contre le râteau ou dans sa trajectoire. Lorsque le jouet est placé à distance du râteau sur la table, les premières réussites spontanées n'apparaissent qu'entre 18 et 22 mois. De même lorsqu'un adulte fait la démonstration de cette condition, l'enfant n'est sensible à la démonstration qu'à partir de 18 mois. Dans la continuité de cette étude, une analyse plus fine des données nous a permis de mettre en évidence l'âge à partir duquel les enfants planifient leur action pour utiliser un outil (**Article 2**). Nous avons ainsi pu mettre en évidence qu'avant 18 mois, les enfants sont principalement influencés par leur préférence pour la main droite lorsqu'ils prennent le râteau. Au contraire, les enfants plus âgés ont plutôt tendance à varier la main utilisée en fonction de la position du jouet par rapport au râteau. Ces résultats mettent en évidence une meilleure anticipation de l'action et de son résultat chez les enfants en phase d'acquisition de la capacité à utiliser un outil.

Une observation faite lors de ces premières études transversale et longitudinale a retenu notre attention. En effet, lorsque le jouet était fixé directement sur le râteau, tous les enfants étaient capables de le récupérer dès 12 mois. Cela suggère que l'enfant a acquis dès 12 mois la notion d'objet composite. Lors d'une étude complémentaire, nous avons observé un changement significatif de la connaissance de la notion de connexion entre objets entre 6 et 8 mois. À partir de 8 mois, on observe une anticipation visuelle vers la partie distale d'un objet composite lors de la prise de sa partie proche, montrant que l'enfant comprend qu'il peut agir sur la partie proche d'un objet composite pour atteindre la partie hors de portée de cet objet. A 8 mois l'enfant utilise donc la notion de connexion lorsqu'il interagit avec des objets composites. De même, on sait que dès 10-12 mois, lorsqu'un objet hors de portée est attaché à l'extrémité d'une ficelle à portée de sa main, un enfant tire sur la ficelle avant de chercher à prendre l'objet. Pourtant, lorsque dans une étude pilote nous avons présenté à des enfants de 16 mois un choix de plusieurs ficelles dont une seule était connectée à l'objet, les enfants ne choisissaient pas systématiquement la ficelle connectée. Nous avons cherché à savoir pourquoi même à 16 mois, l'enfant n'utilise pas cette notion de connexion entre objets pour résoudre cette tâche (**Article 3**). Pour cela, nous avons réalisé une étude comparant les performances des enfants à cette tâche (condition action) avec leurs comportements visuels vis-à-vis de la scène lorsqu'un adulte résolvait la tâche devant eux (condition vision). Les résultats montrent que seuls les enfants qui réussissent à choisir la bonne ficelle, sont également capables d'anticiper visuellement quelle ficelle doit être tirée. De plus, nos résultats montrent que les difficultés de certains enfants à résoudre cette tâche est en partie due à une capacité plus faible d'inhiber une action chez ces enfants que chez les enfants qui réussissent la tâche.

Enfin, nous avons cherché à savoir pourquoi les enfants n'ont pas appris à utiliser l'outil par observation avant l'âge de 18 mois dans nos études. Ce résultat est surprenant puisqu'un enfant est capable d'imiter des actions complexes bien avant cet âge. Une hypothèse possible est que les enfants, ne comprenant pas l'intention de l'expérimentateur, n'ont pas perçu le rôle de l'outil par manque d'anticipation de l'action de l'adulte. Nous avons donc mené une étude sur des enfants de 16 mois, afin de vérifier si l'ajout d'éléments montrant l'intention du démonstrateur avant la démonstration aidait les enfants à apprendre par observation à utiliser un outil (**Article 4**). Les résultats montrent en effet que seuls les enfants à qui le démonstrateur a signifié son intention d'obtenir l'objet avant la démonstration améliorent leur performance après la démonstration.

En conclusion, nous proposons plusieurs mécanismes susceptibles d'être impliqués dans l'émergence de la capacité à utiliser un outil chez le jeune enfant, notamment des processus de contrôle inhibiteur, de planification de l'action et d'apprentissage par observation.

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Part I Theoretical Introduction

General Introduction

In her recent review of the development of problem solving in young children, Rachel Keen defined tool use as “a royal road to the study of problem solving” (Keen, 2011, p.2). Indeed, human tool use has been considered as evidence of 'humanique' cognitive ability (Vaesen, 2012, p. 203), tightly linked with other cognitive capacities, such as high social intelligence and learning, grammatical language and enhanced causal reasoning (see Vaesen, 2012, for an extended comparative review). It has been closely linked to human biological and cultural evolution (e.g., Ambrose, 2001), and has long been used as a classic measure of intelligence, not only in humans but also in a comparative perspective on diverse species such as great apes, monkeys and birds (e.g., Köhler, 1925; Visalberghi & Limongelli, 1994; Lefebvre, Nicolakakis & Boire, 2002). Tool use has also been highlighted as being particularly adapted to offering insight into the interactions among perception, cognition and action (Barrett, Davis & Needham, 2007; although see e.g., Emery & Clayton, 2009 for a different view).

Despite the importance of tool use however, in her review Keen stressed the fact that the study of the mechanisms leading to the development of this capacity has nevertheless been neglected over the last decades. In particular, she insisted on the need for more systematic studies to identify the cognitive processes which lead to the learning of skills related to problem solving related skills. As described in the review of the literature below (Chapter 2), we even lack descriptive knowledge about the fundamental steps in the development of tool use.

The general aim of the present thesis is to contribute to the body of knowledge on the developmental bases of tool use processes in infancy. Our aim was to fill gaps in the literature in two ways. First, we conducted systematic studies on the bases of the development of tool use during the second year of life. Second, we designed experiments focusing on the prerequisites of tool use, and on the role of observational learning in the acquisition of this ability. Finally, we tried to infer some of the mechanisms that may be involved in this development.

This manuscript begins with two theoretical sections. The first chapter is an overview of definitions of tool use in human and non-human animals. The second chapter focuses on development in human infants. It is organized into four main parts: (1) a review on the first developmental steps toward tool use, (2) a description of the main experimental work on tool use in infancy, (3) a presentation of the different perspectives on the emergence of tool use and (4) a summary of what is currently missing in the study of the emergence of tool use in infancy, and the outlines of the experimental work presented in this thesis.

Note to readers

The present dissertation is article-based. Chapters 1 and 2 present the theoretical framework for the topic of the thesis. Chapters 3 to 5 present the experimental work that I conducted during the thesis. Each study is presented in form of a paper that has either already been published or has been submitted to international peer-reviewed journals.

It is important to note that only papers on the studies in which I was integrally involved (that is, from the beginning of the experiment to the final interpretation of the data) have been incorporated into the body of the thesis. In total, four papers were included: two published papers as main author (Chap. 3); one submitted paper as main author (Chap. 4); and one published paper as second author, but in which my participation was equal to that of the first author, R. Esseily (Chap. 5).

Two other experiments related to the present thesis, but in which I was only involved for a part of the process, are briefly described at the beginning of Chapters 3 and 4 (see section 3.1 and section 4.1). The papers related to these experiments have been included as appendices to the thesis and not as chapters. My contributions to each of the four main papers and to the two additional studies (along with those of the other authors) are described in a separate section for each experiment.

Chapter 1. Definitions and functions of tool use

1. Definition of tool use

Tool use is a widespread ability in both human and non-human animals. This type of behaviour can take extremely varied forms such as cracking nuts with stones, using sticks to reach for inaccessible food or to scratch oneself, or transporting food into recipients. This diversity in the actions which are considered as tool use, raises the question of how the term is to be defined. As Bentley-Condit and Smith (2010) pointed out in their extensive catalog of animal tool use, the definition of tool use is controversial, and many definitions have been proposed over the last decades. One of the most cited definitions in behavioural research is the one offered by Beck (1980) in his work on tool use in non-human animals: he describes tool use as “the external employment of an unattached environmental object to alter more efficiently the form, position, or condition of another object, another organism, or the user itself when the user holds or carries the tool during or just prior to use and is responsible for the proper and effective orientation of the tool” (p.10). This precise definition particularly emphasizes the need for the tool to be detached from the environment (i.e., neither attached to the environment, nor to the goal object or organism), excluding for example the use of a support to retrieve an out-of-reach object that is standing on the support, thus not being detached from the goal object in the sens of his definition. In his definition, Beck also included 'social tool use,' which is defined as the manipulation of another individual —instead of an external object— to attain a desired goal. As soon as infants begin to point, by 11-12 months of age (Carpenter, Nagell & Tomasello, 1998), they are able to use this gesture as a 'tool,' either to share their attention to an interesting object or situation with someone ('declarative pointing'), or to get the other person do something for them, and more particularly to bring something into reach ('imperative pointing' Bates, Camaioni & Volterra, 1975). Since Beck's proposal of this general definition of tool use, various modifications have been proposed. Some authors formulated stricter definitions, by excluding 'social tool use' from their behavioural categories (e.g., Bentley-Condit & Smith, 2010; St. Amant & Horton, 2008). Other authors in contrast have broaden the definition, including, for example, nest-building as tool use, even though it does not involve users dynamically holding a tool in their hands (e.g., Fruth & Hohmann, in McGrew, Marchant & Nishida, 1996, p.226).

The tool use tasks presented in this work are based on Beck's definition. As it is one of the most widespread definitions in behavioural research on human and non-human animal tool use, this allows us intra- and interspecies comparisons with animal and human infant studies. Similarly to Bentley-Condit and Smith (2010) and St. Amant and Horton (2008), we were not directly interested in social tool use per se, as the subjects we tested were expected to find a way to attain the goal by themselves, without calling on external help from an adult. However, social behaviours, such as pointing toward the goal, were quantified in some of the analyses. In addition, other social aspects of tool use such as learning by observation are present in our work, because we consider that the social learning of tool use is determinant of the emergence of such behaviours. This aspect is further discussed in Chapters 2, 3 and 5.

2. Functions of tool use

Even in Beck's framework, tool use actions are diverse in terms of both means and functions. In this section, we present an overview of the main functions of tool use that have been isolated by ethologists, which describe tool use by both human and non-human animals. Beck isolated four main functions of tool use: extension of reach, amplification of mechanical force, amplification of aggressive or antagonistic behaviours, and collection and transport of liquids and small solids. Other reviews of animal tool use (e.g., Bentley-Condit & Smith, 2010; Tomasello & Call, 2007), have specified two additional categories of functions for tool use. These categories are body maintenance and the protection of one's own body parts. The following description of these six functions is illustrated by some examples of tool use expressed in humans and in non-human animals in their natural environment. However, these few examples do not represent an exhaustive catalog of animal tool use.

2.1. Extension of reach

This first category occurs in situations where a stick-like object (such as a rod, a rake or a hook) helps its user retrieve an object that is positioned out of its reach. This function of extending the body corresponds to the definition of tool use given by Nabeshima, Kuniyoshi and Lungarella (2006, p.2), as “the ability possessed by humans and other animals … to use different tools to manipulate objects, and hence 'move beyond' the limits set on their action space by the length of their limbs or the type of their end-effectors”. This behaviour has mainly been observed in humans and non-human primates (see Tomasello & Call, 1997 for a review), but also in some birds such as corvids and some species of parrots, and occasionally in other species (see Bentley-Condit & Smith 2010 for an extensive catalog). This definition of 'extension of reach' includes situations where the goal is out of reach, either because it is too far, or because it is inserted in a small cavity that prevents the individual from grasping it directly with its limb. Chimpanzees (*Pan trogolodytes*) for example, insert twigs into holes in termite mounds, to fish for termites (Tomasello & Call, 1997; McGrew, 1992). In the same way, New Caledonian crows (*Corvus moneduloides*) use twigs to extract insect larvae from tree holes in their natural environment (Hunt, 1996, Fig. 1 left). Other forms of 'extension of reach' arise when a stick-like tool is used either to attain an out-of-reach part of the body, or to test depth in an aquatic environment (see Breuer, Ndoundou-Hockemba, & Fishlock, 2005, for an example in an individual from the species *Gorilla gorilla,* Fig. 1 right).

Figure 1. Left: New Caledonian crow using a twig-tool to retrieve food from inside a dead tree (Picture from Michael Sibley, University of Auckland); Right: Gorilla using a branch to test depth of water (Photograph taken from Breuer et al., *PLOS Biology*, 2005).

2.2. Amplification of mechanical force

Hammering is a widespread example of tool use action wherein the mechanical force of the user is amplified. This action is not reserved to humans, as some animals, and especially primates, have been observed for example to crack nuts by placing the nut on a stone (used as an anvil), and cracking it with a second piece of stone used as a hammer (e.g., Inoue-Nakamura and Matsuzawa, 1997). This kind of behaviour has even been shown to be performed with highly skilful strategies comparable to those of humans (e.g., Fragaszy et al., 2013, for an example with capuchin monkeys, *Sapajus libidinosus*).

2.3. Amplification of aggressive or antagonistic behaviours

The use of external objects as weapons makes it possible to augment aggressive or antagonistic behaviours. Humans are not the only species to use weapons to threaten and attack: non-human primates have aslo been shown to brandish or throw sticks and stones during fighting situations (e.g., Goodall, 1986). Other animals have also been observed to exhibit this type of tool use behaviour (see Bentley-Conditt 2010). For example, elephants have been reported to roll objects toward smaller animals to threaten them (Chevalier-Skolnikoff & Liska, 1993).

2.4. Collection and transport of liquids and small solids

This type of tool use involves containing and/or transporting liquids or small solids, as well as absorbing liquids with sponge-like objects. In everyday life, humans regularly use dozens of such tools, such as bottles, plastic containers and boxes, plastic bags and backpacks, etc. In humans, the tool usually first used by infants is the spoon, which allows them to feed properly with liquid food such as applesauce. This tool is also considered as to extend the reach when being held in the hand (see Chapter 2 section 2.1 for a review on spoon-use in infants). Collection and transport of liquids has also been observed in the wild. Chimpanzees for example use leaves to collect fresh water in crevices (Goodall, 1986).

2.5. Body maintenance

Body maintenance is the use of an external object to act on a reachable part of one's body or appearance. Toothbrushes, scissors, hairbrushes and combs are good examples of typical human tools used for body maintenance. In wild animals, one of the most recent examples is stone-rubbing behaviour observed in an adult brown bear (*Ursus arctos*), using stones to scratch his face, neck and arms, presumably to relieve itching skin caused by the moulting of his fur, instead of rubbing himself against a standing object, as brown bears usually do (Deecke, 2012, see Fig 2).

Figure 2. Series of photographs of a brown bear using a stone to scratch parts of his body, adapted from Deecke (*Animal Cognition*, 2012), University of Cumbria.

2.6. Protection of one's own body part

The last category of tool use functions evoked in this section is the use of tools to avoid harm to a part of the body, as when investigating a fire (Seed & Byrne, 2010). In animals, a well-known example is the wearing of sea sponges by dolphins, presumably to protect their rostra when foraging on the sea floor (Mann et al., 2008, Fig. 3).

Figure 3. Picture of a dolphin carrying a sponge. Taken from Mann et al. (*PLOS One*, 2008), Georgetown University.

The most studied tool-functionality in animals and human infants is the first: the use of an external object to extend the reach. More particularly, in the present work we will focus on the use of a tool to retrieve an out-of-reach object. This complex behaviour is considered as to be of the first intelligent behaviours expressed by young infants (Stoytchev, 2007; Piaget, 1936/1952). It requires an understanding of specific causal relations, a key aspect of early cognitive development (Chen & Siegler, 2000). The next chapter describes the development of infants' interactions with objects, from simple manipulation to tool use actions such as these.

Chapter 2. The emergence of tool use

Before they can use tools, infants first have to acquire physical knowledge about objects in the environment. Psychologists agree that this knowledge is based on continuous discovery of the environment with all of the sensory systems that are already present at birth (vision, touch, hearing, smell, and taste). This exploration of the environment requires manual skills. The present chapter begins with a first succinct section surveying infants' behavioural development prior to tool use. More especially, this survey focuses on the development of manual skills from birth to two years of age, which is the period when tool use behaviours emerge.

1. First steps toward tool use

1.1. Behavioural repertoire during the first months of life

At birth, infants suddenly encounter a new external environment. The behavioural repertoire of newborn infants has been described in terms of reflex movements, spontaneous movements and perception-action loops.

Inborn reflexes were widely described by Piaget, as part of the first stage of his theory of sensorimotor development of intelligence (1936/1952). By definition, reflexes refer to stereotyped and elicited behaviours that are not goal directed. Movements such as the sucking reflex (Wolff, 1968), the Moro reflex (Moro & Freudenberg, 1921) and the grasping reflex (von Hofsten, 1984) are typical reflexes which are present at birth. They progressively disappear over the course of development, either being replaced by or integrated into more elaborate and voluntary movements. Other movements, in contrast, such as the postural reflex, continue to play an important role throughout development and are still present in adulthood.

Apart from the reflexes, some behaviours also frequently appear in the absence of any kind of external input. Researchers describe them as 'spontaneous movements': they consist in rhythmical movements with no particular goal, which might play a role in the development of more elaborate movements. One example is non-nutritive sucking behaviour (see Wolff, 1968), which may serve as a training for nutritive sucking behaviour.

Initially, reflexes and spontaneous movements were thought to make up the whole behavioural repertoire of neonates. However, more recently there has been convergent evidence in the developmental literature that most neonatal behaviours are goal-directed and prospective (von Hofsten, 2007). Nutritive sucking behaviours, for example, have been described as being prospectively monitored by neonates in order to adjust milk flow (e.g., Craig & Lee, 1999). Recent studies using ultrasound recording during pregnancy have revealed that certain types of spontaneous behaviours are present before birth; for example, foetuses suck their thumbs in the womb (e.g., Hepper, Wells & Lynch, 2005) and even show planning abilities when performing such behaviours (Zoia, Blason, D'Ottavio, Bulgheroni, Pezzetta, Scabar & Castiello, 2007). Most of these behaviours are integrated into sensorimotor or perception-action loops (von Hofsten, 2004; 2007). On the basis of continuous feedback from their own commands and actions, infants begin to explore their own movements and make goal-directed behaviours in response to the environment. One example is pre-reaching behaviour (Grenier, 1981; von Hofsten, 1984), which neonates perform when presented with a salient object within the visual field and are given enough head support. According to von Hofsten (1984), pre-reaching behaviours decrease during the first two months of life, replaced by the predominance of intense visual activity toward the object.

Over the course of sensorimotor development, infants adapt their behaviours in reaction to the feedback from the environment, through what are known as 'circular reactions'. First introduced by Baldwin (1896), this terms refers to a behavioural response to some stimulus in the environment which not only adapts to the stimulus itself, but also introduces some modifications to old reactions through the influence of environmental changes. According to Eleanor Gibson, this kind of exploration is driven by “intrinsic motivation” (E. Gibson, 1988, p.2) to acquire new knowledge. Piaget (1936/1952) described the first circular reactions as essentially related to the infant's own body movements. For example, infants can become fascinated with observing their hand open and close, and try to repeat this gesture numerous times. After a few months, infants become more focused on the external world and begin to repeat actions in order to cause some particular change in the environment.

1.2. From reaching to efficient grasping

About two months after birth, the first voluntary reaching movements in normal conditions appear, and subsequently undergo progressive improvement, in terms of control motor trajectories, velocity of the hand, accommodation of gravitational force, etc. Reaching also improves with the acquisition of postural stability (Spencer, Vereijken, Diedrich & Thelen, 2000).

Soon after the first reaching behaviours, infants begin to intentionally grasp objects, through active coordination between vision and prehension (von Hofsten & Rönnqvist, 1988). This ability enables infants to successfully grasp objects that are within reach, and spend time exploring them. Object explorations can be uni- or bimanual, sometimes involving oral exploration as well, and involve highly diverse behaviours, such as sliding, banging, squeezing, waving, tearing, rotating, transferring from hand to hand, and fingering the objects (von Hofsten, 2013). As early as seven months of age, infants engage in role-differentiated bimanual actions during object manipulations (Fagard & Pezé, 1997; Corbetta & Thelen, 1996; Kimmerle, Mick & Michel, 1995 ; Fagard & Jacquet, 1989). In behaviours of this type, the two hands have complementary functions, one serving as a support, or stabilizer, while the other explores the object. Exploring activities lead to learn about object properties and affordances. The properties of objects that learned include such characteristics as height, colour and shape. Vision studies using habituation paradigms have shown that abilities such as identifying the height of objects (Hespos & Baillargeon, 2001), or their solidity or continuity (Spelke et al., 1992) emerge before 6 months of age. An important aspect of what infants discover when exploring an objects is its range of affordances. The notion of affordance is a term introduced by James Gibson (1966, 1979), referring to the perception of all the possibilities for physical action related to an object, surface, person or anything else in the environment. For example a handle on a cup provides an affordance for holding. In this sense, an affordance is not only a function of the object's independent characteristics, but also involves the perception of the object through and in relation to one's own motor capacity. With the maturation of new action systems over the course of development, infants learn more and more about the world. This developmental accumulation of information about objects and the environment contributes to infants' intellectual development (E. Gibson, 1988).

1.3. From simple object exploration to complex means-end behaviours

After this initial period of acquiring knowledge about objects, environments and affordances, around 8 months of age infants begin to show clearly intentional actions, attempts to achieve a specific desired effect. This involves not only repeating familiar actions, but also adapting to new situations. Furthermore, around this time infants also start to combine objects with other objects or with the environment, and may also combine several actions in order to achieve a particular goal. Such uses of intermediate actions or 'means' to attain a distinct goal or 'end' are what Piaget called 'means-end behaviours' (1936/1952). Infants' first means-end behaviour is usually performed in the intentional use of a support as a means of bringing an object that it supports within reach. Infants aged 9-10 months of age discover that an out-of-reach toy standing on a cloth (the support) can be retrieved by simply pulling on the cloth (Willatts, 1999; Willatts, 1984; Bates, Carlsonluden & Bretherton, 1980; Uzgiris & Hunt, 1975; Piaget, 1936/1952). This type of behaviour (pulling a combination of supporting and supported objects) are already present earlier in development, but are described as limited to object-retrieval without the intention to reach the object. Infants as young as 6 months can do this, but they do not discriminate between this situation and one in which the object stands beside the cloth instead of on it (Willatts, 1999). Also, when presented with a choice between a cloth with a novel attractive object on top of and another with a less attractive, more familiar object, infants will pull eihter cloth at random (Willats, 1984). A very similar means-end behaviour is string pulling. Slightly later in development than the use of supporting objects to attain supported objects, at around 10-12 months of age, infants pull on strings whose extremity is within reach to retrieve out-of-reach objects that are attached to them (Brown, 1990; Bates, Carlsonluden & Bretherton, 1980; Uzgiris & Hunt, 1975; Piaget, 1936/1952; Richardson, 1932). Likewise, the ability to ignore strings that are not attached to the object also increases around 10 months (Richardson, 1932), suggesting that infants' string-pulling behaviour is goal-directed at this age. Piaget (1936/1952), when testing his own children on the string problem at the end of their first year of life, noted that they discovered the pulling effect of the string through active exploration. In this age period, infants engage in numerous trial-and-error explorations, leading to continuous discovery of new means of action by trying out behaviours and paying attention to their results. The aim of such explorations is the search for novelty, as Piaget explicitly mentioned in the following quotations: “The fifth stage (…) is primarily the stage of elaboration of the 'object'. It is characterized, in effect, by the formation of new schemata which are due no longer to a simple reproduction of fortuitous results but to a sort of experimentation or search for novelty as such.” (1952, p. 264). “The child discovers in this way that which has been called in scientific language the 'experiment in order to see'.” (1952, p. 266). From all explorations and the associated discoveries, new possibilities arise. When holding objects to try doing things with them in relation to the environment, the object becomes part of the self, forming a new “arm + object” system that changes the boundaries between body and environment (Smitsman, 1997, quoted in Smitsman & Corbetta, 2010). This phenomenon allows infants to perform new actions in an enlarged peripersonal space and discover new affordances. According to Piaget, this period also corresponds to the first intelligent use of tools. More precisely, infants begin to use objects such as sticks to bring objects into reach (cf. 'la conduite du bâton', Piaget, 1936). From systematic observations on his own children, Piaget reported that infants develop the use of the stick between 12 and 18 months of age, either by active exploration (for his children Lucienne and Laurent) or by observational learning (for Jacqueline). The author stated that the discovery of the affordance of the stick, namely the possibility of extending the reach of the infant's hand, arises from a combination of the desire for the out-of-reach object on one hand, and infants' usual behaviours such as striking and throwing objects on the other. Making the out-of-reach object move by striking it with the stick, allows infants to discover that the object can be moved with the stick, and as a consequence can be brought into the field of reach.

Finally, around 18 months a new period begins, where infants understand their environment through mental operations, also called 'insight'. At this stage, rather than simply using trial-and-error, wherein they mostly understand through active experimentation, infants faced with a problem-solving situation first think about the situation and how to solve the problem that it presents. This is what Piaget defines as the period of 'early representational thought' period, wherein infants begin to develop mental representations of events or objects in the environment.

1.4. Learning by observation

The learning and acquisition of new skills is influenced not only by infants' own actions on the world, but also by observing other agents performing actions. In particular, imitating actions directed toward objects can accelerate infants' discovery of object properties and affordances. The research literature on imitative development in infants is too vast to be presented in detail in this thesis. However, as we are interested in infants' learning of tool use actions by observation (see Chapters 2, 3 and 5), here we will briefly survey the main steps in the development of observational learning of object-directed actions in infancy. It is important to note that in developmental psychology, the term “observational learning” is used to refer to any type of imitation, both of novel and familiar actions. The term “imitation” is usually restricted to actions that are familiar to the infant, whereas “imitative learning” refers to the learning of novel actions by observation (see Esseily, 2010, pp.16-17 for a review on the taxonomy of learning processes).

Infants begin to imitate object-directed actions performed by external agents at around 6 months of age (Elsner, 2007). For example, they easily imitate the squeezing of a plastic duck or the scratching of a surface with a cube (Abravanel, Levan-Goldschmidt & Stevenson, 1976). At this age, infants' imitation abilities are limited to familiar actions, already present in infants' behavioural repertoire (Piaget, 1951 ; Abravanel et al., 1976). At the end of the first year of life, infants start to imitate simple goal-directed actions with objects, like pushing a button that activates a beeping sound (e.g., Meltzoff, 1988). At this age, infants also learn novel means-end actions by imitation, like opening a transparent box to get an object that is inside it (Esseily, Nadel & Fagard, 2010). During the second year of life, observational learning abilities become more and more flexible (Elsner, 2007). For example, infants become sensitive to verbal cues during demonstration, and to situational constraints. Over the course of the second year of life, infants are able to learn increasingly complex means-end actions by observation, including as tool use actions (e.g., Esseily, Nadel & Fagard, 2010; Chen & Siegler, 2000).

2. Summary of empirical facts about the emergence of tool use

Until recently, the study of the development of tool use behaviours in infants has received relatively little attention (see Keen, 2011, for a recent review). Moreover, the first studies focused on the development of the use of the spoon, a tool with a particular status, as infants have numerous opportunities to observe the use of this tool socially, and to try using this tool themselves. Section 2.1 briefly presents the studies that have been conducted on the development of spoon use during the second year of life. Section 2.2 looks at tool use actions that are much less familiar to infants, namely the use of tools to act on out-of-reach objects. In this section, we describe five important issues that have been raised by experimental studies on tool use in infants. The first aspect (section 2.2.1) concerns the role of perceptual factors in infants' tool use performance, more particularly that of the spatial relationship between the tool and the goal. When infants have overcome the problem posed by spatial configurations either spontaneously or by observation, the second issue that interested researchers is infants' ability to identify the functional affordances of a tool, and to transfer this knowledge to a novel situation (section 2.2.2). A third issue (section 2.2.3) that has been of interest involves infants' planning abilities, as tool use actions require not only planning to achieve a specific goal, but also planning how to achieve this goal efficiently. A fourth issue (section 2.2.4) stress the fact that infants' ability to perform and plan actions involving the use of a tool is influenced by their past experience with that tool. A final issue (section 2.2.5) that has been investigated in some studies is the extent to which infants benefit from demonstration when learning to use a tool.

2.1. The case of the spoon

The spoon is one of the first tools that infants use, soon followed by other tools that are commonly used in everyday life, such as the toothbrush. The spoon is a tool that is specific to humans. Its primary goal is to feed someone by transporting food efficiently from a recipient toward the mouth. This differs in three ways from the tool use actions on out-of-reach objects that will be described in this chapter. The first main difference is that with the spoon, the tool action is directed toward the mouth, which is already a characteristic of actions performed soon after birth, and even in utero, as with thumb sucking. The second difference is that infants have numerous opportunities, starting at 4-5 months of age, to observe other agents using spoon-like tools. The last main difference concerns the action itself and its goal. Spoon use is essentially determined by sociocultural rules, whereas other tool actions discussed in this section are the consequence of physical constraints in the environment, such as the goal being out of the subject's reach. For these reasons, work on the development of spoon use will not be reviewed in much detail here. However, spoon does in a sense make it possible to extend the reach of the hand, as do other tools, such as sticks and rakes. Thus, summarizing work the emergence of spoon-use in infants here is of some interest.

Spoon-use usually develops between 9 months of age and the end of the second year of life. Learning is progressive and develops through observation, experience and trial-and-error (Connolly & Dalgleish, 1989). Around 9-12 months, infants are capable of holding a spoon, but with relatively unplanned grasping strategies and trajectories toward the mouth (McCarty, Clifton & Collard, 2001). Around 14-15 months of age, infants become able to manipulate the spoon toward the food-recipient, but are not able either to fill the spoon efficiently, or to bring the bowl to the mouth without spilling its contents (Gesell & Ilg, 1943). At 18 months, infants are able to fill the spoon, but still have difficulty feeding themselves efficiently without spilling food. However, infants at this age show less variability than younger infants in their grasping patterns, as well as more involvement of the contralateral hand in task-related activities (such as holding the plate), and more stable movements in all components of the task (Connolly & Dalgleish, 1989). Also, in one study, when the spoon was presented at a difficult orientation, i.e., with the handle presented toward the non-preferred hand, 19-month-old infants took into account the spoon's orientation, appropriately adjusting their grip before grasping the spoon (see "correct radial grip" in Fig. 4). On the contrary, younger infants are more likely to use "ulnar-" or "bowl-end grips" when the handle of the spoon is oriented toward their non-preferred hand (McCarty, Clifton & Collard, 1999).

Figure 4. Schematic drawing of the three grips on a spoon: correct radial grip (left), ulnar grip (center), bowl-end grip (right), (from McCarty et al., 1999).

This brief description of infants' spoon use highlights several aspects of the learning of this ability. First, infants have to discover the affordances of the spoon: the handle affords grasping, while the bowl can scoop food during meals (van Roon, Van Der Kamp & Steenbergen, 2003). Then, as investigated by McCarty and colleagues, infants have to choose a suitable grip pattern from among a large variety of possible grips. Finally, they have to learn how to fill the spoon, transport the bowl efficiently into the mouth, and coordinate movements of the hand, head and mouth. In light of these characteristics, spoon use is of particular interest in the domain of the development of motor planning activities to attain a specific goal, which is an issue that has also been investigated using other types of tools.

2.2. Tools to act on out-of-reach objects

Tool use actions are defined by a specific goal (e.g., to obtain an out-of-reach object), and by the subgoal of performing an intermediate action to achieve this goal (e.g., grasp and use a stick to bring the object within reach). Tool use actions can thus been categorized as means-end behaviours. As mentioned above, the first means-end behaviours appear at the end of the first year of life, with the use of pulling behaviours on supporting objects and strings to retrieve other objects. These actions are characterized by the involvement of two objects that are spatially connected to each other: the out-of-reach object is either placed on the supporting object, or directly attached to the string. In the case of tool use, however, the tool is, by definition, detached from the environment, from the tool-user and also from the goal-object. Thus, it is probable that this kind of more complex means-end behaviours develop at the same time as cloth- and string-pulling behaviours. The following subsections give an overview of empirical work on tool use across development.

2.2.1. Perceptual factors and spatial relationships

A well-known experiment investigating the perceptual factors that influence infants' problem-solving abilities is the study of Bates, Carlsonluden and Bretherton (1980). They presented infants aged 9-10 months with the following means-end tasks: using cloth- and string-pulling tasks, as well as hoops, hooks and sticks to bring objects into reach. For some of these tasks, the authors varied perceptual factors (such as colour and texture) and spatial contiguity between tool and toy along a gradient of difficulty (see Fig. 5).

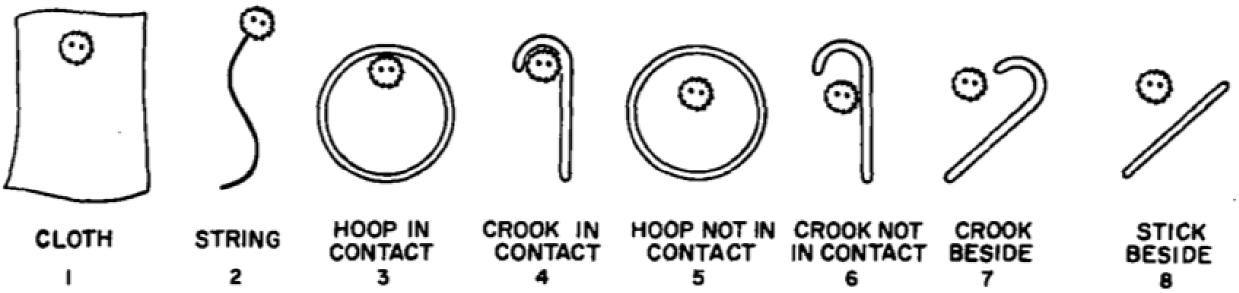

Figure 5. Configurations of tools and objects in one of the experiments conducted by Bates et al., 1980.

Bates et al. found that generally, 10-month-olds had more difficulty solving the the problems when the tool and the goal shared the same colour and texture. Thus, according to the authors, the ability to discriminate the tool and the goal object as two separate entities helps infants uncover the link between the tool and the goal. More importantly, they found that spatial contiguity between the tool and the toy (see conditions 3, 4 and 6) facilitated the infants' performance, while the presence of a spatial gap (as in conditions 5, 7 and 8) made the task very difficult to solve for 10-month-old infants. The main conclusion was that in the absence of spatial contact between tool and toy, “anticipatory imagery” is needed to perceive the function of the tool, which is very difficult for infants of this age (Brown, 1990, p.122). In a similar unpublished experiment, Brown and Slattery (1987, cited in Brown 1990) found that between 13 and 18 months of age, infants could not make contact between the tool and the toy without seeing the solution demonstrated by an adult. In another study, Brown (1990) showed that by 24 months of age, infants become able to spontaneously understand the pulling affordance of tools that are spatially separated from the goal object.

In a similar experiment to that of Bates et al. (1980), van Leeuwen, Smitsman and van Leeuwen (1994), investigated the developmental changes in the use of a hook to retrieve an out-of-reach object, in two age groups (8 to 22 months and 23 months to 3.8 years). The authors varied the number of operations needed to solve the task (see Fig. 6), with the main assumption that not only spatial contiguity between the tool and the toy, but also the number of operations required to perform the task, affects infants' performance. Figure 6 shows the different conditions of spatial relation between the hook and the toy that they used to disentangle the two hypotheses. If the 'contact versus non-contact' hypothesis is correct (cf. the conclusions of Bates et al. above), then infants should succeed equally in conditions *a*, *b* and *d*; whereas if the 'number of operations' hypothesis is correct (van Leeuwen et al.), the infants' performance should decrease from conditions *a* to *e* (with equivalent performances in *e* and *d*), until a certain age where they succeed in all conditions.

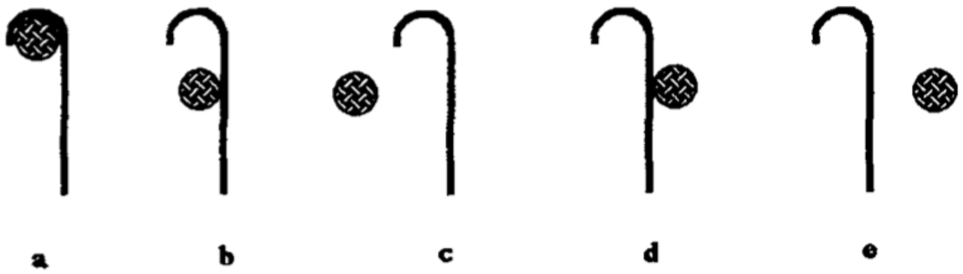

Figure 6. Configurations of hook and toy, in increasing order of difficulty. (From van Leeuwen et al., 1994).

The authors found that the contact hypothesis was not sufficient to explain infants' lack of success in conditions with a spatial gap. Indeed, the infants' performance was generally better in the contact-condition *b* than in *d*, and in the non-contact-condition *c* than in *e*. However, the number of operations hypothesis was only partially validated, as they found another factor that had an effect on infants' performance. This other factor was the perception of the affordance of the tool itself. Indeed, the infants could either perceive the tool as a hook in which the toy can be enclosed (hook affordance) or only take into account the tool's straight handle and use it as a stick (stick affordance). Thus, infants' performance differed according to the functional part of the tool that they used.

In a follow-up experiment, the authors tested infants aged 21.5 months to 25 months on their ability to learn the different hook tasks by demonstration. They presented the same conditions of spatial relationship as those illustrated in Fig. 6 above, in decreasing order of difficulty, that is, from conditions *e* to *a*. The authors showed that as soon as infants succeeded in one difficult condition, either spontaneously or after demonstration, they were able to perform the task spontaneously in all the following easier conditions.

Taken together, these studies highlight the fact that using a tool is more difficult for young infants when the goal and the tool are spatially disconnected. One hypothesis to explain this phenomenon is that in order to perform the task in such conditions, infants have to mentally imagine the connection between the two elements, which is difficult early in the development. Thus, while infants can solve the string- and the support-problems at the end of their first year of life, it is only later in development, about the end of their second year of life, that they develop the ability to use tools. However, it remains unclear how the spatial configuration of tool and goal objects influences infants' understanding of a tool's functionality.

2.2.2. Transfer abilities

As soon as infants are able to use a tool even in the presence of a spatial gap between the tool and the goal, a question arises concerning infants' understanding of the tool. According to some researchers, one way to evaluate true understanding of tool use is to test infants' ability to transfer this competence to another, similar context (Brown, 1990; Piaget, 1936). A well-known paradigm is to present the infants with a selection of tools that are either functional and non-functional for solving a task that they face. In 1990, Brown published a study on early learning transfer in problem-solving tasks in infants between 17 and 36 months of age. She was the first to point out the differences between infants' performance in naturalistic studies on problem solving in comparison with what has been reported in studies conducted in an experimental situation. In a first experiment, Brown designed a series of tool use tasks involving the choice of a functional tool among a set of tools, some of which were non-functional. Infants from three age groups (17-24, 25-30, and 31-36 months) were first trained to successfully retrieve the out-of-reach toy with one of these sets of tools ("learning set", see Fig. 7). Then, another set of tools was presented, containing at least one functional tool ("transfer set", Fig. 7). The infants' task was to choose the correct tool based on its functionality but not on the perceptual features irrelevant to the task, in order to retrieve an out-of-reach object.

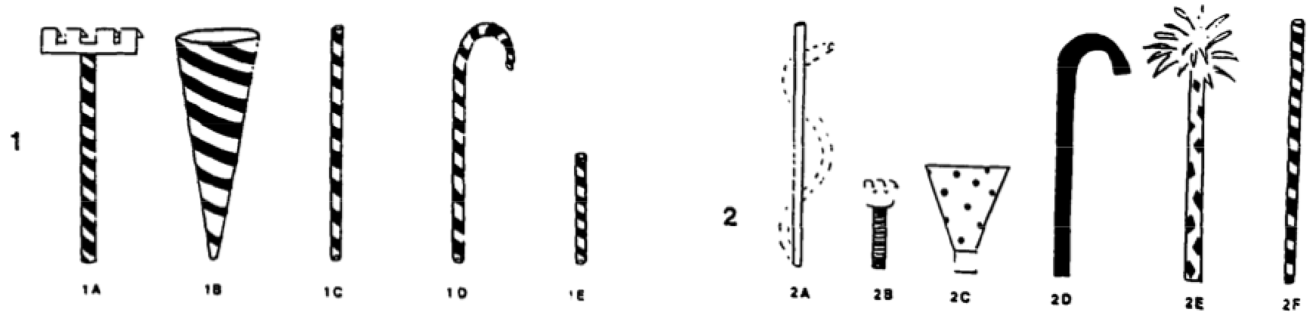

Figure 7. Representative example of a learning set (1) and a transfer set (2) in the first experiment. In this example, the functional tools are respectively the rake (1A) and the hook (1D) in the learning trial, and the hook (2D) in the transfer trial (From Brown, 1990).

As mentioned in the previous section, a first interesting result from this study was that no infants below 24 months of age were able to succeed at the task spontaneously during the learning phase, without first seeing their mother demonstrate the solution. Even between 24 and 30 months, the spontaneous success rate in the learning phase was only about 33%. This first result contrasts with the age at which Piaget found evidence for the spontaneous use of stick-like tools to retrieve out-of-reach objects, and the transfer of this behaviour to other types of tools. The second result concerns infants' ability to transfer their knowledge to a new set of tools immediately after succeeding in the learning phase. The authors found no age differences in infants' transfer abilities. All of them chose the appropriate tool on the basis of its function rather than irrelevant perceptual features. Two additional similar experiments were conducted to control for variables that might have influenced infants' choice (colour, shape, rigidity and length). These experiments also contained an additional test-condition where none of the tools were functional, forcing the infants to choose a non-functional tool. The results of this particular condition showed that the rigid nature of the tool was the most important variable in infants' tool selection, whereas its length was the least important variable, suggesting that infants at this age range had some trouble correctly evaluating the distance between the end of their arm and the inaccessible toy. Taken together, the three experiments confirmed that infants' choice was systematically guided by the pulling affordance of the functional tools. Finally, the author discussed two different possible ways of interpreting the absence of difference in transfer abilities with age. The first possible explanation was that the learning phase and the transfer phase were too similar, making the transfer task easy enough for younger infants to perform at the same level as older infants. The second explanation of the absence of age differences in transfer abilities was that as soon as infants understand the functionality of the tool in a given situation, transferring this knowledge to other similar situations is not an issue. In the same paper, Brown also reported results from a series of experiments on transfer abilities for the string-pulling task, which will be further discussed in the experimental section on the precursors of tool use (Chapter 4).

In an experiment similar to Brown's choice task, Chen and Siegler (2000) tested the transfer abilities of younger (18-24 months) and older (24-36 months) infants. In a first series of trials (pretraining trials), the infants were presented with a choice of six tools, among which only one could be used to retrieve an out-of-reach toy. All infants were encouraged to retrieve the toy, and to use the tool for that purpose, but contrary to Brown's subjects who saw a demonstration of how to solve the task if they were not able to do it spontaneously, Chen and Siegler's subjects were not shown the solution during the pretraining trials. After these first trials, infants were randomly assigned to one out of three instruction conditions: one with no further instruction, one where they received a verbal hint on how to use the tool, or one where they saw four demonstrations by an adult. Two additional trials (posttraining trials) with the same set of tools were then presented. The whole sequence was repeated twice with different sets of tools (rake, cane and ladle) and toys (turtle, bird and doll). Similarly to Brown's findings, the authors pointed out that in the pretraining trials, the infants rarely solved the toy retrieval task spontaneously. This result did not significantly differ between the two age groups. A second result of this study was the significant difference in infants' performance depending on the type of instruction they were given between the pretraining and postraining trials. The hint and demonstration groups performed significantly better after they received either a demonstration or a verbal instruction, whereas the infants in the group that received no further instructions or demonstrations did not improve their performance between the two test phases. Finally, the authors found evidence for transfer-abilities in both age groups. However, older infants transferred more systematically from one trial to another than younger infants, and generally needed fewer trials before being able to transfer.

A first important result that comes out from these studies is that, at least before three years of age, infants' spontaneous performance in tool selection tasks is very poor. Even after several trials, their performance changes little or not at all. In contrast, demonstrations and instructions by an adult help infants as young as 18 months learn to perform the task and transfer this newly acquired knowledge to other sets of tools. In these studies, however, it is difficult to evaluate why the infants needed a demonstration. Was infants' spontaneous failure due to difficulties with using tools and understanding their function spontaneously? Or was it to difficulties with discriminating the functional from non-functional tools? Beginning by presenting infants with only one tool and a goal to be attained would have made it possible to control for this issue.

2.2.3. Planning a tool use action

Experiences that infants gather while acting in the environment guide their actions on the physical world (Barrett, Davis & Needham, 2007), and increase their planning abilities. Infants as young as four months old take into account variables such as the direction and the distance of an object relative to their body in planning their grasping (von Hofsten & Rönnqvist, 1988). When performing a more complex action such as using a tool, infants have several successive actions to perform in order to attain their goal. The first action is to grasp the tool, which researchers have referred to using various terms, such as “grasping phase” (Cox & Smitsman, 2006a), “approach phase” (Claxton, Keen & McCarty, 2003) and “preparation phase” (Claxton, McCarty & Keen, 2009)). The second action is to perform the tool action itself, by transporting the tool toward the goal (“transporting phase”: Cox & Smitsman, 2006a), or in other words to apply the tool to the goal (“application phase”: Claxton et al., 2009). For this reason, tool use particularly well-adapted for evaluating infants' action planning (Smitsman & Corbetta, 2010). These two phases are usually evaluated in two distinct ways in tool use studies: (1) tool grasping and hand change strategies, and (2) time to grasp or to attain the goal. To our knowledge, apart from McCarty et al.'s studies with the spoon (2001, 1999), only one experiment has focused on investigating infants' planning abilities as manifested in a tool use action. Cox and Smitsman (2006a) evaluated infants' grasping strategies in a series of retrieval tasks with a stick and a hook. In an earlier study (see Cox & Smitsman 2006c), the authors observed that effective tool use actions with a hook or a stick were easier to perform with a so called "sweeping movement". It is easier to perform this movement successfully with the hand contralateral to the side of the object (with the tool in a central position relative to the child), to "realize a suitable alignment of tool and object, in which the tool is held orthogonal to the object's movement path that stretches diagonally across the table" (Cox and Smitsman, 2006a, p.631). The aim of this action planning study was to evaluate change through development in the dependency of infants' grasping strategies on the position that the toy had to be pulled in from (in a hole either at the infants' left or their right, see Fig. 8). In a first experiment, they presented two- and three-year-old infants with a centrally and horizontally positioned stick, and a small toy behind the stick. The toy had to be brought into a hole either to the left or the right side of the infant (see Fig. 8a).

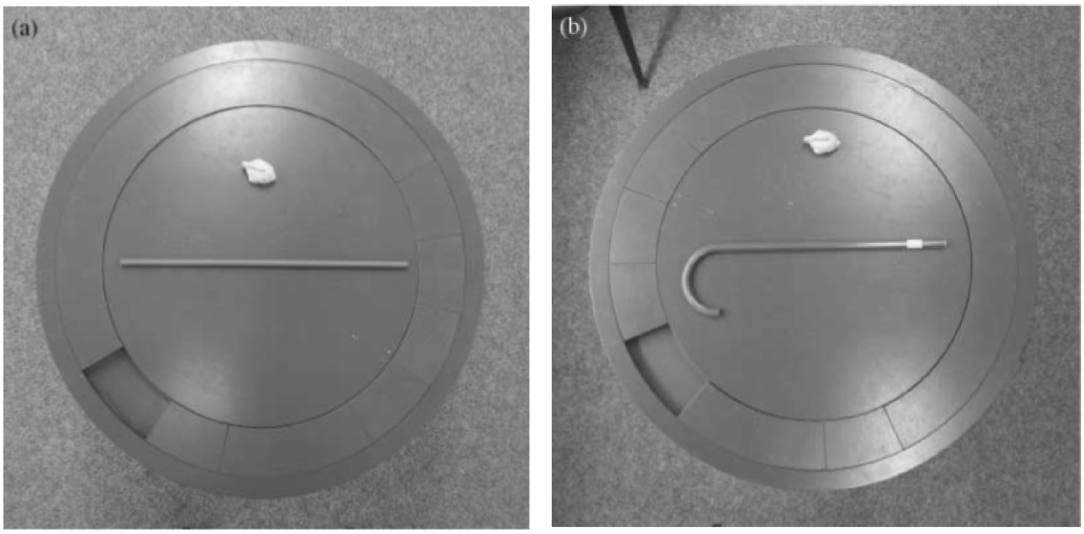

Figure 8. Configurations of the two experiments of Cox & Smitsman, 2006a. In both tasks (*a* and *b*), the toys were placed in a central position behind the tool. The toy had to be pulled in a hole close to the child, either on the right or the left side of the table. In both pictures here the hole is illustrated on the left side of the subject. In *b*, the situation with the hole to the left does not present a conflict, whereas the hole to the right does present a conflict (From Cox & Smitsman 2006a).

The authors found a significant difference, in terms of hand choice, between the grasping strategies of older infants, who grasped the tool more often with the hand contralateral to the toy, and those of younger infants, who were more influenced by their right-hand preference. It is worth noting here that the authors did not test individual hand preference, but considered that infants were generally right-handed. However, these results confirm McCarty's observations with younger infants and simpler tasks (McCarty et al., 1999). In a second experiment, Cox and Smitsman added an additional constraint to the task by replacing a stick with a cane, and varying the position of the hook (either to the left or to the right: see Fig 8*b*). With this new configuration, the task became asymmetrical, which can lead infants to a conflict in hand choice between the side of the hole and the side where the functional extremity of the tool is located. The results showed that both elements influenced infants' initial hand choice and their hand change during the task, at two and three years respectively. The authors explained the difference in the two-year-olds' planning strategies between the two experiments in terms of perception of the affordance of the tool. With the cane, the older infants immediately perceived that the tool afforded enclosure of the object, which accordingly directed their choice to the side of the hole into which the object had to be pulled.

This study illustrates how infants' planning abilities are mediated by various internal and external inputs. Internal factors, in this example, include hand and motor preference, as well as dexterity with the tool. External factors include perceptual sources of information. The authors stress that these factors are integrated together in a “dynamic action-selection process” (Cox & Smitsman, 2006a).

2.2.4. Familiarity versus novelty of the tool

Along with internal and external factors, past experiences with a tool also influence infants' actions and planning abilities, notably in terms of the flexibility of the action. In other words, the knowledge we have of a particular tool may somehow influence or constrain our use of this tool. Here we present several studies investigating the extent to which familiarity with a tool influences infants' performance of a particular action, and, how much experience is needed to observe such an influence, if any.

To test this question, Barrett, Davis and Needham (2007) looked at how infants' prior experience with a tool influenced their performance of an unfamiliar action. The authors hypothesized that, due to experience, infants would be less likely to use a familiar tool than an unfamiliar one in an appropriate way in a novel situation. They tested 12-18 month-old infants' ability to learn a new tool action with either a familiar tool (a spoon) or a very similar but novel tool (see Fig. 9) by imitation. The action was to insert the end of the tool into an opening in a box in order to switch on a light. This kind of action is not novel in terms of the required motor repertoire, as infants are used to inserting objects into apertures from the beginning of the second year of life. However, the infants were expected never to have encountered a situation where inserting something into a box had a direct effect such as causing light to be emitted. In half of the trials, the opening was small, so that only the straight end of the tool could be inserted, whereas the bowl end could not.

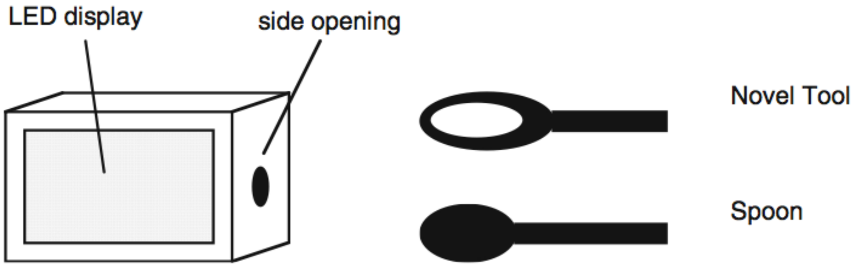

Figure 9. Illustration of the light box, the novel tool and the familiar tool (spoon) presented in Barrett, Davis & Needham's first experiment (2007). Both tools had a straight end (handle) and a bowl-end (From Barrett et al., 2007).

In accordance with their main hypothesis, the authors found that infants were less likely to use the familiar spoon appropriately (i.e., insert the straight end when the opening was small), in comparison with the novel tool. Interestingly, older infants grasped the bowl end of both tools more often than did younger infants, and were also more likely to change hands between the grasping phase and their first attempt to insert the tool. Prima facie, this result seems to compete with the authors' familiarity hypothesis, as older infants should have more experience with the spoon than younger infants. Thus, on this hypothesis, older infants should have expressed a stronger bias toward a familiar action (i.e., grasping the spoon at the handle rather than at the bowl end) than younger infants. The authors argued that instead the older infants' actions toward the spoon were more flexible than those of younger infants because of a refinement of their cognitive abilities. Moreover, this age effect was not found in a follow-up experiment with infants within the same age range. This second experiment aimed to test the familiarity hypothesis with a single tool, thus eliminating the potential differences of shape between the spoon and the previous 'novel tool'. Infants were familiarized during a whole week with the performance of on an insertion task using the same novel tool as the one presented in the first experiment seen in Figure 9 above. One group was trained to grasp the tool at its handle, another group was trained to grasp the tool at the bowl end, and a third group was alternately trained on both types of grasping. After the one-week familiarization period, the infants were presented with two novel tasks: an insertion task requiring them to insert the straight end of the tool into an opening, and a tracking task requiring them to use the bowl end. The results showed significant biases toward the familiar type of grasp when trying to perform both of the tasks, influencing success rate.

With this pair of experiments, the authors showed that familiarity (past experience) with a tool not only influences the type of actions that infants perform with the tool, but even influences their initial action on the tool itself. This familiarity can have an effect even on a small time-scale, as infants in the second experiment only had one week of experience with the new tool. In fact, Smitsman and Cox (2008) found that even the familiarity accumulated within a single session can influence infants' action with a tool. In a first experiment, they studied the extent to which 3-year-old children's previous exclusive experience of either the 'pushing or pulling function of an L-shaped tool would influence their performance when the goal changed, requiring them to perform the other action (pulling or pushing respectively). They found that familiarization with one particular action during four consecutive trials creates a bias toward this action when the goal is changed on the following trial, theoretically requiring the child to perform another action to achieve the goal of the task efficiently. Similarly, in a second experiment, they tested the grasping strategies of 3-year-old children toward a spoon. The handle of the spoon was presented centrally, after having been presented in a left or right orientation during four consecutive trials, thus influencing infants' hand choice to grasp the spoon (see Fig. 10).

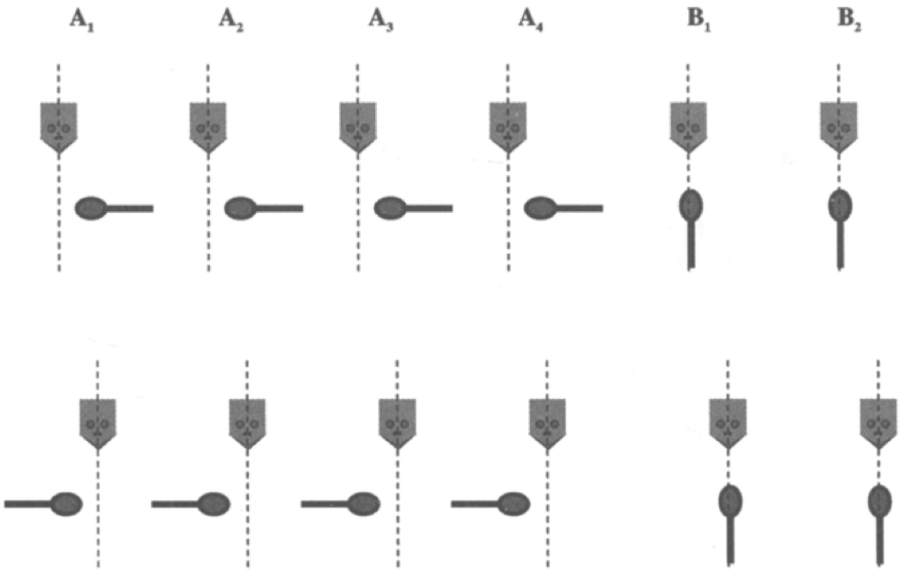

Figure 10. Configuration of the second experiment of Smitsman & Cox, 2008. The spoon was presented four times with its handle oriented either to the right or the left, and then presented centrally (From Smitsman Cox, 2008).

Again, the authors found that hand choice during the four first trials influenced the infants' hand choice when the spoon was presented centrally.

To sum up, these studies show that infants' past experiences with a tool strongly influence the way they use it. Infants' performance with familiar tools in novel situations can be hampered by previous knowledge of these tools that infants have acquired. In addition, a very short experience with a tool suffices to affect actions that are performed with it—such as how it is grasped. Taken together with section 2.2.3, we see that past experiences, internal and external factors act together in a continuous and dynamic interplay to determine how infants use a tool in both familiar and unfamiliar situations.

2.2.5. social learning of tool use

Demonstrations of a tool use action can facilitate infants' understanding and use of tools (Björklund, 2011). Among the studies on the emergence of tool use previously described in this chapter, more than half explored infants' ability to perform a task with a tool after one or more demonstrations by an adult. For example, in their transfer studies, both Brown (1990) and Chen and Siegler (2000) showed that most children under 30 months of age failed to spontaneously find a solution to problems requiring them to use a tool to retrieve an object, but that they could succeed after demonstration by an adult from 18 months onward. It is worth noting that several abilities were evaluated in this type of task. First, children have to select the correct tool (“choice-task”) and then to use it to retrieve the object (“retrieval-task”). Thus it is not straightforward in these cases to determine which of these sub-tasks, retrieval or choice, the demonstration helped the children to perform.

In simple tool use situations, where infants are presented with a tool that is spatially separated from the goal, few studies have tested the effect of demonstrations of the tool action. For example, in van Leeuwen et al.'s (1994) experiments investigating their number of operations hypothesis, more than half of the children aged 21.5-25 months benefited from seeing a demonstration of the hook task. According to Brown (1990), infants can benefit from the demonstration of tool use action at a still-younger age. She reports on an experiment by Brown and Slattery (1987, unpublished data, in Brown, 1990), showing that 13-18 month-olds “can learn, with a demonstration, to envision the point of contact” between the toy and the tool (Brown, 1990, p.123). However, since to our knowledge this study has not yet been published, the conditions in which infants benefit from the demonstrations are not clear. The only experiments explicitly investigating the effect of the demonstration of tool use actions in young infants are two studies conducted in parallel, one with infants (Esseily, Nadel & Fagard, 2010) and another similar study comparing young infants and macaques (Fattori, Brevegliery, Bosco, Marzocchi, Esseily & Fagard, 2008). Both studies evaluated the performance of infants aged 8 to 18 months on different means-end task, both spontaneously and after demonstration. Means-end tasks of varying difficulty were chosen, in accordance with the age of the infants. Thus, younger infants (8-, 10- and 12-month-olds) were tested on simple tasks not involving the use of tools. Infants of 15 months were tested on a rake task requiring them to retrieve an out-of-reach toy, and 18-month-olds were presented with a box and a velcro-covered stick that would allow them to retrieve an object that was stuck in the box. Infants were able to learn the tasks by observation starting at 12 months of age. Thus, 15- and 18-month-olds succeeded better at the tasks involving tool use after observing it demonstrated. In contrast, none of the tested macaques in Fattori et al. (2008) were able to solve the task either spontaneously or after observation. Even after observation, however, the infants' success rate remained remarkably low. For example, the success rate on the rake task at 15 months was around 30% after observation, as compared with 12% spontaneous success. This is somewhat striking given that, as reported in the review of infants' development of object manipulations above (see section 1, this chapter) that infants are proficient imitators of simple actions starting at 8 months of age, and for means-end tasks starting at 12 months of age. However, there is still a dearth of studies that systematically investigate the development of infants' abilities to learn to use tools by demonstration during their second year of life. Thus, the questions of when infants become sensitive to the demonstration of a tool, and how direct and indirect demonstrations influence human infants' learning of tools remain open.

3. Developmental perspectives on the emergence of tool use

The developmental origins of the capacity to use tools have been the subject of controversy in recent decades. A number of perspectives on how tool use develops in human infants and non-human animals have been articulated. One debate concerns the question of whether using tools requires sensitivity to physical principles, or whether no particular form of causal understanding is required to use tools (McCormack, Hoerl & Butterfill, 2011). From this question arises the second main debate: if tool use indeed involves causal understanding, how does this causal cognition arise? Through what mechanisms does causal understanding of tool use develop? This section presents an overview of the different perspectives on these issues presented to explain the emergence the ability to use tools.

3.1. Does tool use require causal understanding?

By definition, means-end behaviours involve attaining a desired goal by means of intentional actions. But does performing those “intentional actions” necessarily imply a true understanding of the mechanical relations between these actions and the desired effect? Let us take the example of the first means-end behaviour that emerges in infants during their first year of life: pulling a cloth to bring closer an object that is laying on top of it. Willatts' (1984) observed that 6-month-old infants were able to successfully bring the object into reach by pulling the cloth. This behaviour was expressed in the absence of a clear understanding of the relations between the cloth and the object, as when presented with two cloths, only one of them supporting an object, the six-month-olds chose a cloth at random, independently of the position of the object. Piaget (1936/1952) defined these means-end behaviours without clear intention as transitional behaviours, where infants can perform the task effectively, but are not able to effectively perceive the solution as such. In their review of cognitive skills and abilities in tool use and tool making, Bushnell, Sidman and Brugger (2006) also raised this question about the need to understand the mechanical relations between means and end. They refer to the example of Schlesinger and Langer (1999), who tested infants aged 8 and 12 months on a tool use task, as well as a cloth-pulling task similar to the one from Willatts (1999). One group of infants was presented with the task (pulling either a cloth or a hook to retrieve an out-of-reach toy), several times, with the toy positioned either in contact or not in contact with the tool. They showed that infants as young as 8 months were able to use the cloth to intentionally retrieve the toy, and that 12-month-olds succeeded on the hook task. In a second experiment, they contrasted these observations with observations of infants who had no direct access to the hook or the tool, but who were shown visual displays of possible versus impossible versions of the performance of same tasks (the toy being retrieved with the hook or the cloth, in conditions either of contact or no contact). In the "impossible" condition, the toy appeared to be retrieved without contact with the hook or the cloth. The authors found a delay between the ages where infants could perform the two means-end tasks (i.e., 8 months for the cloth and 12 months for the tool) and the ages where infants displayed discriminative mean looking times between possible and impossible events (12 months for the cloth, and above 12 months for the hook). The researchers interpreted their results as a developmental shift between causal action and causal perception, from a Piagetian point of view. The fact that the infants could use the hook before showing complete causal understanding supports the hypothesis that tool use does not necessarily imply that these cognitive abilities are in place.

However, from a critical point of view, two aspects of these results merit examination. First, the study stopped at 12 months, and the authors did not continue testing the looking-time paradigm for the hook task at a later age to precisely determine the age at which infants actually discriminate between possible and impossible events (if they do discriminate). A second point is the authors' interpretation of "successful" behaviours on the hook task. In the no-contact condition of the action-part of the experiment, a trial was classified as successful when infants "offered the tool to the experimenter" or "dropped tool on the floor, etc." (Schlesinger & Langer, 2000, p. 198). These behaviours were interpreted as evidence that the infants had understood that the tool and the toy were not in the appropriate spatial conditions to allow them to solve the task. However, it could also be hypothesized that success in the contact condition was due to the proximity of the tool and the toy in itself, as the toy lay in the trajectory of the tool and thus could be retrieved without the infant's thinking about the tool as a tool. Thus, in the no-contact condition, behaviours such as giving or discarding the tool may reflect the infants' inability to figure out what to do with the hook, rather than any form of success. Schmuckler (2011) also raised this issue in a discussion of Schlesinger and Langer's study, and on his own results on a similar experiment (Cheng & Schmuckler, 2008). The authors asked 8-, 12- and 16-month-old infants to perform a similar tool action with a hook, and to discriminate between possible and impossible tool use events. Although they found age differences in the action task, with 12- and 16-months olds performing better than younger infants, they observed that none of the infants demonstrated truly competent tool use. Even at 16 months, all infants' performance was far from the highest score of true competency in tool use (Schmuckler, 2011, p. 254). In contrast, and similarly to Schlesinger and Langer's prediction in the vision part of their experiment, they found that 16-month-olds were able to discriminate between possible and impossible events. These latter results call into question the conclusion of Schlesinger and Langer about the precedence of causal perception over causal action in a tool use situation.

3.2. The cognitive perspective

According to the cognitive perspective, tool use behaviours find their origins in a cognitive change leading to a sudden insight into the potential connection between the tool and the goal. This insight is preceded by a period of unsuccessful trials, as described by Köhler (1925) in his series of empirical observations in captive chimpanzees. Anthropoid apes are good models to investigate the question of how tool use behaviours emerge as they share more traits with humans (such as body and brain structures) than with “lower apes” (Köhler, 1925, p.1), but who are almost never confronted to such problems, contrary to human adults who encounter such situations in their everyday life. Köhler presented nine chimpanzees with different means-end tasks, among them tasks involving the use of external objects that were already present in the environment. Köhler often observed that the animals did not solve the tasks spontaneously, but first showed signs of great frustration. The following text (Box 1) is a representative extract of the behaviours that Köhler observed in the nine chimpanzees. In this extract, Nueva, a female chimpanzee, is faced with an out-of-reach banana standing outside of the cage.

“She grasps at it, vainly of course, and then begins the characteristic complaint of the chimpanzee: she thrusts both lips—especially the lower—forward, for a couple of inches, gazes imploringly at the observer, utters whimpering sounds, and finally flings herself on to the ground on her back—a gesture most eloquent of despair, which may be observed on other occasions as well. Thus, between lamentations and entreaties, some time passes, until—about seven minutes after the fruit has been exhibited to her—she suddenly casts a look at the stick, ceases her moaning, seizes the stick, stretches it out of the cage, and succeeds, though somewhat clumsily, in drawing the bananas within arm's length.”

Box 1: Extract from Köhler (1925), *The mentality of Apes*, p. 33.

Applied to human infants the cognitive perspective predicts a discontinuity in the development of their capacity to manipulate objects, and more especially tools. This discontinuity is attributed to cognitive changes leading to the sudden understanding of an object's functionality as a tool. Such cognitive changes are linked to other newly acquired knowledge, such as physical knowledge about objects (e.g., Hespos & Baillargeon, 2006, for infants' knowledge about supporting objects), knowledge about means-end behaviours (e.g., Willatts, 1999), the ability to represent events or objects mentally (e.g., Piaget, 1936/1952) and enhanced attentional skills (e.g., Bushnell & Boudreau, 1998). However, Matheson (1931), in his replication of Köhler's experiments with young infants, investigated whether infants aged two to three years would show a degree of insight similar to chimpanzees when confronted with similar problem-solving tasks. The author reported that, at least before three years of age, infants rarely solved the task by insight. The behaviours he observed on different string and tool tasks were closer to simple trial-and-error, as the children made pointing gestures and tried out various object manipulations before eventually succeeding on the tasks.

3.3. The perception-action perspective

Lockman (2000, see also Gibson & Pick, 2000) presented the perception-action perspective on the development of tool use in infancy. On this view, tool use arises from a cumulative result of infants' sensorimotor explorations during their first year of life. On the basis of these perception-action experiences, infants develop their manual skills and dexterity, and gradually learn about object-object interactions, as described in Piaget's account of sensorimotor development. In the perception-action view, and in contrast with the cognitive view, the emergence of tool use is embedded in a continuous developmental process that runs from early exploratory behaviours to more complex manipulations and means-end behaviours such as tool use. Action serves here as a mediator for knowledge about the affordances of objects, but does not necessarily require some new level of representation (Schmuckler, 2011). On this view, the study of the emergence of tool use should start at a very early stage in development, to allow for the continuous evaluation of infants' perceptual and motor skills from simple object manipulations until the beginning of tool use (Guerin, Krüger & Kraft, 2013). For example, the study of infants' patterns of banging objects on surfaces should provide meaningful information on the way infants learn about the possible functions of objects, such as hammering (Kahrs, Jung & Lockman, 2012; Greif & Needham, 2011; Lockman, 2000). The expression of complex manipulatory behaviours has already been pointed out as a possible precursor of tool use. For example, Vauclair and Bard (1983) reported that human infants perform more complex manipulatory behaviours (such as bimanual explorations, exploring objects while holding them, etc.) than young chimpanzees and bonobos. Moreover, human children develop complex skills very early in their development, whereas such skills are only present during adulthood these other primate species. From a similar perspective, Kenward, Schloegl, Rutz, Weir, Bugnyar and Kacelnik (2011) showed that tool-using crows developed significantly more combinatory behaviours with objects before using tools, while the tendency in non-tool-using crows was for these behaviours to decrease and disappear.

3.4. Social influence

The three perspectives described above do not specify the role of social influence in the transmission and learning of tool-using skills. Humans show complex social behaviours, involving not only imitation but also teaching and complex collaborative activities (Vaesen, 2012). Several animal species, and especially non-human primates, engage in different forms of socio-cultural transmission, but to a limited extent in comparison to human social behaviours. Tomasello (1999) reviewed the social behaviours that nonhuman primates do not express in their natural environments: pointing objects out to others, holding and showing objects to others, actively offering objects to others, and most importantly, intentionally teaching new behaviours to others. To a limited extent, the influence of social interactions in the learning of tool use during development has been addressed both in human infants (as described in the previous section) and animals. For instance, two-year-old human infants were reported to imitate a tool use action significantly more than its goal (known as “true imitation”), whereas young chimpanzees are more likely to reproduce the goal than the action (also called “emulation”, Nagell, Olguin, Tomasello, 1993). By reproducing the demonstrator's action (e.g., using a rake to retrieve an object), an individual is more likely to discover the affordance of the tool itself than when they try to reproduce only the goal (e.g., retrieving an object by any means). Vauclair (1993) pointed out another social difference between juvenile chimpanzees and human infants in his comparative report on tool use and object manipulation in the two species (1993): human infants and adults often engage in mutual communication during manipulatory behaviours, whereas adults' chimpanzees do not usually intervene in explorations by their infant (Bard & Vauclair, 1984). Other tool-using species, such as juvenile New Caledonian crows, have been shown to develop tool-using behaviours even in the absence of social demonstrators, and at the same time as juveniles who have been exposed to regular demonstrations (Kenward, Rutz, Weir & Kacelnik, 2006). The socio-cultural differences between human and non-human animals is one issue that has been suggested by some researchers as an explanation for the much greater variability and complexity of human tool use as compared to non-human animal tool use (e.g., Vaesen, 2012; Vauclair, 1993).

As a conclusion regarding these perspectives on tool use development, it is worth noting that some of them have been presented in direct opposition to each other. For example, the continuous perception-action perspective was proposed as an alternative to the discontinuous cognitive perspective involving sudden insight. According to some researchers, however (see for example Guerin, Krüger & Kraft, 2013; Keen, 2011; Vauclair, 1993), tool use learning arises from complex and continuous interactions between cognitive, perceptive, social and motor systems. For example, Guerin, Krüger & Kraft (2013) presented a interesting overview of the interactions between sensorimotor behaviours (“concrete track”, see Fig. 11) and representations of the physical world (“abstract track”) that infants develop on the basis of their sensorimotor experience until they reach the stage of tool use. Figure 11 illustrates these interactions, starting at a simple level (Stage 1) wherein sensorimotor behaviours progressively lead to the development of simple representations of the world, which in turn influence new sensorimotor behaviours. At some point, on the strength of accumulated sensorimotor experiences, infants begin to link some representations to each other, provoking the development of new kinds of representations that make new sensorimotor experiences possible (Stage 2, 3...). Thus, the apparent insights that have been proposed as a factor in the emergence of tool use from the cognitive perspective, arise out of the continuous exploration of the world in a rich physical and social context, leading to the development of complex representations such as the ones involved in tool use.

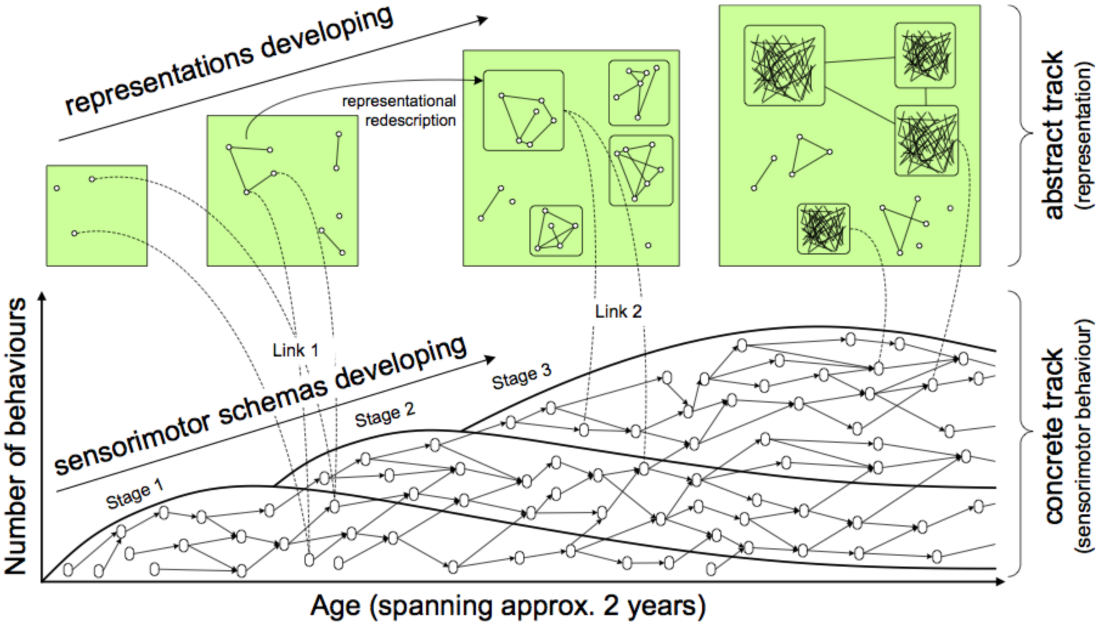

Figure 11. schematic overview of the developments leading to tool use (From Guerin, Krüger & Kraft, 2013).

As Keen mentioned in her review of the development of problem-solving in children (2011, p.3), “perception, cognition, and motor development are so intertwined and related that it is usually unwise to study a single process in isolation. […] even language and attachment are related to problem solving”. In the present work, we have sought to investigate the emergence of tool use in infants by taking most of these aspects into account.

4. What is missing? Main objectives of the present thesis

As this review of literature has highlighted, very little work has been published on the emergence of tool use in infancy, despite a resurgence of interest on the topic in the last decade. In addition, most of the studies that have been done so have isolated and described a single factor potentially involved in the learning of tool use, whereas no study has actually focused on the overall development of this capacity. Moreover, existing studies on the emergence of tool use have been conducted either on a single small age span (e.g., Brown, 1990: Esseily et al., 2010) or on comparisons between two or three broad age groups (e.g., Brown, 1990; Chen & Siegler, 2000; van Leeuwen et al., 1994). Thus, it is difficult to derive a clear picture of the developmental steps leading to tool use during the second year of life on the basis of existing studies. Finally, most recent reports on the emergence of tool use in infants point out that the mechanisms involved in tool use are still unknown. Stoytchev, for example, in his recent work on the elaboration of a developmental approach to autonomous tool use in artificial intelligent systems mentions that: “After ninety years of tool-using experiments with animals, there is still no comprehensive theory attempting to explain the origins, development, and learning of tool behaviours in living organisms” (Stoytchev, 2007). In the present thesis, we aim to contribute some more systematic studies on the bases of the development of tool use in humans during the first two years of life, by jointly considering three aspects: spontaneous tool use, prerequisites for tool use, and the role of observational learning in the acquisition of tool use. The ultimate aim of this work is to better understand how tool use abilities emerge in human infants, and to try to infer what might be some of the mechanisms involved in this development.

4.1. Developmental steps leading to tool use

Chapter 3 aims to clearly draw the developmental sequence of tool use during the second year of life. We report longitudinal and cross-sectional data from 12 to 22 months of age on a tool task involving the use of a rake to retrieve an out-of-reach object. The position of the tool relative to the goal varied in increasing order of difficulty to further investigate the role of spatial relationships between tool and goal. Although here the role of demonstrations was not the main point of interest, as it was in later experiments, we nevertheless systematically included demonstrations by an adult when infants failed in some condition. We performed a detailed analysis, identifying 26 behavioural patterns, in order to evaluate the infants' understanding of the rake's functionality. Finally, we investigated the extent to which infants plan their actions when using a rake to retrieve an object.

4.2. Prerequisites leading to tool use

The longitudinal and cross-sectional studies in Chapter 3 raise several questions about what infants perceive of the physical relations between objects, and in particular their connectedness. A first question that will be briefly addressed in **Chapter 4** concerns the perception of composite objects. This work was motivated by the intriguing observation that, at an age where infants do not seem to understand that a tool may help retrieve an out-of-reach object, they nevertheless immediately grasp the tool if the object is attached to its end. Earlier studies also reported this phenomenon in macaques, which are non tool-using monkeys. We thus wondered at what age and in what conditions infants start to perceive a composite object as a whole, making infants act on a proximal part of the object to act on a distal, interesting part, of an object.

The second question is directly related to the first. As very young infants perceive and experience that two connected objects can move together, it seems that the notion of connectedness is acquired quite early in development. However, infants have difficulty using this knowledge when the task involves more components. For example, infants in the middle of their second year of life are able to successfully retrieve a toy attached to a string to bring the object into reach. However, these same infants fail if the situation involves choosing the connected string among a set that also includes non-connected strings. We pose here the question of the perceptual and attentional abilities involved in infants' means-end behaviours, along with those involved in tool use.

4.3. Observational learning of tool use

The data from the two studies in Chapter 3 are unequivocal about the rather late effect of demonstrations of tool use in infants' development. In **Chapter 5** we look at why the observational learning of tool use appears so much later for tool use than for other means-end behaviours. We present data from a study investigating whether additional information about the demonstrator's intention during a tool use action helps infants to learn by observation earlier in development.

Part II Experimental work

Chapter 3. Principal steps in tool use

1. Introduction

As described in the previous chapter, infants' capacities to use tools efficiently is influenced by the spatial relationship between the goal object and the tool, as well as by past experience and planning abilities. However, two important issues have been neglected in research on the emergence of tool use in infants. First, we do not yet have a precise picture of the developmental steps leading to tool use. Apart from a few studies on the mastery of self-feeding with the spoon (McCarty et al., 1999; 2001), and the work of Piaget (1936/1952) on the description of the development of stick use, systematic experimental work investigating how tool use emerges during infancy is still lacking. Doing such work is the first aim of the two studies presented in this chapter. The second issue concerns the developmental mechanisms through which tool use emerges. As stressed in the conclusion of the last chapter, we still lack insight on how exactly tool use develops. Is it by sudden insight or by progressive familiarization with tool affordances? Do infants need to observe a model before being able to use tools?

The development of infants' acquisition of skills can be investigated using different methods. One method is to observe infants' daily experience with objects in different contexts until the skill emerges. However, this type of “naturalistic observation” is very time-consuming and involves many external elements that cannot be controlled from one child to another. For this reason, experimental psychologists usually explore the emergence of a capacity either with longitudinal or cross-sectional experiments. Longitudinal studies are based on regular observations (e.g., every day, week or month) during a specific period during development of infants' behaviour and performance on particular controlled tasks. In cross-sectional studies, on the other hand, the performance of independent age-groups on controlled task is observed, with each infant only observed once. The two methods represent complementary ways of exploring a given issue in development. Both types of studies are of interest with regard to the two issues that I am focussing on here. Longitudinal studies are particularly well-adapted for use in investigating the process by which infants achieve mastery of a particular skill (Keen, 2011). As longitudinal studies in developmental research are usually conducted on small numbers of infants, cross-sectional studies can be used to replicate their findings on a larger scale and to control for the influence of experience and familiarity that infants from longitudinal studies may have gathered over the course of various sessions.

Section 1 briefly describes a longitudinal study on five infants observed every month from 12 to 22 months of age. This study was conducted in our laboratory before the beginning of the present thesis. However, it is of importance to look at this study in the first section for the two following reasons. First, the results of this longitudinal study are closely linked to the whole of the present work, and in particular to the study presented in Section 2 of this chapter. Moreover, the scoring scale of the longitudinal study is a joint work, which was produced in collaboration and which has been reused in all of our further studies on tool use. Thus, in section 1 here I present the longitudinal study (quite briefly), with particular emphasis on the methods and scoring. Two papers linked to this experimental work (Fagard, Rat-Fischer & O'Regan, 2012; Fagard, Rat-Fischer & O'Regan, *submitted*), can be found in appendices 2 and 3 of the thesis.

Section 2 presents a cross-sectional study, which investigates similar questions to the longitudinal experiment in a more controlled framework and on 60 infants aged 14, 16, 18, 20 and 22 months (Rat-Fischer, O'Regan & Fagard, 2012a).

In section 3, on the basis of the cross-sectional data, we evaluated infants' planning abilities in a tool use action to retrieve an out-of-reach object, in relation with their hand-preference (Rat-Fischer, O'Regan & Fagard, 2012b).

2. Brief description of the longitudinal study

Contribution to the study

This study was designed and conducted by J. Fagard and J.K. O'Regan. The data were coded by J. Fagard, A.-Y. Jacquet, L. Rat-Fischer and J.K. O'Regan. All authors of the paper participated in the creation of the scoring system, the discussions and the interpretation of the data. Two papers were written on the basis of this study by J. Fagard and J.K. O'Regan, and can be found in the appendices of the thesis (Appendices 2 and 3).

2.1. Goals of the study

The goals of this study conducted by J. Fagard and J.K. O'Regan were, first, to characterize the steps in infants' development toward tool use, and second, to investigate the possible mechanisms leading to the emergence of this capacity by following the development of tool use in individual infants.

2.2. Methods

Four infants aged 12 months at the beginning of the study, were tested on a regular basis (approx. every 1 to 1.5 months) on a tool use task until the age of 20 months. The subjects were presented with an out-of-reach attractive toy and a white T-shaped rake-like tool placed centrally on the table. As we know from the developmental literature that infants' difficulty with using tools is related to the spatial relationship between the tool and the object (e.g., Bates, Carlsonluden, & Bretherton, 1980; van Leeuwen, Smitsman, & van Leeuwen, 1994), several spatial configuration conditions were presented (see Fig. 1). The conditions were presented in increasing order of difficulty, according to van Leeuwen et al.'s (1994) description of the number of steps needed to complete the task. Thus, in the first condition (C1), the tool and the out-of-reach toy were attached to each other, forming a single “composite-object”. In condition C2, the toy was placed against the rake, inside its trajectory. In condition C3, the toy was also inside the tool's trajectory, but not in contact with it. In C4, the toy was outside the rake's trajectory and not in contact with it. Finally, in C5, the out-of-reach toy was presented centrally on the table, and the tool was placed directly in the infant's hand.

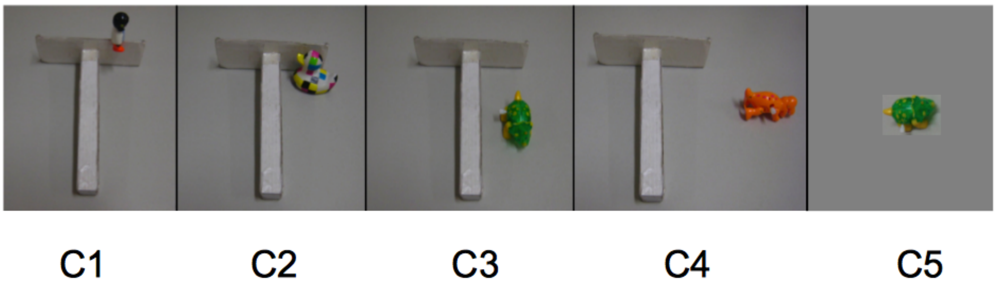

Figure 1. Tool use conditions (C1 to C5) presented in the longitudinal study (the same conditions were used in the cross-sectional study presented below).

Besides spatial arrangement, another aspect that was investigated is the learning of tool use by observation. Thus, when infants failed to complete the tool task in a given condition, they received a series of two successive demonstrations of that condition. Overall, there were 6 test sessions per infant, 303 trials in total, and between 1 and 3 demonstrations per session.

2.3. Data coding

Table 1. Strategies observed over all trials (in a few trials two strategies, and more rarely three, occurred in succession)

NT: No try (score 0)

- Grasps tool, gets rid of it, loses interest in it (*tool is grasped here without being the focus of attention)*
- Looks at toy, looks at tool, looks at adult, doesn't do anything
- Refusal

T1: Begging for toy and not using tool after its grasping leads to failure (score 1)

- Points to toy and refuses or ignores the tool
- Points to toy, then grasps tool (either spontaneously or upon encouragement by the experimenter), points again toward toy with other hand
- Grasps tool, the toy does not come, does not try again with the tool, may then point to toy with bare hand
- Grasps tool, gets rid of it (throws it away, places it on the table), and points to the toy
- Looks at toy, pulls tool while looking at toy, stops action with tool on seeing that the toy does not come, points to toy

T2: Exploring tool but not using it in connection with the toy (score 2)

- Points to toy, then grasps tool and plays with it (puts into mouth or rubs, swipes, hits, etc. on table)
- Grasps tool, interested in tool only (puts into mouth or rubs, swipes, hits, etc. on table)
- Grasps tool, swipes table with it and sweeps toy away by accident
- Grasps tool, plays with it and then rejects it, may be interested in toy again

T+T: Using tool in connection with toy not for retrieval (score 3)

- Points to toy, then grasps tool (spontaneously or upon encouragement by the experimenter) and touches or pushes toy with it
- Grasps tool, touches or pushes object with tool
- Grasps tool (after pointing first to toy or not), points to toy with tool

S1: Using tool for retrieval: trial and error, difficult or half success, or only after demonstration (score 4)

- Grasps tool, moves tool, tries to bring back toy, failure
- Grasps tool (after first pointing to toy or not), retrieves or tries to retrieve toy after demonstration
- Grasps tool after encouragement (after first pointing to toy or not), moves tool and retrieves toy with it
- Grasps tool (after first pointing to toy or not), awkward movements to bring toy to hand, success
- Grasps tool (after first pointing to toy or not), retrieves toy after several attempts

S2: Using tool for retrieval: Intentional mature success (score 5)

- Grasps tool, moves tool to retrieve toy, success

Ambiguous cases (not interpretable, thus no score)

- Points to toy, hand on tool more or less by chance, grasps tool, rakes with it, toy comes by chance (in C2 or C3)
- Points to toy then grasps tool upon encouragement by experimenter and brings the toy to hand possibly by chance (in C2 or C3)
- Points to toy, grasps tool spontaneously, retrieves toy possibly by chance (in C2 or C3)
- Grasps tool spontaneously, retrieves toy possibly by chance (in C2 or C3)
- Grasps tool (spontaneously or upon encouragement by the experimenter) and gives tool to adult

("Moves" tool excludes successes where by simply pulling the tool toward himself the infant could retrieve the toy by pure chance (C2 or C3). R1 and R2 were coded only for C4 and C5 conditions, when the tool first had to be moved to the side to be used.

Infants' performance on the tool tasks was evaluated on the basis of a set of elementary behaviours, such as looking behaviours, pointing gestures, grasping and manipulation of the rake (either as an object or as a tool), and social interaction with an adult. Overal, there were 26 typical behaviours expressed by infants over all trials, which we devided into 5 categories (see Table 1 above). The first category (NT), refers to trials where infants showed no interest in the task: they did not explore the rake or try to get the toy (approx. 9% of all trials). Trials categorized as NT were given a score of 0. Category T1, scored 1, involved behaviours that were directed only toward the out-of-reach toy, with no particular interest toward the tool shown (e.g., discarding or ignoring the tool). Category T2, scored 2, included trials where the rake was manipulated for its own sake, as an object, but not as a tool. Category T+T, scored 3, refers to trials in which infants manipulated the rake in interaction with the toy, without showing a clear intention to retrieve it. Category S1, scored 4, refers to trials where the infant used the rake as a tool to retrieve the object, but with somewhat awkwards movements, or attempted to do so but still failed because of motor difficulties such as inappropriate grasping of the handle, unefficient movements, accidental pushing of the toy out of the reach of the tool, etc. Finally, category S2, scored 5, was for trials where infants showed mature success in using the tool to retrieve the object.

2.4. Results

2.4.1. Mean spontaneous success

In the condition where the toy was attached to the tool (C1), infants succeeded in 100% of trials, starting from the first trial. Infants performed significantly fewer pointing gestures toward the toy in this condition than in all other conditions, suggesting that in C1 the infants already knew how to get the out-of-reach toy.

As infants already succeeded in C1 at the youngest age tested, all further analyses were restricted to C2-C5, to evaluate change in successful performance of the task with age. Figure 2 illustrates the infants mean success rate as a function of age.

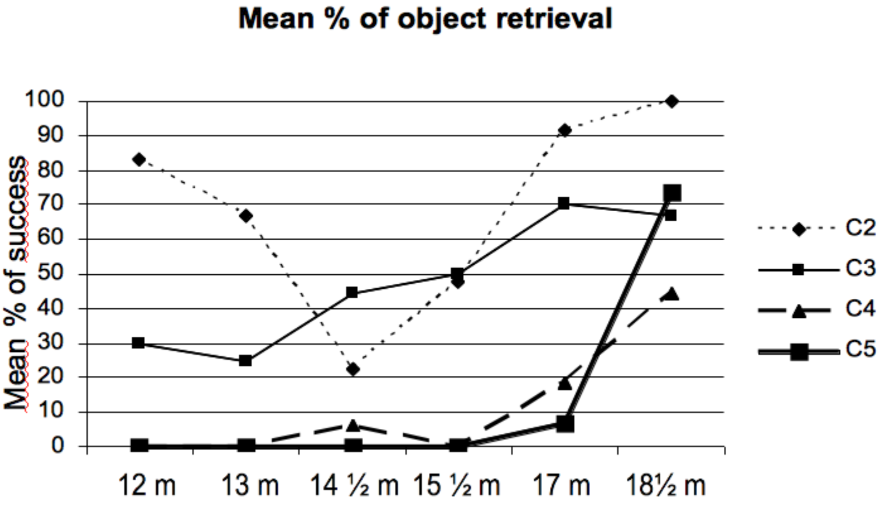

Figure 2. Mean success as a function of condition and age (data from the longitudinal study).

As can be seen on this graph, C4 and C5 (toy outside the trajectory of the rake) were quite never succeeded before 17-18m of age, whereas conditions C2 and C3 (toy inside the rake) were already succeeded at some trials at 12 months. Considering this differences, C2-C3 has been discussed together, and compared with C4-C5.

C2-C3: To succeed in these conditions, the infants needed to perform a simple raking movement, as the toy stood in the trajectory of the rake. Interestingly, success in C2 over time was U-shaped. At a young age, infants usually grasped the rake and succeeded at the task by performing such raking movements. Later, infants were more likely to perform behaviours directed either toward the rake or toward the toy, without managing to retrieve the toy. Success in C3 seems to have increased steadily as the infants got older.

C4-C5: Before 17 months, all infants failed to retrieve the toy in the conditions where the toy was not in the trajectory of the rake. Success in these conditions seems to have increased drastically between 17 and 18.5 months of age.

2.4.2. Observational learning

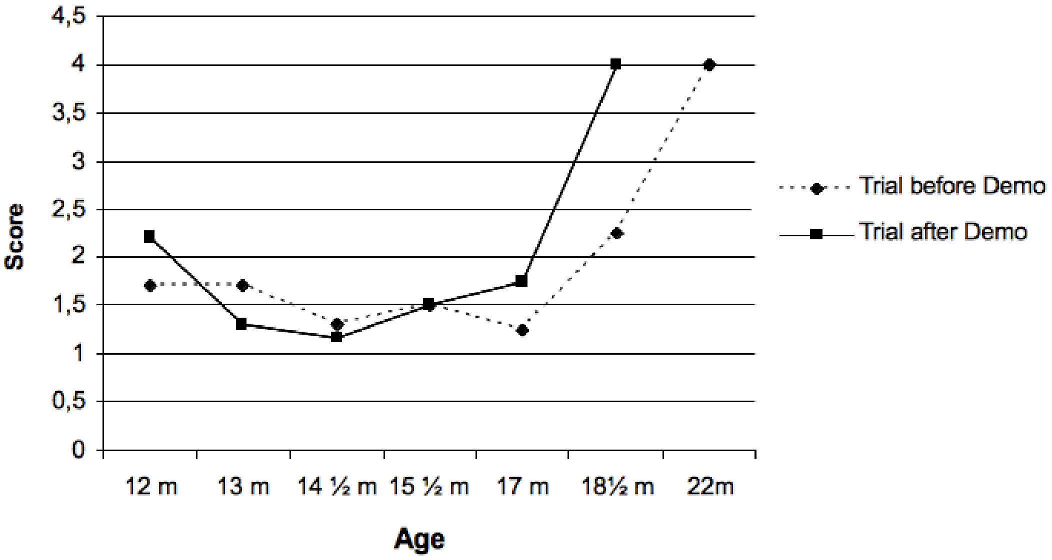

Figure 3. Mean score in C4/C5 before and after demonstration, as a function of age

To evaluate the effect of demonstrations, only data from C4 and C5 were considered, as they success could not be achieved in these conditions by haphazardly pulling the rake and thereby accidentally retrieving the object. As can be seen in Figure 3, the infants' mean score across sessions mostly did not change before 18.5 months of age. Between 12 and 17 months, the mean score was about 1.5, meaning that infants' behaviours were mainly directed either toward the toy (score 1) or to the tool (score 2).

2.5. Discussion

The U-shaped evolution of success rate with age in condition C2 (toy inside/against the rake) could be explained in several ways. One possibility is that the development of tool use is not continuous, and that there is a temporary regression in infants' capacity to use the rake as a tool in conditions whithout a gap. Such temporary regressions in infants' behavioural development are common, as for example the resurgence of two-handed reaching when learning to walk around the end of the first year of life (Corbetta & Bojczyk, 2002). However, the fact that at 15.5 and 16.5 months infants more rarely managed to retrieve the goal object in this simple condition than at a younger age, instead raking around the toy and/or pointing toward the toy with the other hand, suggest that infants had no idea that the rake could be usefull for retrieving the toy. Taken along with the lack of success in the conditions with a gap

(C4 and C5), it seems that it is only starting at 17 months of age, when infants succeed in conditions with spatial gaps, that infants make a clear link between the rake and the toy, and come to understand the functionality of the tool. This conclusion contradicts Bates et al.'s (1980) interpretation of an experiment, wherein they observed similar differences between conditions with a gap and conditions without a gap in 10-month-old infants. Finding that the conditions with no gap were easier for infants to solve, they concluded that infants understood the tool's functionality, but only in the condition where the means and the end were spatially connected.

A second finding from this longitudinal study, is that infants benefit from demonstration only starting at 18 months of age. The fact that infants did not learn from demonstrations before 18 months is surprising, as we know from the developmental literature that infants can learn other means-end actions by observation starting at 12 months of age. Given the small number of infants in this study, it was important to confirm this result on with a larger number of infants. This is one aim of the cross-sectional study that I will present in the next section.

Finally, the results were discussed in terms of possible mechanisms underlying the development of tool use. First, the fact that young infants were mostly interested either in the toy or in the rake, but did not connect them, suggests that there might be some age-related attentional limits. The second issue concerns the importance of manipulation and experience with the tool before being able to perceive the affordance of the tool. In fact, it seems that infants needed to spend a significant amount of time manipulating the tool, either for its own sake or in interaction with the environment and the out-of-reach object, before understanding its affordances. In addition, behavioural strategies differed from one session to another. These two facts are in line with the perception-action perspective formulated by Lockman (2000), who suggested that the precursors of tool use may be found in earlier manipulatory behaviours. The last aspect that was highlighted as important in infants' acquisition of tool use is the ability to learn this action by observation, which appeared at around the same age as the first spontaneous success.

3. Cross-sectional study

Contribution to the study

This study was designed on the basis of the longitudinal study described above, with the main contribution of L. Rat-Fischer. All the subjects were recruited and tested at the Laboratoire Psychologie de la Perception by L. Rat-Fischer. The data were coded by L. Rat-Fischer, with double coding by J. Fagard and the master student Cecilia Florean. The statistical analyses and interpretation of the data were conducted by all the authors of the paper, which was written by L. Rat-Fischer. The results were presented as a poster at a developmental robotic conference (Epirob, Francfurt, 2011) and as an oral presentation at the annual conference of the Société Française de Psychologie (Metz, 2011), and the student Symposium of the CNRS research group *Neurosciences Cognitives du Développement* (2011).

3.1. Introduction

The main goal of the cross-sectional study was to verify the findings of the longitudinal study with more infants, and in more controlled conditions. The purpose of this replication at a greater scale was to establish the developmental steps leading to the emergence of tool use, and to further investigate the potential underlying processes.

Because the longitudinal study confirmed that spatial arrangements and learning by observation were playing an important role in the acquisition of tool use, we tested these two issues in a similar way in the cross-sectional study. One slight difference was that the demonstration in the present experiment was performed by the parent whose lap the infant was sitting in, contrary to the longitudinal study where the demonstrations were mostly performed by the experimenter in front of the infant. This was to ensure that the demonstration was properly visible to the child, in a more ecological way, to control for any effect of perspective. However, as will be seen in the paper, no differences were found between the two types of demonstrations.

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Brief Report

The emergence of tool use during the second year of life

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ABSTRACT

Despite a growing interest in the question of tool-use development in infants, no study so far has systematically investigated how learning to use a tool to retrieve an out-of-reach object progresses with age. This was the first aim of this study, in which 60 infants, aged 14, 16, 18, 20, and 22 months, were presented with an attractive toy and a rake-like tool. There were five conditions of spatial relationships between the toy and the tool, going from the toy and tool being connected to there being a large spatial gap between them. A second aim of the study was to evaluate at what age infants who spontaneously fail the task can learn this complex skill by being given a demonstration from an adult. Results show that even some of the youngest infants could spontaneously retrieve the toy when it was presented inside and touching the top part of the tool. In contrast, in conditions with a spatial gap, the first spontaneous successes were observed at 18 months, suggesting that a true understanding of the use of the tool has not been fully acquired before that age. Interestingly, it is also at 18 months that infants began to benefit from the demonstration in the conditions with a spatial gap. The developmental steps for tool use observed here are discussed in terms of changes in infants' ability to attend to more than one item in the environment. The work provides insight into the progressive understanding of tool use during infancy and into how observational learning improves with age.

Introduction

Learning to use a tool is a critical step in human development, and there has recently been a growing interest in the emergence of this ability in infants (see Keen, 2011, for a recent review). To our

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knowledge, however, no study so far has systematically investigated how learning to use a tool to retrieve an out-of-reach object progresses with age. This was the first goal of the study presented here. A second goal was to evaluate at what age infants who fail spontaneously can learn this fairly complex skill from a demonstration given by an adult.

Tool use in human infants develops during the period from 8 to 24 months of age following a development described by Piaget's (1952) sensorimotor Stages 4 to 6 (McCarty, Clifton, & Collard, 2001). At sensorimotor Stage 4 (8–12 months), where infants start being able to sequentially plan steps to attain a goal, the literature shows evidence for the beginnings of tool use. Infants are able to retrieve an out-of-reach object when no spatial gap disrupts the link between the tool and the toy, as when the toy is on a cloth, at the end of a string, or even inside and against the tool (Bates, Carlsonluden, & Bretherton, 1980; Brown, 1990; Piaget, 1952; see also Van Leeuwen, Smitsman, & van Leeuwen, 1994). At Stage 5 (12–18 months), where infants begin to be able to combine and relate two objects together, the literature suggests that infants are still not able to use tools when there is a spatial gap (Brown, 1990; see also van Leeuwen et al., 1994, although these latter authors did not precisely specify the age range). On the other hand, infants may start being able to do the task with the spatial gap if they are given a demonstration by an adult (Esseily, Nadel, & Fagard, 2010; see also van Leeuwen et al., 1994). It is also worth noting some other studies that are related to tool use performed on children at this sensorimotor stage and that concern the development of the motor skill involved in using a spoon (Connolly & Dalgleish, 1989; McCarty, Clifton, & Collard, 1999). This behavior may be easier than many tool-use situations because the movement involved is directed toward the child (Keen, 2011; McCarty et al., 1999). It develops gradually over Stage 5 and involves diverse strategies where hand preference, trajectory control, and type of grasping play a role. Finally, at Stage 6 (18–24 months), where infants start to make plans that imply mental representations and transformations of objects, existing studies provide evidence that infants more fully understand tools. In conditions of spatial gap, infants are now even more easily able to profit from a demonstration by an adult (Chen & Siegler, 2000). During the later part of this period (from 24 months), conditions of spatial gap begin to no longer pose a problem for children even without a demonstration (Brown, 1990; Keen, 2011). Furthermore, infants are able to spontaneously choose the relevant tool among a choice of functional and nonfunctional tools (Brown, 1990; but see Chen & Siegler, 2000). Again, it is worth noting that at the beginning of the period from 18 to 24 months, the motor skills involved in spoon use are optimally planned as a function of hand position (McCarty et al., 1999).

From this quick overview of the existing studies, we see that the spatial gap between the tool and the toy seems to play an important role. Another interesting factor seems to be whether infants are able to profit from an adult's demonstration. Unfortunately, existing studies are limited either to broad age group ranges (e.g., Brown, 1990; Chen & Siegler, 2000; van Leeuwen et al., 1994) or to a single small age span (e.g. Bates et al., 1980; Esseily et al., 2010 [for the rake task]), or in the case of the spoon (Connolly & Dalgleish, 1989; McCarty et al., 1999, 2001) they concern the progress of motor skill acquisition more than cognitive development itself.

Given the importance of tool use as a hallmark of human cognitive development, the lack of systematic age-linked studies is surprising. The aim of the current work was to fill this gap by systematically describing developmental changes in learning how to use a tool, spontaneously and after a demonstration, while varying the spatial gap between the tool and the toy.

Materials and methods

Participants

A total of 60 healthy full-term infants (20 girls and 40 boys) participated in this cross-sectional study. Five age groups of 12 participants were tested: 14-month-olds (13 months 28 days to 14 months 13 days), 16-month-olds (15 months 28 days to 16 months 9 days), 18-month-olds (17 months 26 days to 18 months 4 days), 20-month-olds (19 months 27 days to 20 months 10 days), and 22-month-olds (21 months 25 days to 22 months 5 days). Infants were recruited from a list of local families who expressed interest in taking part in studies of infant development. Prior parental consent was granted before observing the infants.

Design and materials

The experimental apparatus was designed to assess at what age and in which conditions infants are capable of using a tool to retrieve an out-of-reach toy. A desired toy was placed out of reach at different positions near a white cardboard rake-like tool (15 × 20 cm), designed to be visually plain (see Fig. 1). During the whole experiment, infants sat in the lap of one of their parents in front of a table (80 × 120 cm). An experimenter sat facing the infants behind the table. A digital video camera recorded the whole session.

Procedure

Infants were first allowed to familiarize themselves with the toy and tool by manipulating them for approximately 30 s to 1 min. In the tool-use test itself, an attractive toy was placed in front of infants successively in five conditions (see Fig. 1): toy attached to the rake part of the tool (C1: no spatial gap, attached), toy inside and against the rake part of the tool (C2: no spatial gap, unattached), toy inside the tool but not against it (C3: small spatial gap), toy to the side of the tool (C4: large spatial gap), and toy in the middle of the table with the tool directly held out to the infant by the experimenter (C5: effectively a very large spatial gap). The conditions were presented in order of increasing spatial gap from C1 to C5. All infants received one trial at C1, where they all immediately succeeded. They were then directly presented with two trials at C2. If both trials were successful, they received two trials at C3 (and so on until C5). If infants failed in one or both trials of a condition, they were given one or two additional trials of that condition. If infants failed to retrieve the toy on two of three trials, parents were asked to give two consecutive demonstrations of the failed condition. If infants failed in a condition after a demonstration, they were directly presented with the C5 condition. Thus, the C3 and C4 conditions were presented only if infants succeeded in the previous condition either spontaneously or after a demonstration; only the C1, C2, and C5 conditions were presented to all of the infants.

Data analysis

Data were analyzed (a) in term of success/failure for each condition (C1–C5) and (b) on the basis of a behavioral category for each infant. For this, a score of 0 was attributed when infants expressed no interest in the toy, the tool, or (more generally) the task; a score of 1 was attributed when infants were mostly interested in the out-of-reach toy, pointing toward it and possibly trying to retrieve it without using the tool; a score of 2 was attributed when infants were mainly interested in manipulating the

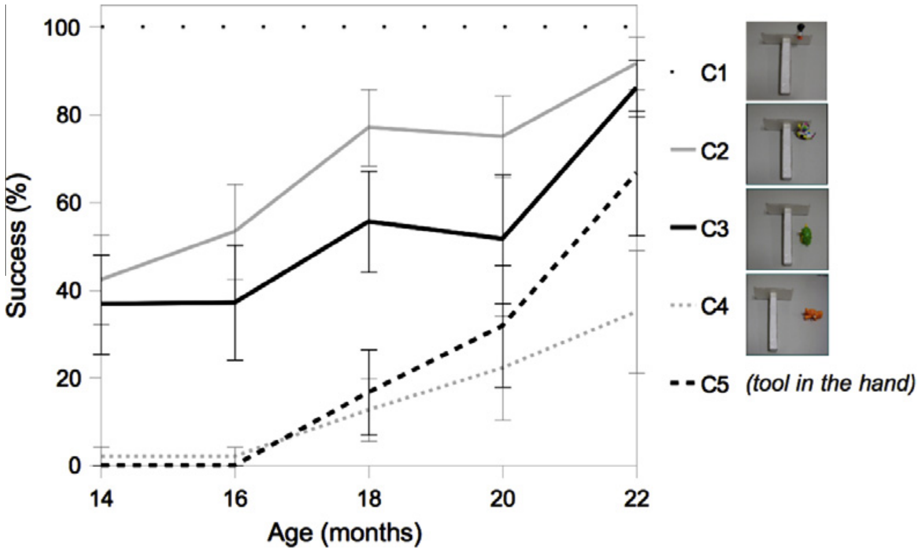

Fig. 1. Mean percentage of success in each condition as a function of age (with error bars showing 1 standard error above and below the mean).

tool itself, possibly alternating their attention between the toy and the tool but not in connecting the two; a score of 3 was attributed when infants systematically and repetitively brought the tool to bear on the toy but seemingly not with the purpose of retrieving the toy; and a score of 4 was attributed when infants succeeded in retrieving the toy with the tool. We also coded as 4 the rare cases when infants clearly attempted to retrieve the toy with the tool but failed because they inadvertently moved the toy out of reach (means of 2, 3, 3, 0, and 1% of trials at 14, 16, 18, 20, and 22 months of age, respectively). An important point should be noted about the C2 and C3 conditions, where the tool and toy were spatially close. In these conditions, the toy was positioned so that it lay between the tool head and the infants. This had the consequence that simply pulling the tool through a small distance would inevitably bring the toy into reach. Thus, in these conditions, successes scored as 4 could have been achieved by chance because infants could pull the tool and obtain the toy by pure spatial contingency (O'Regan, Rat-Fischer, & Fagard, 2011). High scores in the C2 and C3 conditions with little or no spatial gap, therefore, should not be considered as true indicators of infants' comprehension of the tool. For this reason, we analyzed these conditions separately in some analyses.

Scoring reliability

Infants' behaviors were coded from the videotapes, and 13 infants (22%) were coded independently by a second observer to assess interobserver reliability. Reliability between the two observers was 90%.

Results

Does spontaneous success vary with age and condition?

Fig. 1 presents the mean percentage of spontaneous success for each condition as a function of age. Infants succeeded spontaneously in the C1 condition on the first trial, leading to a mean of 100% at each age; thus, this condition was not further analyzed. For the other conditions, a repeated measures analysis of variance (ANOVA) on the percentage of spontaneous successes ($n = 2–5$ per infant for each condition) as a function of age (14, 16, 18, 20, or 22 months) and condition (C2, C3, C4, or C5) showed a main effect for age, $F(4,49) = 11.87$, $p < .001$, $\eta^2 = .16$, and a main effect for condition, $F(3,147) = 33.48$, $p < .001$, $\eta^2 = .26$. The age by condition interaction was not significant. A post hoc least significant difference (LSD) test for age effect showed that the 14- and 16-month-olds (mean success = 20.31 and 23.13%, respectively) were different from the 18- and 20-month-olds (mean success = 40.15 and 45.18%, respectively) and from the 22-month-olds (mean success = 69.86%). The 18- and 20-month-olds were also different from the 22-month-olds. A post hoc LSD test showed that all conditions differed significantly from each other except C4 and C5 ($p = .20$). All 18- and 20-month-olds who succeeded spontaneously at C4 and C5 had seen a demonstration leading to success in a simpler condition. In contrast, 4 22-month-olds succeeded spontaneously in conditions with a large spatial gap without any previous demonstration in simpler conditions.

Does the effect of a demonstration vary as a function of age and condition?

Success versus failure

All infants who received a demonstration had failed at the previous trial. We compared the percentage of infants who succeeded after a demonstration. Because the number of infants was not necessarily the same between age groups for each condition, we could not use a standard chi-square analysis. Thus, the data were analyzed using the procedure of Marascuilo, corresponding to a chi-square analysis adapted to multiple comparisons when sample size is not equal between groups. For the C2 and C4 conditions, there were no significant age differences. The only significant differences were between the youngest and oldest age groups at the C3 condition, $\chi^2(df = 1, N_{14} = 5, N_{22} = 1) = 0.80$, $p < .05$ (20% success after a demonstration at 14 months, 100% success after a demonstration at 22 months), and the C5 condition, $\chi^2(df = 1, N_{14} = 11, N_{22} = 4) = 0.75$, $p < .05$, (0 vs. 75% success at 14 and 22 months, respectively).

Level of performance (0–4)

To further analyze the effect of a demonstration, we used the score defined in the data analysis section to compare the behaviors toward the toy and tool before and after a demonstration. Given the fact that there were few demonstrations for some infants, we decided to pool little or no spatial gap conditions (C2 and C3) as well as large spatial gap conditions (C4 and C5). Thus, for infants who received a demonstration at the two conditions (e.g., C2 and C3), the value considered is the mean over the two conditions, whereas for infants who received a demonstration at only one of the two conditions (e.g., C2 or C3), the value considered is this value.

C2 and C3 conditions

The difference in scores before and after a demonstration was tested using a paired t test for each age group. The effect of a demonstration was significant for 18-month-olds ($m_{\text{before}} = 0.83$, $m_{\text{after}} = 3.00$), $t(5) = -3.08$, $p < .05$, $d = 1.26$, and 20-month-olds ($m_{\text{before}} = 1.71$, $m_{\text{after}} = 2.86$), $t(6) = -2.83$, $p < .05$, $d = 1.07$. The t test showed no significant effect of demonstration for 14-month-olds ($m_{\text{before}} = 1.56$, $m_{\text{after}} = 2.33$), $t(8) = 2.19$, $p = .06$, $d = 0.73$, and 16-month-olds ($m_{\text{before}} = 1.10$, $m_{\text{after}} = 2.30$), $t(9) = -2.17$, $p = .06$, $d = 0.69$. The 22-month-old group could not be tested because only 2 infants needed a demonstration over all trials in the C2 and C3 conditions. Both infants switched from a score of 1 (before demonstration) to a score of 4 (after demonstration).

C4 and C5

Fig. 2 shows the scores before and after a demonstration at C4 and C5. Paired t tests showed evidence for a significant effect of the demonstration at 18 months, $t(6) = -2.32$, $p = .05$, $d = 0.88$, and at 22 months, $t(7) = -2.47$, $p < .05$, $d = 0.87$. There was no significant score difference between before and after a demonstration for the three other age groups: 14 months ($p = .19$), 16 months ($p = .72$), and 20 months ($p = .16$).

Discussion

The aim of this study was to investigate the developmental steps leading to tool-use acquisition in infants across specific age groups during the second year of life. Five conditions involving different spatial relationships between the toy and the tool were successively presented, with a demonstration being provided by the experimenter in case of failure.

The results show that in all conditions, when the toy was not attached to the tool, performance increased significantly with age, with 14- and 16-month-olds differing from older infants and 18- and

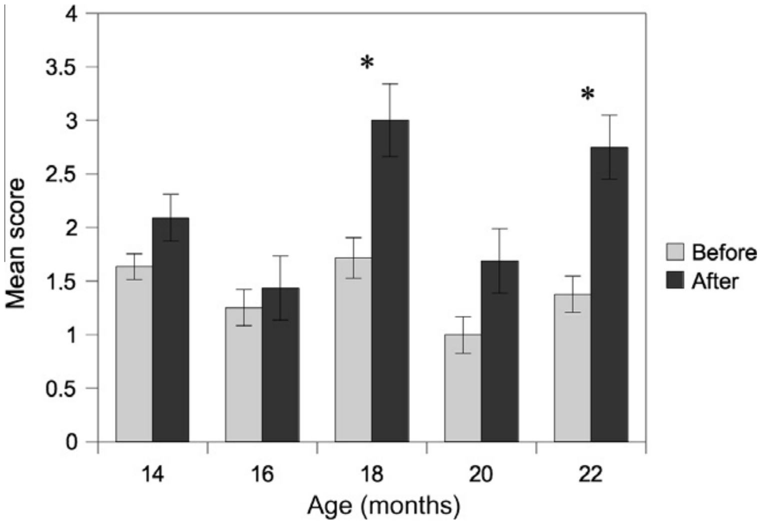

Fig. 2. Mean scores before and after demonstration as a function of age (with bars showing 1 error above the mean) in conditions with a large spatial gap (C4 and C5). The asterisks indicate significant differences between the conditions before and after demonstration ($p \leqslant .05$).

20-month-olds also differing from 22-month-olds. For all age groups, the difficulty of using a tool increased with the spatial distance between the toy and the tool. Thus, the task was very easy when a physical connection between the toy and the tool was present (C1), more difficult with the toy against the tool (C2), even more difficult with the toy inside but not against the tool (C3), and most difficult when there was a large spatial gap between the toy and the tool (C4 and C5). These results are in accordance with previous results stressing the importance of the spatial gap between the toy and the tool (Bates et al., 1980; Brown, 1990; van Leeuwen et al., 1994).

The following is a more detailed analysis of infants' ability to succeed in the task without a demonstration according to age group. At 14 and 16 months, in the comparatively easy conditions with little or no spatial gap, the success rate was less than approximately 50%, which is in line with a longitudinal study on a similar task (O'Regan et al., 2011). O'Regan et al. (2011) suggested that the early successes in these conditions are due more to the fact that the toy can move with the tool by contingency, as the toy lies in the trajectory between the tool head and the infants, than to a true understanding of the tool's functionality. In this 14- to 16-month age period, infants never succeeded in conditions with a spatial gap, which also fits with previous results (Brown, 1990; O'Regan et al., 2011; van Leeuwen et al., 1994). At 18 months, infants begin to succeed in conditions with a large spatial gap, when the toy is not between the tool head and the infants, which is coherent with O'Regan and colleagues' results suggesting that 18 months of age is a landmark for this kind of tool-use task. However, O'Regan and colleagues' results bore on only 4 infants followed longitudinally and needed to be confirmed. At 22 months, infants still did not systematically succeed in the two conditions with a large spatial gap, which is in accordance with the literature (Keen, 2011).

With regard to the necessity for a demonstration of the use of the tool, infants benefit from watching an adult demonstration starting at around 18 months of age. This is fairly coherent with the findings of Chen and Siegler (2000), who, in a task requiring a group of 18- to 26-month-olds to choose between alternative tools, including one similar to our tool, found that adult demonstrations can be very effective. In the current study, this effect was particularly visible when we analyzed the change in behavior between the trial directly before the demonstration and the trial after the demonstration. For C2 and C3 (little or no spatial gap), it was only starting from 18 months of age that infants changed their behavior between the trial directly before the demonstration and the trial after the demonstration. For C4 and C5 (spatial gap), only the 18- and 22-month-olds showed an improvement after the demonstration. This improvement manifested itself by the fact that infants in these two age groups mostly went from focusing their initial attention either on the toy (scored 1) or on the tool (scored 2) to focusing their attention on the combination of both the toy and the tool (scored 3 or 4). At 20 months, however, no significant effect of a demonstration was found. The global and individual results indicate that all 7 participants who needed a demonstration in these conditions had an initial score of 1, focusing their attention mostly on the toy. After a demonstration, only 2 infants changed their behavior to combine the two components. We have no explanation for this drop in performance at 20 months and assume that it is due to a quirk in the 20-month group of infants.

It is worth noting that at C4 and C5, the 14-month-olds tended to have a higher score than the 16-month-olds. A fine-grain analysis of the frequency of the different behaviors observed at each age shows that 14-month-olds globally manipulate the tool (scored 2) more than the other age groups. In contrast, the 14-month-olds seemed to express less interest toward the out-of-reach toy (scored 1) than the 16-month-olds. Thus, even if all of the 14-month-olds noticed the toy and showed interest in it, it seems that their attention was more easily attracted toward the tool and its exploration.

Why did tool-use learning from the demonstration appear only after 18 months in this study? After all, infants are known to learn means–end tasks from observation from the beginning of their second year of life (Esseily et al., 2010; Provasi, Dubon, & Bloch, 2001; see Elsner, 2007, for a review). The absence of effect of the demonstration before 18 months may be partly explained by the particular conceptual difficulty of the tool-use task compared with other simpler tasks and because of the several successive steps it involves. But the absence of an early effect of demonstration may also be due to the way we provided the demonstration, which was relatively restricted in content and variety. If this is true, then adding more information to the demonstration such as pedagogical cues (e.g., Csibra & Gergely, 2006; Sage & Baldwin, 2011) and social cues (Kiraly, 2009; Nielsen, Simcock, & Jenkins, 2008), making the goal of the experimenter more obvious (Carpenter, Call, & Tomasello, 2002; Kiraly, 2009), and/or providing more instances would allow infants to learn the tool-use task from a demonstration earlier. In addition, as in many studies of social learning, we assessed infants' behavior directly after a demonstration. Hirata, Morimura, and Houki (2009), in their study of the acquisition of tool-use ability by observing a conspecific model in chimpanzees, suggested that it may be necessary to consider the effect of learning by observation over a longer term. Furthermore, longitudinal studies will help to elucidate this question and may also allow better understanding of the mechanisms underlying the process of tool-use learning in human infants.

Taken together, the results suggest that the development of tool use emerges from a continuous and gradual process rather than abruptly (Lockman, 2000). What mechanisms could underlie this progression over the period from 14 to 22 months, in particular as concerns the difficult conditions of a spatial gap, where the toy cannot be retrieved without understanding the tool's functionality? At 14 months, even if infants almost always express their interest in the toy at some time during the trial, they seem to be mainly interested in exploring the tool without keeping the goal of retrieving the toy in mind. At 16 months, infants are more likely to focus their attention on the goal of retrieving the toy, often ignoring or discarding the tool. From 22 months onward, infants seem to become able to spread their attention simultaneously on the toy and the tool and to make the link between the two. This attentional change is sometimes possible even at a younger age when infants see an adult demonstrating the tool-use task or if they succeed after a demonstration at a simpler condition of the tool-use task. It would be interesting to further investigate the link between the increase in tool-use performance observed here at around 18 months and the change, at around the same age, in the capacity to learn a complex skill by observation.

References

Bates, E., Carlsonluden, V., & Bretherton, I. (1980). Perceptual aspects of tool using in infancy. *Infant Behavior & Development, 3*, 127–140.

Brown, A. L. (1990). Domain-specific principles affect learning and transfer in children. *Cognitive Science, 14*, 107–133.

Carpenter, M., Call, J., & Tomasello, M. (2002). Understanding "prior intentions" enables 2-year-olds to imitatively learn a complex task. *Child Development, 73*, 1431–1441.

Chen, Z., & Siegler, R. S. (2000). Across the great divide: Bridging the gap between understanding of toddlers' and older children's thinking. *Monographs of the Society for Research in Child Development, 65*(2), i–vii, 1–96.

Connolly, K., & Dalgleish, M. (1989). The emergence of a tool-using skill in infancy. *Developmental Psychology, 25*, 894–912.

Csibra, G., & Gergely, G. (2006) Social learning and social cognition. The case for pedagogy. In Y. Munakata (Ed.), *Processes of change in brain and cognitive development: Attention and performance XXI* (pp. 249–274). Oxford, UK: Oxford University Press.

Elsner, B. (2007). Infants' imitation of goal-directed actions: The role of movements and action effects. *Acta Psychologia (Amsterdam), 124*, 44–59.

Esseily, R., Nadel, J., & Fagard, J. (2010). Object retrieval through observational learning in 8- to 18-month-old infants. *Infant Behavior and Development, 33*, 695–699.

Hirata, S., Morimura, N., & Houki, C. (2009). How to crack nuts: Acquisition process in captive chimpanzees (*Pan troglodytes*) observing a model. *Animal Cognition, 12*, 87–101.

Keen, R. (2011). The development of problem solving in young children: A critical cognitive skill. *Annual Review of Psychology, 62*, 1–21.

Kiraly, I. (2009). The effect of the model's presence and of negative evidence on infants' selective imitation. *Journal of Experimental Child Psychology, 102*, 14–25.

Lockman, J. J. (2000). A perception–action perspective on tool use development. *Child Development, 71*, 137–144.

McCarty, M. E., Clifton, R. K., & Collard, R. R. (1999). Problem solving in infancy: The emergence of an action plan. *Developmental Psychology, 35*, 1091–1101.

McCarty, M. E., Clifton, R. K., & Collard, R. R. (2001). The beginnings of tool use by infants and toddlers. *Infancy, 2*, 233–256.

Nielsen, M., Simcock, G., & Jenkins, L. (2008). The effect of social engagement on 24-month-olds' imitation from live and televised models. *Developmental Science, 11*, 722–731.

O'Regan, J. K., Rat-Fischer, L., & Fagard, J. (2011). Mechanisms leading to tool use: A longitudinal study in human infants. Paper presented at IEEE conference on development and learning and epigenetic robotics (IEEE ICDL–EpiRob 2011), Frankfurt, Germany.

Piaget, J. (1952). *The origins of intelligence in the child*. New York: Routledge.

Provasi, J., Dubon, C. D., & Bloch, H. (2001). Do 9- and 12-month-olds learn means–ends relation by observing? *Infant Behavior and Development, 24*, 195–213.

Sage, K. D., & Baldwin, D. A. (2011). Disentangling the social and the pedagogical in infants' learning about tool use. *Social Development, 20*, 825–844.

Van Leeuwen, L., Smitsman, A., & van Leeuwen, C. (1994). Affordances, perceptual complexity, and the development of tool use. *Journal of Experimental Psychology: Human Perception and Performance, 20*, 174–191.

4. Planning the use of the rake

Contribution to the study

This paper was based on the same study run by L. Rat-Fischer as the previous paper. The statistical analyses and interpretation of the data were conducted by J. Fagard and L. Rat-Fischer. The paper was written by J. Fagard, and the results presented as a poster by L. Rat-Fischer at the Workshop *Lateralization, praxis and communication gestures* (Paris, 2012).

4.1. Introduction

In the cross-sectional study, two main types of movements were observed: lifting up the rake in the air, and raking it on the table, either in a straight trajectory toward the subject, or in a "sweeping movement". Such sweeping movements were first described by Cox and Smitsman (2006a, 2006c) as a movement of the rake directed diagonally toward the subject. This natural movement is usually easier to direct toward the right diagonal when the tool is grasped with the left hand, and vice versa. As we presented the rake in a central position on the table, with the toy either to the right or to the left side of the rake (conditions C2, C3 and C4 only, see Fig. 4), we might expect that infants who efficiently planned their tool use action would choose the hand to grasp the tool with according to the side that the object was on. For example, when the toy was placed to the left of the rake, infants should have chosen their right hand to perform the sweeping movement toward the left, to enclose the object within the rake (see Fig. 4).

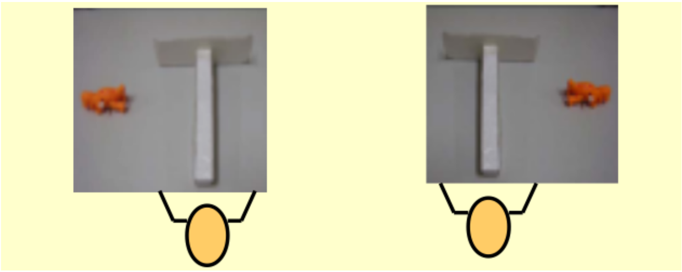

Figure 4. Condition C4 with the object to the left and to the right of the tool.

However, hand choice for grasping might also be influenced by infants' handedness at the moment of the test. The spoon-studies of McCarty et al. (1999, 2001) were the first to highlight this trade-off between hand preference and efficient planning for grasping. Young infants (i.e., 9- and 14-month-olds) grasped the spoon more frequently with their preferred hand, leading in some conditions to an uncomfortable grasping position. In contrast, 19-month-olds were able to adjust the hand that grasped the spoon depending on the position of the handle. Cox and Smitsman (2006a) found a similar difference between 2- and 3-year-old children, on a tool task with a hook involving the use of a sweeping movement. However, both the spoon and the hook tasks were asymetrical. The spoon was presented in a horizontal line in front of the child, with the handle to one side and the bowl to the other side. In the hook task, it was asymetrical because of the crook part of the hook. In our tool task with the rake, we presented the rake in a central position, which should not have influenced infants' initial grasping.

In the cross-sectional study, we evaluated infants' hand preference with a test adapted to young infants (see Fagard & Marks, 2000). Thus, conditions in our study were ideal to evaluate which factor most influenced infants' grasping of the tool with age. In line with the findings of McCarty et al. (1999, 2001) and Cox and Smitsman (2006a), we hypothesized that younger infants would be more influenced by their hand preference, leading to lesser success in conditions C2, C3 and C4. Older infants, in contrast, who perceive the tool's functionality (that is, starting at 18 months), should more frequently use their contralateral hand in response to the position of the toy. The paper presented here investigates this hypothesis.

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Handedness in Infants' Tool Use

ABSTRACT: *In this study, we investigated whether hand preference influences infants' choice of what hand to use in grasping a new tool presented at the midline, and whether this will change in the course of learning the functionality of a tool. The tool was a rake within reach placed beside an out-of-reach toy presented either to its right or to its left. Forty-eight infants from 16 to 22 months of age were tested. The results show that use of the right-preferred hand to grasp the rake is strong as of 16 months of age and does not change significantly with age in the condition where using the right hand leads to a better outcome than using the left hand. In the condition where using the left-non-preferred hand makes toy retrieval easier, infants increasingly use the left hand with age. Thus, when grasping the tool, younger infants are more influenced by their hand preference than older infants, who are better at anticipating the most successful strategies. © 2012 Wiley Periodicals, Inc.* Dev Psychobiol

Keywords: *hand preference; tool use; development*

INTRODUCTION

There has long been much interest in the evolution of handedness in tool use, considered as a marker of hemispheric specialization for sequential behaviors requiring the interplay of sensory input and motor output. Many indices show that a majority of early hominids already preferentially used their right hand to make and manipulate tools 2 millions of years ago (Steele & Uomini, 2005). In modern human adults, the use of a tool such as a hammer is considered one of the best items to evaluate handedness, being among the actions subject to the strongest degree of hand preference (Corey, Hurley, & Foundas, 2001; Mackenzie & Peters, 2000; Porac, Coren, Steiger, & Duncan, 1980; Steenhuis, Bryden, Schwartz, & Lawson, 1990). Another tool, the pencil for writing, also elicits a high level of handedness. Writing is an over-practiced skill. For the hammer, adults expect that using it will require finely coordinated action and that they will need their best hand to achieve the precision required in the successive steps of the action. Contrary to adults, infants have little practice and little anticipation of their action with a tool, and one can wonder what will drive their choice of hand when they are presented with a new tool in the mid-sagittal plane, next to an object to be acted upon, before they have a good understanding of the tool's functionality. Will hand choice go from a slight to a stronger bias in favor of the preferred hand as they come to anticipate the action that the tool is used in? This hypothesis seems compatible with existing data suggesting that tool use develops the most in infants during the second year of life (McCarty, Clifton, & Collard, 2001), and that by this age handedness can already be observed, even though not as strongly as in adults (Dellatolas, Tubert Bitter, & Curt, 1997; Gesell & Ames, 1947). Testing this hypothesis is the goal of the study presented here.

The emergence of hand preference in infants has been extensively studied, in particular for unimanual object grasping and manipulation in cross-sectional studies. As soon as grasping emerges there are clear signs of hand preference (Cornwell, Harris, & Fitzgerald, 1991; Fagard & Lockman, 2005; Hawn & Harris, 1983; Lewkowicz & Turkewitz, 1982; McCormick & Maurer, 1988; Michel, Ovrut, & Harkins, 1985; Morange & Bloch, 1996; Ramsay, 1980). This hand preference does not lead to a

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population ratio of right-handers as high as the one found in adults for writing, and many infants show no preference. The percentage of non-lateralized infants varies between studies and depends on the number and kind of items used to observe handedness, and of the criteria used to categorize the infants as right- or left-handers. One finding common to most studies, however, is that many more infants are found to be right- than left-handers from the beginning (Fagard & Streri, 2004).

The early emergence of handedness has been found in longitudinal studies as well, but these studies have also often shown that handedness fluctuates during the first months of prehension and that infants may alternately use either of the two hands, or both, depending on the session. However, the overall distribution of percentages always shows a clear tendency toward using the right hand in the majority of infants. In addition, handedness in the first sessions predicts handedness in later sessions rather well (Corbetta & Thelen, 1999; Coryell & Michel, 1978; Ferre, Babik, & Michel, 2010; Flament, 1975; Gesell & Ames, 1947; Ramsay, 1985) and handedness changes relatively little over the first 2 years of life (Cochet, Jover, &Vauclair, 2011; Jacquet, Esseily, Rider, & Fagard, 2012; Michel, Tyler, Ferre, & Sheu, 2006). In this last study, infants were tested every 3 months between 8 and 20 months on a 10-item handedness test. The results showed that by 8 months of age infants already show a hand preference for reaching and grasping simple objects that is predictive of later handedness.

Most of the items used to evaluate infants' handedness involve simple actions consisting of grasping objects directly. In contrast, when grasping a tool, the aim is to use it to perform a secondary action on another object or on the self. In contrast with the many studies on handedness for tool use in non-human primates (Hopkins & Rabinowitz, 1997; Humle & Matsuzawa, 2009; Lonsdorf & Hopkins, 2005; McGrew & Marchant, 1997), only a few studies on handedness for tool use in infants have been published. These studies have mostly used handedness as a window to study the development of action planning (Claxton, McCarty, & Keen, 2009; Cox & Smitsman, 2006; McCarty, Clifton, & Collard, 1999; McCarty et al., 2001). For instance, in their 1999 study, McCarty et al. investigated the hand used to grasp the handle of a spoon (in addition to toys with handles) depending on which side the food-loaded bowl was presented to. The infants were first tested for hand preference. Then the authors placed the object in such a way that, for half of the trials (when the handle was on the side of the non-preferred hand), grasping with the preferred hand would lead to an awkward retrieval of the food. They observed that 9-month-olds and most 14-month-olds generally grasped the spoon with their preferred hand, disregarding the item's orientation, whereas older children (19-month-olds and some 14-month-olds) used the hand that was likely to be the most efficient for retrieving the food. In another study (McCarty et al., 2001), the authors also presented tools with a handle oriented to the left and right on alternate trials. The tools included a spoon, a hairbrush, a hammer and a magnet. The first two tools were used in two conditions: toward oneself and toward a puppet. The results showed the same tendency of the younger infants to grasp the tool with the preferred hand irrespective of the side of presentation of the handle, whereas older infants used their non-preferred hand when it was on the side of the handle.

These studies show that when the task constrains infants to choose between using their preferred hand but with the result being that using the tool becomes more difficult, or using the non-preferred hand when it is more likely to result in successful action, they start by using their preferred hand (usually the right) and give up using it between 14 and 19 months. However, infants are not completely naïve to the spoon at 9 months of age, and they may have been influenced by the observation of right-handed persons caring for them and feeding them or themselves using their right hand (Fagard & Lemoine, 2006). In addition, the spoon was presented laterally and the tendency to grasp the spoon to the side ipsilateral to the preferred hand may have been too strong for the younger infants. Older infants may be better at inhibiting this tendency. We thought it interesting to check the relative influence of spontaneous hand preference and level of skill with a completely new tool presented in the sagittal plane so that the asymmetry is a feature not of the tool itself, but of the relative position of the independent object that is to be acted upon using the tool. In the study presented here, we tested which factor, hand preference or anticipation of the more suitable hand, would have a greater influence on infants' choice of hand to grasp a new tool, and whether this choice would change as the infants progress in their understanding of the tool's functionality.

In order to do this, we decided to observe infants' hand choice to retrieve a tool at different stages of tool use. Infants learned to use a rake to use a toy placed in different spatial positions in relation to it (toy to the left of the tool or to its right). Because of humans' tendency to bend the arm slightly when pulling something toward themselves, it is easier to use the right hand than the left to rake in an object located to the left of the rake, and vice versa. Thus, two conditions were compared, one leading to easier success with the tool grasped with the right hand (toy to the left), and one leading to easier success with the tool grasped with the left hand (toy to the right). We investigated whether hand choice (right vs. left) changed between 16 and 22 months, an age span during which progress in understanding the functionality of the rake to retrieve an out-of-reach object has been observed (O'Regan, Rat-Fischer, & Fagard, 2011; Rat-Fischer, O'Regan, & Fagard, 2012).

METHODS

Participants

A total of 48 healthy full-term infants participated in the study (15 females). They included 16-month-olds (*15mo 28d to 16mo 9d*), 18-month-olds (*17mo 26d to 18mo 4d*), 20-month-olds (*19mo 27d to 20mo 10d*), and 22-month-olds (*21mo 25d to 22mo 5d*), Each age group was made up of 12 infants. The infants were recruited from a list of local families who had expressed interest in taking part in studies on infant development. Prior parental consent was granted before observing the infants.

Procedure

The experimental apparatus was a desired toy placed out of reach at different positions near a cardboard rake (15 cm × 20 cm). After being tested for unimanual handedness, infants were first familiarized with the toy alone and with the rake alone for approximately 30 s to 1 min of manipulation. Then they were tested successively in five tool-use conditions, among which three could be analyzed for handedness: toy inside/touching the rake (C1), toy inside the rake but not touching it (C2), and toy to the side of the rake, at about 10 cm from the rake head (C3; see for example C3 in Fig. 1). The two other conditions that could not be analyzed for handedness were toy attached on one side of the rake and rake given in hand. The toy was always just out of arm's reach. The rake was always presented within reach, in front of the infant, in the middle of the table. The toy was presented in alternation to the right or to the left of the rake, with the first side of presentation in counterbalanced order. The conditions were presented in order of increasing difficulty, from C1 to C3. All infants underwent two trials in C1. If they successfully retrieved the object, these were followed by two trials in C2. If both of these trials were successful, then two trials in C3 followed after. If they failed on one of the two trials for a condition, then the infants were given a third trial in this condition. If, in a given condition, the infant failed to retrieve the object on two trials out of three, the parent was asked to give two consecutive demonstrations of obtaining the toy with the rake in that condition. Infants were then tested again after the demonstration. If they failed again on a condition after seeing a demonstration, the infants were not tested on the subsequent condition(s). Thus, the infants only underwent trials in conditions C2 and C3 if they succeeded in the previous condition, either spontaneously or after demonstration. The number of trials per infant was 2–6 in each condition. For the demonstration, the parents were asked to pick up the rake once with the right and once with the left hand.

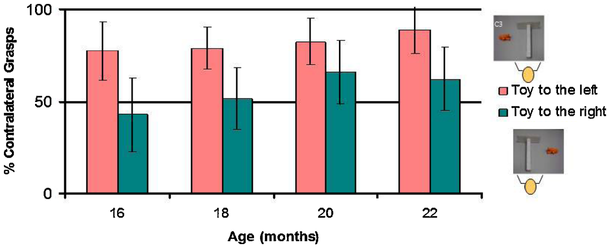

FIGURE 1 Percentage of grasps with hand opposite to the toy side as a function of toy's position and age of participant.

The participants sat in the lap of one of their parents, in front of the test table (80 cm × 120 cm), throughout the experiment. An experimenter sat facing the infant behind the table. A digital video camera recorded the whole session.

Evaluation of Unimanual Handedness

We used a handedness test to compare each infant's handedness for grasping simple objects (Sacco, Moutard, & Fagard, 2006) with their preferred hand for tool use. In this test, infants were presented with five small objects placed along their mid-sagittal plane.

Data Recording and Analyses

Each session was taped using a video camera. The videos were analyzed frame by frame and the hand used to grasp (left, right, or both hands)was coded. Interrater agreement, based on two independent observers coding three infants per age group, was 100%.

For the handedness test, the laterality index (LI*ht*) was calculated as follows: [Nb of right hand grasps − nb of left hand grasps]/[Nb of right G + nb of left hand G + nb of bimanual G]. Based on the LI*ht*, infants were categorized as right-handed ($\mathrm{LI}ht \geq .5$), left-handed ($\mathrm{LI}ht \leq -.5$) and non-lateralized ($-.5 < \mathrm{LI}ht < .5$). A laterality index for tool use (LI*tu*) was calculated using the same formula.

RESULTS

Unimanual Handedness for Grasping Objects (Handedness Test)

The mean laterality index (LI*ht*) was .14 (16 months), .38 (18 months), .41 (20 months), and .36 (22 months). Although the LI*ht* tends to increase with age, particularly between 16 and 18 months, an ANOVA on LI*ht* as a function of age (×4) showed no significant age effect. As can be seen in Table 1, many infants were non-lateralized, but the percentage decreased with age, particularly between 18 and 22 months. The proportion of right-handers tended to increase with age, but was

Table 1. Percentage of Infants Categorized by the Test for Handedness as a Function of Age

	16	18	20	22
Right-handers	41.7	50	58.3	66.7
Non-lateralized	41.7	50	33.3	8.33
Left-handers	16.7	0	8.3	25

already much higher than the percentage of left-handers from the start. A chi-squared test showed that the age effect was not significant ($p = .27$).

Handedness for Tool Use

We first checked whether there was a difference in the use of the two hands as a function of condition: the percentage of right-hand use was 66.7%, 66.9%, and 59.7% for conditions C1, C2, and C3, respectively. An ANOVA on these percentages as a function of condition showed that there was no effect of condition ($p = .38$). We also checked whether there was a difference in the use of the two hands depending on the status of the trial (spontaneous or after demonstration). There was no significant difference ($p = .13$). Thus, we decided to pool the three conditions, as well as spontaneous and after-demonstration trials, to analyze the results for handedness. Since we wanted to evaluate handedness for tool use per se, and not only handedness as defined by the test, we started each analysis by evaluating the whole group, before separately analyzing right-handers (and non-right-handers when possible) as determined by the test. The mean laterality index for grasping the tool, both spatial conditions pooled (LI*tu*) was .39 (16 mo), .25 (18 mo), .16 (20 mo), and .27 (22 mo). An ANOVA with repeated measures on Condition (×2, simple grasping on the handedness test and tool use, repeated measures) and age (×3) showed no effect of condition, no effect of age and no age × condition interaction. Thus, as for the test of handedness for simple grasping, there was no age effect for grasping the tool, no difference between simple grasping and tool grasping, and no interaction between condition and age. Thus, it appears that hand preference is present for grasping the tool to the same extent as for simple grasping at 16 months of age, before the infants understand the tool's functionality.

Grasping the Rake as a Function of Side of Presentation

The whole group of infants more often used their right hand (RH) to grasp the rake when the toy was to the left of the rake (RH: 81.9%; LH: 18.1%) and their left hand (LH) more often when the toy was to the right of the rake (RH: 45.4%; LH: 55.6%). A *t*-test for matched samples showed that the difference between the percentage of right-hand use in the two conditions was significant ($t(46) = 7.08$, $p < .000001$). When the results of the infants categorized as right-handed on the handedness test were analyzed separately, the right hand was more often used to grasp the rake when the toy was to the left of the rake (RH: 86.5%; LH: 13.5%), but also, to a much lesser extent, when it was to the right of the rake (RH: 54.8%; LH: 45.2%). A *t*-test for matched samples showed that the difference between the percentages of right-hand use in the two conditions was significant ($t(25) = 4.1$, $p < .001$). When only results from the infants categorized as non-right-handers on the test were analyzed, the right hand was still used more often to grasp the rake when the toy was to its left (RH: 75.3%; LH: 24.7%), but left-hand use clearly predominated when the toy was to the right of the rake (RH: 33.7%; LH: 66.3%). A *t*-test for matched samples showed that the difference between the percentages of right-hand use in the two conditions in non-right-handers was significant ($t(19) = 6.5$, $p < .00001$). Thus, non-right-handed infants more often used the hand contralateral to the toy (left hand for toy to the right but right hand for toy to the left), whereas right-handed infants more often used their right hand.

All infants used the contralateral hand more often when it was the right hand than when it was the left hand, although this was less true for non-right-handers. A *t*-test for matched samples showed that this difference (81.9% vs. 55.6%) was significant ($t(45) = 3.48$, $p < .01$). It was even more significant when only right-handers were considered (86.5% vs. 45.2%, $t(25) = 4.46$, $p < .001$). In contrast, it was not significant when only non-right-handers were considered (75.3% vs. 66.3%, $p = .43$).

Influence of Age

The difference in hand use between the two spatial conditions also varied between age groups (see Fig. 1). When the toy was positioned to the left of the rake, infants in all age groups grasped the rake with their right hand, with a slight increase from 16 to 22 months (77.5%, 78.9%, 82.3%, and 88.9%, at 16, 18, 20, and 22 months, respectively). An ANOVA on the percentage of right-hand grasps as a function of age was not significant ($p = .74$). When only the infants categorized as right-handers were considered, the percentage of right-hand grasps is slightly higher, except at 18 months (83%, 70.8%, 96.4%, and 91.7%, at 16, 18, 20, and 22 months, respectively). Again, an ANOVA on the percentage of right-hand grasps as a function of age in right-handed infants was not significant ($p = .22$). When only the infants categorized as non-right-handers were considered, the percentage of right-hand grasps did not change much with age (72.9%, 86.9%, 62.6%, and 77.8%, at 16, 18, 20, and 22 months, respectively). Again, an ANOVA on the percentage of right-hand grasps as a function of age was not significant ($p = .62$).

When the toy was positioned to the right of the rake, 16-month-olds also tended to grasp the rake with their right hand (RH: 57.2%) whereas the majority of the older infants grasped the rake more often with the contralateral left hand in this case (RH: 48.6%, 34%, and 37.8% at 18, 20, and 22 months, respectively). An ANOVA on the percentage of right-hand grasps as a function of age was not significant ($p = .42$). The percentage of right-hand grasps in this condition was higher when only the infants categorized as right-handers were considered (73.3%, 62.5%, 43.4%, and 47.5% at 16, 18, 20, and 22 months, respectively). Again, an ANOVA on the percentage of right-hand grasps as a function of age in right-handed infants was not significant ($p = .49$). When only the infants categorized as non-right-handers were considered, the percentage of right-hand grasps was lower and tended to diminish with age (45.7%, 34.7%, 21%, and 24.4% at 16, 18, 20, and 22 months, respectively). Once again, an ANOVA on the percentage of right-hand grasps as a function of age in non-right-handed infants was not significant ($p = .67$).

When the two side conditions (toy to the left and toy to the right) were compared age by age, results varied across age groups. A *t*-test for matched samples comparing the percentage of right-hand grasps in the two side conditions showed no significant difference at 16 months ($p = .13$), but did show significant differences at 18 months ($t(11) = 2.6$, $p < .05$), 20 months ($t(11) = 6.2$, $p < .0001$), and 22 months ($t(11) = 5.1$, $p < .001$). The increasing difference with age between the two side conditions is due to the fact that the frequency of right-hand use when the toy was to the right tends to decrease with age, whereas the frequency of right-hand use when the toy was to the left increases slightly. When the same *t*-test is calculated only on the infants categorized as right-handed by the handedness test, the 18-month-olds, like the 16-month-olds, show no significant difference in their choice of hand between the two conditions ($p = .56$ at 16 months and $p = .63$ at 18 months). For the two oldest age groups the difference remains significant (20 months: $t(45) = 3.48$, $p < .01$; 22 months: $t(45) = 3.48$, $p < .02$). There were not enough non-right-handed infants in each age group to perform the same analysis for them. Thus, it appears that, with age, infants increasingly use the hand contralateral to the toy, even when it is the left hand rather than their preferred right hand, to grasp the rake. However, in Figure 1 it is noticeable that even older infants used their contralateral hand more when this hand was the right hand than when it was the left hand.

Finally, it is clear that handedness (as evaluated by the test) influenced strategy more when the toy was to the right of the rake than when it was to the left. When the toy was to the left of the rake, the percentage of infants grasping the rake with the contralateral right hand varied little with handedness as evaluated by the test. In contrast, when the toy was to the right of the rake, right-handers used their right hand to grasp the rake more often than non-right-handers, and this difference is significant (see Tab. 2).

Does It Pay to Grasp the Rake With the Contralateral Hand?

We performed an analysis to determine whether the infants truly succeeded more often when they grasped the rake with the hand contralateral to the toy. We first checked whether success differed as a function of the side of the toy. A chi-squared test on the percentage of success as a function of side of presentation did not prove significant ($p = .46$). The percentage of success was greater when the hand contralateral to the toy was used to grasp the rake, as opposed to the ipsilateral hand, and chi-squared tests calculated for each age group separately showed that the difference was significant for all age groups (see Tab. 3).

Hand Preference and Success at Tool Use

Finally, we wondered whether being right-handed versus being non-lateralized would influence the success rate. We first analyzed change in the percentage of success as a function of age and condition. Success was more frequent in older than in younger infants, more frequent in C1 than in C2, and more frequent at C2 than at C3 (see Fig. 2). An ANOVA on the percentage of success as a function of condition (repeated measures) and age showed a significant effect of age

Table 2. Percentage of Infants' Use of the Right Hand to Grasp the Tool as a Function of Their Handedness on the Handedness Test

Handedness Test	Toy to the Left	Toy to the Right
Right-handers	86.5 (23)	54.8 (36.5)
Non-lateralized	75.3 (29)	33.6 (35)
ANOVA	NS	$F(1, 45) = 4.01$, $p = .05$

Table 3. Percentage of Success as a Function of Age and of the Hand Used for Grasping the Rake

Age (Months)	Contralateral	Ipsilateral	Chi-Sq.
16	60.5	26.3	9.53, $p < .01$
18	60	39.5	4.05, $p < .05$
20	61.9	40.7	3.6, $p = .05$
22	72	45.2	6.9, $p < .01$

($F(3,\ 88) = 8.56$, $p < .001$), a significant effect of condition ($F(2,\ 88) = 39.78$, $p < .0001$), but no age × condition interaction. A LSD post-hoc test showed that the age effect was due to a difference between 16-month-olds and the three older age groups. All three conditions differed from each other.

To determine whether being right-handed, left-handed, or non-lateralized (as categorized by the handedness test) made a difference for tool use, we performed ANOVAs on the percentage of success as a function of handedness category. Since there was no interaction between age and condition for success, we used mean percentage of success in this analysis. Three series of ANOVAs were conducted: right-handers versus left-handers versus non-lateralized; right-handers versus non-right-handers; and lateralized versus non-lateralized. The ANOVAs were first performed on the whole population, and then separately for each age group. None of the ANOVAs proved significant. Thus, type of handedness does not seem to have affected success at tool use.

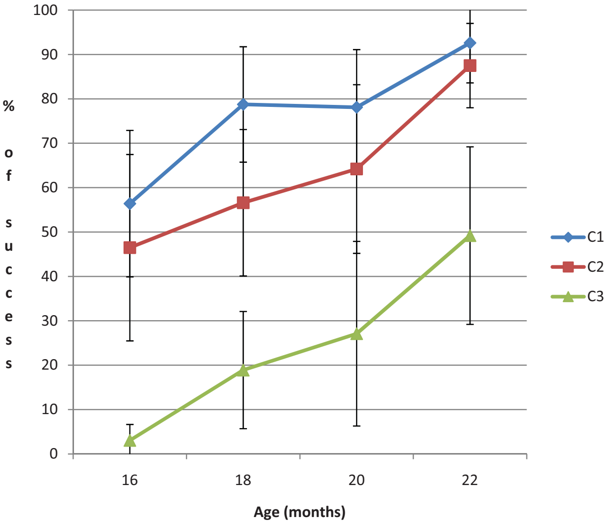

FIGURE 2 Percentage of success as a function of age and condition: (C1: toy inside/touching the rake; C2: toy inside the rake but not touching it; C3: toy to the side of the rake, at about 10 cm from the rake head).

DISCUSSION

The goal of this study was to evaluate the extent to which hand preference influences infants' choice of hand to grasp a new tool, and whether this influence changes as infants' understanding of the tool's functionality improves. To this end, we observed 16- to 22-month-old infants grasping a rake to retrieve an out-of-reach toy in two lateral grasping conditions: in one condition the toy was placed to the left of the rake, and in the other the toy was placed to the right of the rake. In addition, the position of the toy relative to the tool (inside touching, inside not touching, or to the side) made the task more or less difficult. Since the differences between these three levels of difficulty did not affect the frequency with which the infants used their right and left hands, we pooled them to analyze the results for handedness. The rake itself was always presented in the infant's sagittal plane.

We first checked handedness for simple grasping using a test of handedness. More infants were categorized as right-handers than as left-handers (between 2.6 and 7 times more). This was the case as of 16 months of age, and there was a slight but non-significant tendency toward an increase in right-handedness with age, and a decrease in non-lateralization, in particular between 18 and 22 months. Although these results are based on a relatively small number of testing items due to the fact that we did not want to extend an already relatively long testing session, they correlate well with results obtained with the same items presented twice (Sacco et al., 2006). The results are in accordance with previous results showing that hand preference for grasping simple objects is established by 16 months of age for the majority of infants, and that there is only a slight tendency toward an increase in the frequency of right-handers with age (Cochet et al., 2011; Jacquet et al., 2012).

The results concerning the hand chosen to grasp the rake showed that the right hand was used more often than the left, to the same extent as for the handedness test. The overall tendency to use the right hand to grasp a rake presented in the midline did not change with age. Thus, already at 16 months of age, a majority of infants are right-handed for grasping a tool, but no more than for grasping simple objects, and this is true for all age groups. Comparing hand use as a function of the spatial constraints of the task, at 16 months of age most infants used their right hand more than their left to grasp the rake in both lateral conditions. Even though they used their right hand more when the toy was to the left of the rake than when it was to the right, the difference between the two lateral conditions was not significant at this age. On the other hand, all three older groups used their right hand more when the toy was to the left of the tool, but they used their left hand more when the toy was to the right of the tool. The difference in the percentage of right-hand use between the two lateral conditions was significant at 18, 20, and 22 months. This change at 18 months is interesting to relate to previous results showing an increase in the understanding of the rake's affordances to retrieve a far-away toy at that age (Fagard, Rat-Fischer, & O'Regan, 2012; O'Regan et al., 2011; Rat-Fischer et al., 2012). However, at 18 months the infants categorized as right-handed on the handedness test have still some difficulty to inhibit the use of their right hand, as shown by the absence of difference between the two spatial condition when right-handers are considered separately: this could not be interpreted as only due to a lack of anticipation since at the same age, non-right-handed infants show a significant greater use of their right hand than of their left hand when the toy was to the left of the rake.

Hand preference, as evaluated by the handedness test, influenced the results. Infants categorized as non-right-handers by the handedness test grasped the rake more with their left hand than infants categorized as right-handers, and they grasped the rake more with their left hand than with their right hand when the toy was to the right of the rake.

These results show that two factors influence the choice of hand when grasping a new tool to retrieve an out-of-reach object: hand preference, as evaluated by a handedness test, and the placement of the object to be acted upon with respect to the tool. Hand preference does not change much with age and influences infants of all age groups, as shown by the greater use of the hand contralateral to the object when it was the preferred hand than when it was the non-preferred hand. The side of the object relative to the tool influences older infants to a greater extent than younger infants. This increasing use of the contralateral hand with age, when the spatial condition makes it easier to perform the task with this hand, is in accordance with previous results showing that infants start using their non-preferred hand more than their preferred one when it will lead to a better outcome sometime between 14 and 19 months (Claxton et al., 2009; Cox & Smitsman, 2006; McCarty et al., 1999, 2001). The effect of the relative positions of the toy and the rake could have been explained by low-level visual constraints if this effect had been observed in younger age groups as well as older ones. The fact that the effect increases with age means that it reflects some anticipation of the results of the action depending on the hand used to grasp the rake. Thus, it seems that younger infants do not anticipate as well as older infants that using the contralateral hand may be useful to retrieve the toy; it is conceivable that their understanding of the task is not strong enough to help them inhibit their tendency to use the preferred hand, as for 18-month-old right-handers. This fits with the finding that an increase in the capacity to incorporate visual information about the objects' structure into the action increases during the second year (Barrett, Traupman, & Needham, 2008).

Behind the question of the development of hand preference tested in a simple grasping handedness test and choice of hand during tool use lies an important point, which is the relationship between hand preference and hemispheric lateralization for praxis (i.e., planning of complex actions, real, or simulated). There are two main theories on this relationship. One theory ("shared" theory) claims that left-hemispheric dominance for praxis and hand preference in both simple and complex actions are associated (Geschwind & Galaburda, 1985), and that right-hand preference can be explained by the left hemisphere's direct control over it. However, this would mean an opposite hemispheric lateralization of praxis for left-handers, which is far from being systematically the case, as we shall see below. According to another theory ("independent" theory), hand preference and praxis are relatively independent (Vingerhoets et al., 2012). Such a view has received support from a large study on patients undergoing an intracarotidamobarbital procedure (IAP) as part of their preoperative evaluation for epilepsy surgery (Meador et al., 1999). This study showed a left-hemisphere specialization for praxis, independently of hand preference. Data from brain injured patients also suggest a distributed network within the left cerebral hemisphere in the representation of skilled action, including tool use, in right-handers as well as in left-handers (Johnson-Frey, Newman-Norlund, & Grafton, 2005; Vingerhoets et al., 2012). In other words, a left-hander whose left hand is controlled by the contralateral right hemisphere for executing simple actions, such as grasping an object, should nevertheless show a left-hemisphere control for planning complex actions. The two theories lead to different hypotheses for the development of hand preference (Fagard, 2012). If left-hemisphere specialization for praxis and hand preference are closely associated, as postulated by the first theory, then infants should increasingly use their right-preferred hand as they increasingly master new more complex manual skills and form representations of the corresponding motor programs. On the other hand, if handedness and praxis lateralization are independent, hand preference should not increase particularly with the development of complex manual skills.

Testing these hypotheses would require a longitudinal study to check whether right-hand preference changes as complex skills emerge during the first years of life ("shared" hypothesis) or whether the development of hand preference for simple grasping and the emergence of complex skills are independent. Our results are more in favor of some independence, since hand preference does not wait understanding of tool use to be expressed, and does not change significantly (in the absence of constraints against the use of the preferred hand) as understanding of tool use emerges. In fact the only changes that we observed is a better capacity to inhibit the use of the preferred right hand when the spatial constraints favored the use of the left hand, and thus a better anticipation of the hand most fitted for the task. This fits with the observation that hand preference can be observed in 16-week-old fetuses (Hepper, Shahidullah, & White, 1991), at a time when praxis is probably very limited, and that this early hand preference is well correlated with the child's handedness 12 years later (Hepper, Wells, & Lynch, 2005).

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REFERENCES

Barrett, T. M., Traupman, E., & Needham, A. (2008). Infants' visual anticipation of object structure in grasp planning. Infant Behavior & Development, 31(1), 1–9.

Claxton, L. J., McCarty, M. E., & Keen, R. (2009). Self-directed action affects planning in tool-use tasks with toddlers. Infant Behavior & Development, 32(2), 230–233.

Cochet, H., Jover, M., & Vauclair, J. (2011). Hand preference for pointing gestures and bimanual manipulation around the vocabulary spurt period. Journal of Experimental Child Psychology, 110(3), 393–407.

Corbetta, D., & Thelen, E. (1999). Lateral biases and fluctuations in infants' spontaneous arm movements and reaching. Developmental Psychobiology, 34(4), 237–255.

Corey, D. M., Hurley, M. M., & Foundas, A. L. (2001). Right and left handedness defined: A multivariate approach using hand preference and hand performance measures. Neuropsychiatry, Neuropsychology, and Behavioral Neurology, 14(3), 144–152.

Cornwell, K. S., Harris, L. J., & Fitzgerald, H. E. (1991). Task effects in the development of hand preference in 9-, 13-, and 20- month-old infant girls. Developmental Neuropsychology, 7(1), 19–34.

Coryell, J. F., & Michel, G. F. (1978). How supine postural preferences of infants can contribute toward the development of handedness. Infant Behavior & Development, 1, 245–257.

Cox, R. F. A., & Smitsman, A. W. (2006). Action planning in young children's tool use. Developmental Science, 9(6), 628–641.

Dellatolas, G. P., Tubert Bitter, P., & Curt, F. (1997). Evolution of degree and direction of hand preference in children: Methodological and theoretical issues. Neuropsychological Rehabilitation, 7(4), 387–399.

Fagard, J. (2012). *Hand preference, communicative gestures, and praxis in infants*. Paper presented at CogEvo, Rovereto, Italy.

Fagard, J., & Lemoine, C. (2006). The role of imitation in the stabilization of handedness during infancy. Journal of Integrative Neuroscience, 5(4), 519–533.

Fagard, J., & Lockman, J. J. (2005). The effect of task constraints on infants' (bi)manual strategy for grasping and exploring objects. Infant Behavior & Development, 28(3), 305–315.

Fagard, J., Rat-Fischer, L., & O'Regan, J. K. (2012). Comment le bébé accède-t-il à la notion d'outil? How do infants acquire the concept of tool? Enfance, 1, 73–84.

Fagard, J., & Streri, A. (2004). Développement des asymétries chez le bébé. In J. Fagard (Ed.), Droitiers/Gauchers: des asymétries dans tous les sens (pp. 49–70). Marseille: Solal.

Ferre, C. L., Babik, I., & Michel, G. F. (2010). Development of infant prehension handedness: A longitudinal analysis during the 6- to 14-month age period. Infant Behavior & Development, 33(4), 492–502.

Flament, F. (1975). Coordination et prévalence manuelle chez le nourrisson. Paris: Editions du Centre National de la Recherche Scientifique.

Geschwind, N., & Galaburda, A. M. (1985). Cerebral lateralization: Biological mechanisms, associations and pathology, I: A hypothesis and a program for research. Archives of Neurology, 42, 428–459.

Gesell, A., & Ames, L. B. (1947). The development of handedness. Journal of Genetic Psychology, 70, 155–175.

Hawn, P. R., & Harris, L. J. (1983). Hand differences in grasp duration and reaching in two- and five-month-old infants. In G. Young, S. J. Segalowitz, C. M. Corter, & S. E. Trehub (Eds.), Manual specialization and the developing brain (pp. 331–348). New York: Academic Press.

Hepper, P. G., Shahidullah, S., & White, R. (1991). Handedness in the human fetus. Europsychologia, 29(11), 1107–1111.

Hepper, P. G., Wells, D. L., & Lynch, C. (2005). Prenatal thumb sucking is related to postnatal handedness. Neuropsychologia, 43(3), 313–315.

Hopkins, W. D., & Rabinowitz, D. M. (1997). Manual specialisation and tool use in captive chimpanzees (*Pan troglodytes*): The effect of unimanual and bimanual strategies on hand preference. Laterality, 2(3–4), 267–277.

Humle, T., & Matsuzawa, T. (2009). Laterality in hand use across four tool-use behaviors among the wild chimpanzees of Bossou, Guinea, West Africa. American Journal of Primatology, 71(1), 40–48.

Jacquet, A.-Y., Esseily, R., Rider, D., & Fagard, J. (2012). Handedness for grasping objects and declarative pointing: A longitudinal study. Developmental Psychobiology, 54(1), 36–46.

Johnson-Frey, S. H., Newman-Norlund, R., & Grafton, S. T. (2005). A distributed left hemisphere network active during planning of everyday tool use skills. Cerebral Cortex, 15(6), 681–695.

Lewkowicz, D. J., & Turkewitz, G. (1982). Influence of hemispheric specialization in sensory processing on reaching in infants: Age and gender related effects. Developmental Psychology, 18(2), 301–308.

Lonsdorf, E. V., & Hopkins, W. D. (2005). Wild chimpanzees show population-level handedness for tool use. Proceedings of National Academy of Sciences United States of America, 102(35), 12634–12638.

Mackenzie, K., & Peters, M. (2000). Handedness, hand roles, and hand injuries at work. Journal of Safety Research, 31(4), 221–227.

McCarty, M. E., Clifton, R. K., & Collard, R. R. (1999). Problem solving in infancy: The emergence of an action plan. Developmental Psychology, 35(4), 1091–1101.

McCarty, M. E., Clifton, R. K., & Collard, R. R. (2001). The beginnings of tool use by infants and toddlers. Infancy, 2(2), 233–256.

McCormick, C. M., & Maurer, D. M. (1988). Unimanual hand preferences in 6-month-olds: Consistency and relation to familial-handedness. Infant Behavior & Development, 11(1), 21–29.

McGrew, W. C., & Marchant, L. F. (1997). Using the tools at hand: Manual laterality and elementary technology in *Cebus* spp. and *Pan* spp. International Journal of Primatology, 18(5), 787–810.

Meador, K. J., Loring, D. W., Lee, K., Hughes, M., Lee, G., Nichols, M, & Heilman, K. M. (1999). Cerebral lateralization: Relationship of language and ideomotor praxis. Neurology, 53(9), 2028–2031.

Michel, G. F., Ovrut, M. R., & Harkins, D. A. (1985). Hand-use preference for reaching and object manipulation in 6- through 13-month-old infants. Genetic, Social, and General Psychology Monographs, 111(4), 407–427.

Michel, G. F., Tyler, A. N., Ferre, C., & Sheu, C. F. (2006). The manifestation of infant hand-use preferences when reaching for objects during the seven- to thirteen-month age period. Developmental Psychobiology 48(6), 436–443.

Morange, F., & Bloch, H. (1996). Lateralization of the approach movement and the prehension movement in infants from 4 to 7 months. Early Development and Parenting, 5(2), 81–92.

O'Regan, J. K., Rat-Fischer, L., & Fagard, J., (2011). *Mechanisms leading to tool use: A longitudinal study in human infants*. Paper presented at the IEEE ICDL-EPIROB 2011, Franckfurt.

Porac, C., Coren, S., Steiger, J. H., & Duncan, P. (1980). Human laterality: A multidimensional approach. Canadian Journal of Psychology, 34(1), 91–96.

Ramsay, D. S. (1980). Onset of unimanual handedness in infants. Infant Behavior and Development, 3, 377–385.

Ramsay, D. S. (1985). Fluctuations in unimanual hand preference in infants following the onset of duplicated syllable babbling. Developmental Psychology, 21, 318–324.

Rat-Fischer, L., O'Regan, J. K., & Fagard, J. (2012). The emergence of tool use during the second year of life. Journal of Experimental Child Psychology (in press). http://dx.doi.org/10.1016/j.jecp.2012.06.001

Sacco, S., Moutard, M. L., & Fagard, J. (2006). Agenesis of the corpus callosum and the establishment of handedness. Developmental Psychobiology, 48(6), 472–481.

Steele, J., & Uomini, N. (2005). Humans, tools and Handedness. In V. R. B. Bril (Ed.), Stone knapping (pp. 217–239). Cambridge, UK: McDonald Institute Monographs.

Steenhuis, R. E., Bryden, M. P., Schwartz, M., & Lawson, S. (1990). Reliability of hand preference items and factors. Journal of Clinical and Experimental Neuropsychology, 12(6), 921–930.

Vingerhoets, G., Acke, F., Alderweireldt, A. S., Nys, J., Vandemaele, P., & Achten, E. (2012). Cerebral lateralization of praxis in right- and left-handedness: Same pattern, different strength. Human Brain Mapping, 33(4), 763–777.

Chapter 4. Developmental steps leading to tool use – basic mechanisms

1. General introduction

The results of the longitudinal and cross-sectional studies presented in the previous chapter raise question about two important issues regarding the development of tool use in infants.

The first issue concerns infants' perception of spatial relations (connectedness or lack thereof) between objects. In the condition where the object to be retrieved was directly attached to the rake-like tool (C1), infants as young as 12 months spontaneously grasped the handle of the tool and successfully reached for the attractive object. In the opposite case, in the conditions where the object was not attached to the tool, the infants' performance was much lower. This result leads us to the conclusion that at 12 months, infants are able to understand that when two objects are physically connected in space, they form a unique object that can be handled as a single composite object. Thus, at least at the end of the first year of life, infants seem to know that they can grasp the part of an object that is within reach (in this example the handle of the tool) to get the part that is out of reach (the attractive object). In light of this result, the question we were interested in was the following: when do infants start to perceive that when a composite object is made of two clearly distinct parts, grasping any part will make the whole object move? In section 2, I will briefly report the results of a study conducted in our lab that investigated this question (Fagard, Florean, Rat-Fischer & O'Regan, *in prep*).

The second issue concerns infants' use of the notion of connectedness in other problem-solving situations. The fact that at 12 months of age infants have knowledge about composite objects suggests that they understand that objects that are spatially connected can be moved together. This corresponds to the age at which infants are able to use a supporting object or a string to retrieve an out-of-reach object that stands on it or a string to retrieve something attached to it. However, when presented with a choice of several strings, only one which is connected to the out-of-reach object, the 12-month-old infants from our longitudinal study, and even older infants (*unpublished data*), usually fail to select the appropriate string to retrieve the object. This is striking with respect to the results on the composite object. Twelve-month-old infants understand the notion of connectedness, but are not able to use this information in contexts involving multiple objects, only one of which is connected. One hypothesis is that infants might have difficulty inhibiting a motor response toward the multiple strings, independently of their understanding of the notion of connectedness. This hypothesis was tested in the experiment presented in Section 3.

2. Perception of composite objects

Note : The study on composite objects is only presented very briefly, as it was not the main topic of this thesis, and because I was only involved in a part of this work. However, as the results are interesting in the context of the tool and multiple strings problems, it is nevertheless relevant to survey them here.

Contributions to the study

This study was designed by J. Fagard, J.K. O'Regan and C. Florean. The subjects were recruited by L. Rat-Fischer and tested by C. Florean (100%) and L. Rat-Fischer (~20%). The coding and interpretation of the data were performed by C. Florean, S. Margules and J. Fagard. The paper was written by J. Fagard and J.K. O'Regan. The results were presented jointly with results from other studies by L. Rat-Fischer in the form of oral communications at developmental robotic conferences (Robotdoc, Lausanne, 2012; Dagstuhl Seminar 13072, Dagstuhl, 2013) and at the student symposium of the CNRS research group *Neurosciences Cognitives du Développement* (2012).

The perception of object as wholes is influenced by a range of characteristics, such as featural properties (e.g., colour, texture), motion information (all parts of an object typically move together in the same direction), and spatial information (presence or absence of spatial gaps). Infants are known to be sensitive to the physical laws that govern objects, and in particular to the notion of cohesion between objects. Habituation paradigms have shown that 3-month-old infants perceive the unity of objects (Spelke & Van de Walle, 1993). However, to our knowledge, no study has yet investigated the question of how infants take this information into account when presented with a composite object. To test this, we presented to 6-, 8- and 10-month-old infants with an attractive out-of-reach toy and a handle within reach (see Fig. 5). In one condition (connection), the toy and the handle were spatially and physically connected to each other, forming a unique composite object. In a second condition (touching but not connected), the toy and the handle were spatially connected, but were not attached to each other. In a third condition (invisible connection), the toy and the handle were spatially separated, but were physically connected to each other by an invisible fishing line.

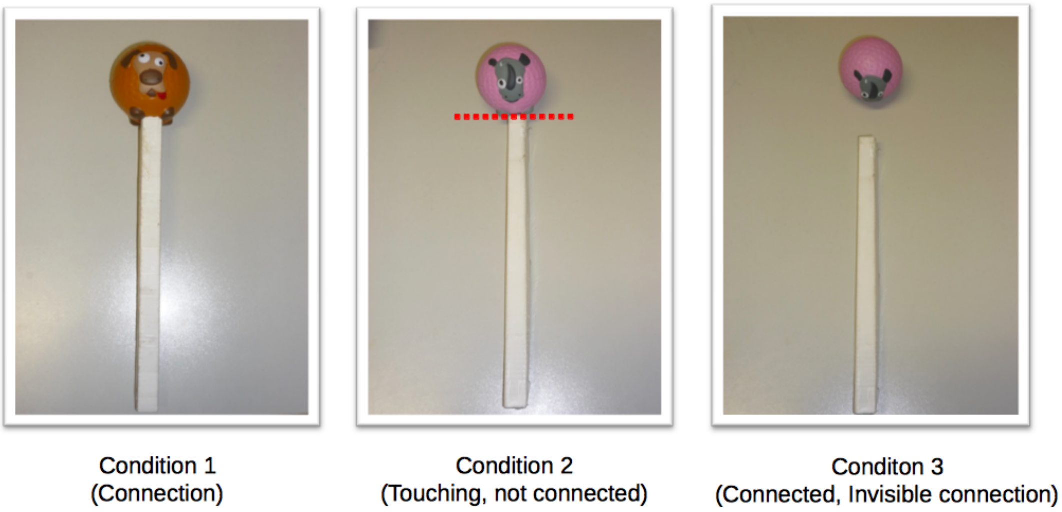

Figure 5. Three conditions for the straight object. The same conditions were presented for the L-shaped object, see the figure below (Pictures by C. Florean).

All conditions were repeated twice, once with a straight handle (as presented in Fig. 5), once with an L-shaped handle (see Fig. 6). The task with the L-shaped handle was supposed to be more difficult than the one with the straight handle, as the out-of-reach part was not in the same line of vision as the reachable part of the handle, thus forcing infants to visually follow the handle to see the connection between the two parts of the composite object. With the L-shaped handle, it was easy to code the part of the object that the infant was looking at, the ball or the part of the handle that was within reach. The straight object was presented obliquely in order to make it possible to code the infant's gaze in a similar way.

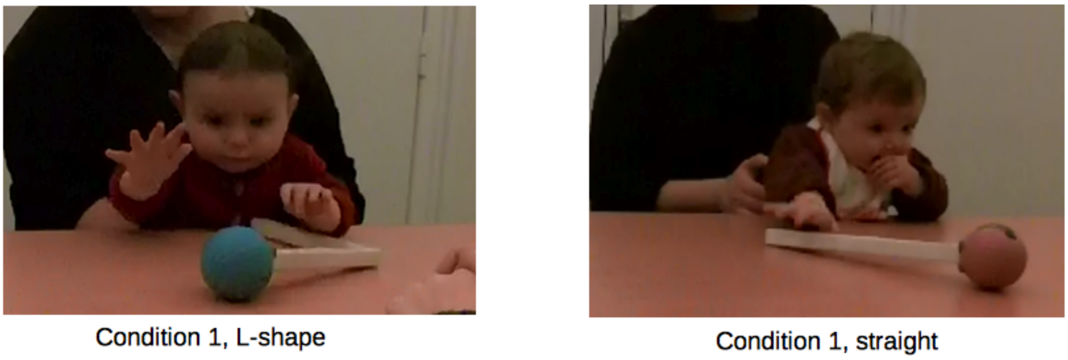

Figure 6. Examples of subjects presented with both kinds of handle: straight handle and L-shaped handle. Pictures extracted from the videotapes.

Condition 1 was scored according to the infant's visual and manual performance with the object. For example, infants who pointed toward the out-of-reach part of the object, or that grasped the handle without looking at the out-of-reach part, were given the lowest score of 1. In contrast, infants who grasped and pulled the handle while looking at the out-of-reach object, or while anticipating the grasping of the out-of-reach part of the object by preparing the free hand, were given the highest score of 3. Infants whose behaviour was difficult to score, meeting neither the criteria for a score of 1 nor of 3, were scored 2. Conditions 2 and 3 were used as control conditions. We hypothesized that infants who were sensitive to the notion of composite objects (i.e., who scored 3 in condition 1) should be surprised when the out-of-reach part of the composite object did not come along with the handle, in condition 2 (touching but not connected, which was visually similar to condition 1). Similarly, we expected these infants to be surprised when the non-connected attractive part did come along with the handle, in condition 3 (invisible connection), despite the spatial gap between the two parts of the object. Similarly to condition 1, infants were scored in terms of levels from 1 to 3, with 1 reflecting no surprise behaviours, and 3 obvious surprise behaviours (such as stopping the movement, looking at the experimenter or laughing). Level 2 was again an intermediate score between 1 and 3.

The analyses of the data from condition 1 showed a significant score difference between the 6-month-olds and the older infants. The difference was the same for the L shape and the straight handles. In conditions 2 and 3, there was a significant difference between the surprise scores of the younger and older infants infants, with older infants showing more surprise. Again, the difference remained the same for both types of handles. Finally, a correlation between conditions 1 and 2 showed a significant positive correlation between the scores from the two conditions. Thus infants who had a the best score in condition 1 were also significantly more surprised in condition 2.

The results of the present study suggest a developmental change in infants' integration of the notion of composite objects around 8 months of age. When presented with a composite object, composed of a handle part that is within reach and an attractive part that is out-of-reach, older infants anticipate that the out-of-reach part can be retrieved by moving the handle, whereas 6-month-olds do not. Moreover, the performance level with a composite object (condition 1) was correlated with the level of surprise in a condition that presented the same initial appearance, when the out-of-reach part did not move with the handle (condition 2). These results confirm that infants have acquired the notion of connectedness between objects very early in development. This is in line with studies showing that in the second half of the first year of life, infants can use connected objects (supporting objects and strings) as a means to retrieve out-of-reach objects.

3. Perception of connectedness: The multiple-strings task

Contributions to the following study

This study was designed by L. Rat-Fischer, in collaboration with J. Fagard, K. O'Regan and with technical help from Antoine Luu, of Tobii Technology. The 14 subjects in the preliminary study and all the subjects in the paper were recruited and tested at the Laboratoire Psychologie de la Perception by L. Rat-Fischer (100%) and the Master's student Blandine Filluzeau (~20%). Both experimenters participated in the data coding. The statistical analyses and interpretation of the data were performed by L. Rat-Fischer, who also wrote the paper. The final version of the paper has been submitted at the time of the submission of the present thesis. The design of the study was presented by L. Rat-Fischer as a poster at the Eyetrackids Conference in Montreal (2011). The results were presented with results from other studies by L. Rat-Fischer as oral communications at developmental robotic conferences (Robotdoc, Lausanne, 2012; Dagstuhl Seminar 13072, Dagstuhl, 2013) and at the student GDR Symposium *Neurosciences Cognitives du Développement* (2012).

3.1. Introduction to the paper

The results of the previous study show that before the end of the first year of life, infants have acquired the notion that two objects attached in space can be moved together. Also, it is known from the developmental literature that in the same age period, infants can use strings and supporting objects as means for bringing an out-of-reach object closer. However, a number of personal observations raised questions about infants' capacity to perceive connectedness between objects in other problem-solving tasks. A first observation arose during the longitudinal study described in Chapter 3 (Fagard, Rat-Fischer & O'Regan, 2012), which we did not mention in the publication because it was an exploratory part of the study. The infants in this longitudinal study were regularly presented with either two or four strings —one end of each was in reach of the subject— and an out-of-reach object that was attached to one of the strings. The gap between the object and the non-connected strings varied between 5 and 10 cm. A striking result was that even at 16 months of age, most infants seemingly chose the strings at random. In an additional preliminary study, we reproduced this result with 14 infants aged 16 months (Rat-Fischer, O'Regan & Fagard, *unpublished data*). Infants were tested on the multiple-strings task, for five to eight trials, depending on their level of motivation. Four strings were presented on each trial, only one being connected to the toy. The mean percentage of success for these 16-month-old infants was 55% (min = 29%; max = 83%). On many of these trials, success was ambiguous, as infants bimanually pulled two strings at a time. When considering only the trials where infants pulled only one string at a time, the mean success rate dropped to 40%, with only 3/14 infants above 50% mean success (number of trials for all infants: 4 to 7). This success rate is remarkably low considering the fact that at this age infants can use the notion of connectedness in the single-string task and in the composite-object task. In light of the results of these two preliminary studies, we conducted a study, presented in the next paper, which investigates why most 16-month-old infants failed to solve the multiple-strings task.

Paper 3 (submitted)

Visual attention in a means-end task: the case of multiple strings

Authors: Rat-Fischer, L., O'Regan, J.K., Fagard, J.

Abstract

The aime of the present study was to understand what factors influence infants' problem-solving behaviours on the multiple-strings task. The main question focused on why infants usually solve the single string-pulling task at 12 months at the latest, whereas most 16-month-old infants still cannot solve the task when several strings are presented, only one of which is attached. We investigated whether this difficulty is related to inhibitory control abilities using a perception-action paradigm. During the first part of the experiment, we assessed the ability of infants aged 16 to 20 months to solve the multiple-strings task. The infants were then divided into three groups based on performance (a “failure” group, an “intermediate” group, and a “success” group). The three groups' looking strategies were compared, particularly with regard to predictive gaze when seeing an adult performing the task. We found that only infants who successfully performed the action task also visually anticipated which string the adult had to pull in the visual task. Our results show that lack of inhibitory control is one factor that contributes to infants' failure at the task, and support the direct matching hypothesis, according to which infants need to be able to perform the actions themselves before being able to anticipate similar actions performed by others.

1. Introduction

Physical properties of objects and their relations to other objects are detected very early in infancy. Vision studies using habituation paradigms have shown that abilities such as identifying objects' height (Hespos & Baillargeon, 2001), solidity or continuity (Spelke et al., 1992) emerge before 6 months of age. At this age, infants also understand some dynamic aspects of objects, in particular the cohesion of two objects moving together in the same direction (Spelke et al., 1992) and the principle of contact (Leslie et al., 1987) wherein one object is affected by another only if there is contact between them.

In action studies, this notion of contact between objects, also known as “connectedness”, has been explored in older infants, mainly using two paradigms: pulling a support to retrieve an out-of-reach object placed on top of it, and pulling a string attached to the out-of-reach object. Studies have shown that infants are able to use the support as a means for bringing the goal object within reach at around 9-10 months of age (Willatts, 1999; Schlesinger & Langer, 1999; Willatts, 1984; Bates, Carlsonluden, & Bretherton, 1980; Uzgiris & Hunt, 1975; Piaget, 1936/1952). Concerning the string paradigm, Richardson (1932) was, to our knowledge, the first to write about the string task in infants. He reported an increase in the occurrence of pulling a string when an object was attached to it around 10 months. Piaget reported from observations on his own children that the capacity to pull a string to retrieve an object emerged at about 11 months of age (Piaget, 1936/1952). For each of his three children, Piaget noted that they discovered the pulling effect of the string through active exploration. Later, the string behaviour was included in assessments of psychological development, and the age of 10-12 months was found to be the period when infants began solving the string problem (Uzgiris & Hunt, 1975). Thus, it appeared that at this period, infants understand the notion of connectedness between objects.

One way to decide whether infants understand a physical concept is to give them a choice of possible ways to perform a particular task. Some tool use studies for example have investigated whether infants are capable of selecting the correct, functional tool from among a set of non-functional alternatives to retrieve an out-of-reach object (e.g., Brown, 1990; Chen & Siegler, 2000). Perceiving which tool affords the retrieval of the object and being able to complete the task with the correct tool has been interpreted as an indicator of true understanding of the tool's use. Following this principle in a substantially simpler situation, one way to evaluate whether infants understand and use the notion of connectedness in the string- and cloth-pulling situations is to present infants with a choice of strings, only one of which is connected to the toy. Infants who understand the notion of connectedness should identify which string is connected to the toy, therefore affording its retrieval. Richardson (1932) noted that the ability to ignore strings not attached to the object increases around 10 months; however, even at 12 months of age, infants rarely succeeded on their first attempt at the task by pulling the connected string. In a more recent study, Brown (1990) found that the capacity to ignore the unattached strings increases with age during the second year of life. However she noted that the infants did not immediately succeed in choosing to pull the attached string among three strings aligned toward the object at 14 months, but only having succeeding at simpler situations of the string pulling task, involving lesser strings. In an exploratory study on 14 infants aged 16 months (unpublished data), we observed that they rarely chose the correct string among a set of four including three non-connected strings, whereas infants can theoretically pull a string to bring an object closer at around 11 months (cf. Piaget, 1936/1952; Uzgiris & Hunt, 1975; personal unpublished data). Such age differences between the time when infants apparently understand the notion of connectedness and the age where they can use the notion in choice situations are striking. What factors are responsible for this delay?

One candidate is inhibitory motor control. Infants presented with multiple strings have to inhibit automatic, string-pulling motor responses, in order to choose the correct string. Inhibitory motor control has been reported to develop between 8 and 12 months of age in situations involving object retrieval or detour reaching (Diamond, 1991). Also, as mentioned above, researchers investigating string- and cloth-pulling problems have reported increases in the ability to ignore strings or clothes not in contact with the object starting at 10 months of age (e.g., Aguiar & Baillargeon, 2000, for the cloth task; Brown, 1990, and Richardson, 1932, for the string task). However, it seems plausible that the complexity of the task, involving (1) scanning the multiple-strings scene in order to (2) isolate the correct spatial information, followed by (3) choosing and (4) pulling the correct string until the object is retrieved, could compete temporarily with infants' abilities to inhibit the action of pulling. This might be reinforced by the fact that in general it is not particularly costly for infants to pull the strings randomly until they retrieve the object.

To investigate whether infants' difficulties with the multiple-strings task result from inhibitory limitations, we designed a perception-action experiment. We compared infants' performance on the multiple string-pulling task with their visual explorative behaviour using an eye-tracker. Eye-tracking techniques are ideal to measure infants' visual exploration of experimental scenes (e.g., Franchak, Kretch, Soska & Adolph, 2011). The experiment was divided into two parts: an action task and a vision task. In the action task, infants were presented with four strings, only one of which was connected to an out-of-reach attractive toy. The infants' task was to choose the correct string in order to retrieve the toy. The vision task involved the same situation as the action task, but the string was pulled by an adult rather than by the infant, while the infant's looking behaviour was recorded. In particular, we checked for predictive gaze toward the connected string before the adult chose which string to pull. Predictive gaze has recently been used as a measure of infants' ability to anticipate an outcome when observing ongoing actions (see Biro, 2012, for a brief review). This situation allowed us to isolate infants' visual exploratory behaviour from their motor activity, in a task where no motor response was required. Thus, we expected that if a lack of inhibitory control were the only factor responsible for infants' failure at the action task, all infants would show similar visual anticipatory behaviours on the vision task, independently of their success or failure at the action task. In contrast, if infants failed at the action task because of limitations other than a lack of manual inhibition, we expected infants who failed to pull the correct string in action, to also fail to visually identify the correct string in the vision task. In this case, looking strategies on the vision task should differ between infants who fail at the action task and those who succeed. To test these predictions, we compared infants' looking strategies as a function of their performance on the string task, independently of their age, which ranged from 16 to 20 months. This age range was chosen because preliminary observations suggested that over this age period some infants fail to solve the multiple-strings problem while others succeed, thus enabling comparison between the looking strategies of the two categories of infants. Since the coding of “true” success was sometimes ambiguous due to bimanual strings choices, we assigned infants to three groups based on performance (failure, intermediate and success) as described in the Methods section. If the inhibitory control hypothesis is correct, we expected to find no differences in looking strategy between groups. In contrast, if inhibition is not involved, or at least if it is not the only factor involved in infants' difficulty solving the string problem, then we expected to find differences in looking strategies, at least between the failure group and the success group.

Methods

Participants

The final sample of the study consisted of 41 healthy full-term infants. We tested infants between 16 and 20 months of age: seventeen 16-month-old infants (M = 15months 31days, Range = 15mo 21d to 16mo 10d, 7 girls), nine 18-month-old infants (M = 18months 0day, Range = 17mo 16d to 18mo 12d, 7 girls), and fifteen 20-month-old infants (M = 20months 3days, Range = 19mo 16d to 20mo 13d, 10 girls). Five additional 16-month-olds, four additional 18-month-olds and three additional 20-month-olds were tested, but not included in the final sample because of inattentiveness during the vision experiment (the total looking time at the scene took up less than 20% of duration of trials ; n = 4 infants), lack of interest in the action task (n = 2), uncorrected vision (infant was tested without glasses because the system could not track looking behaviour with glasses on, n = 1), experimenter error in the presentation order of the strings (n = 3), or technical problems with the eye-tracking system (n = 2). All infants were recruited from a list of local families who expressed interest in taking part in studies on infant development. Parental consent was granted before the infants underwent the experiment. The infants were given a small gift for their participation in the study.

Design and materials

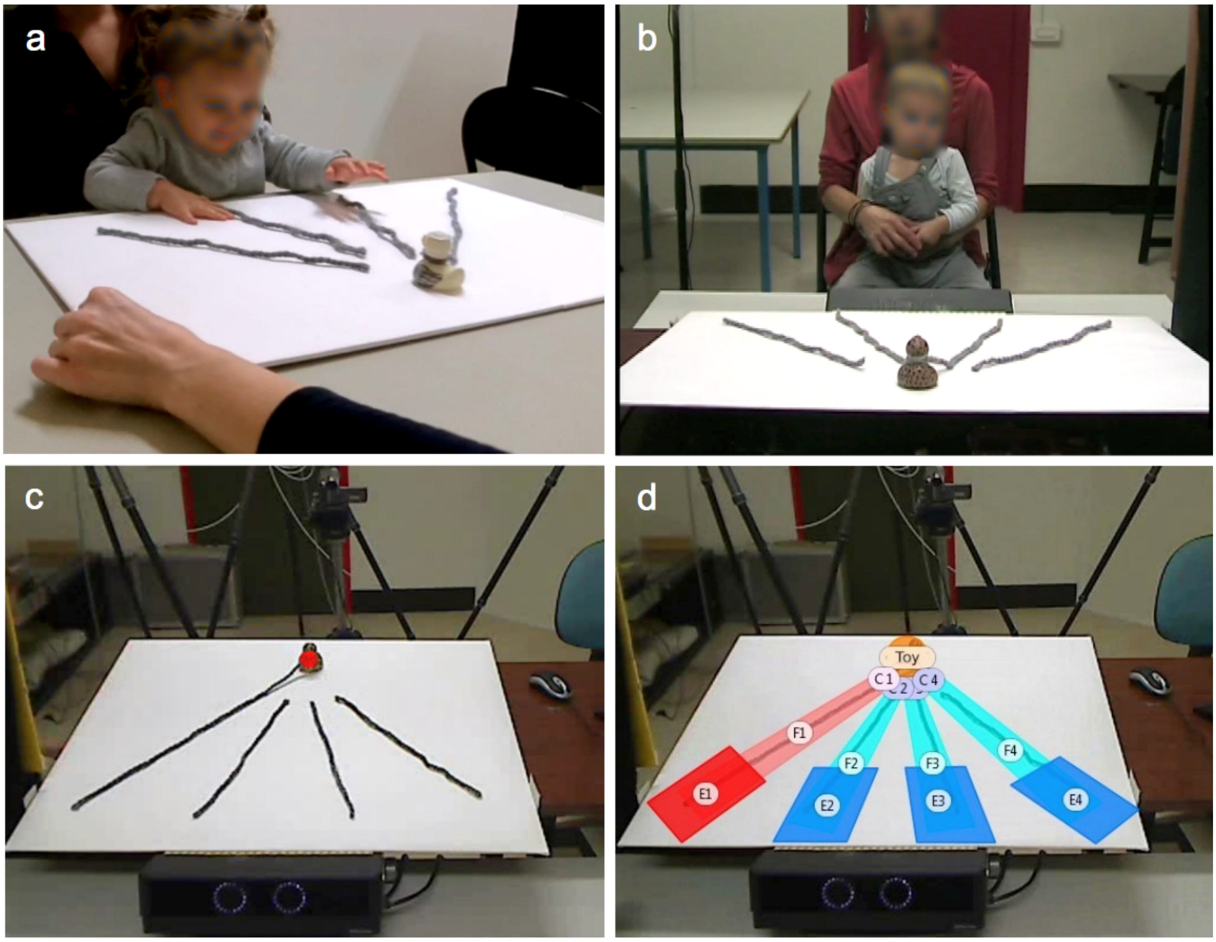

Figure 1. Illustration of the two experimental tasks. (1a) Infant performing the action task. (1b) infant looking at the scene in the vision task (front camera). (1c) View of the vision task from the scene camera, above the subject's head. (1d) View of the four areas of interest (AOIs): E = string-end, F = string, C = area between string and toy (either a gap or a connection), and Toy = toy connected to one of the four strings. In this example, the connected string is F1, which is the first string on the left. The scene area includes the entire white cardboard area.

1. Action task *(Figure 1a)*

The task was presented on a solid white carton board (50 cm x 70 cm) which the experimenters could slide from their side of the table toward the opposite side, at around 5-10 cm from the infant. The four strings placed on the board were dark grey, made of wool and measured either 35 cm for the two strings placed on the side, or 30 cm for the two strings placed in the middle, to make them equally graspable for the infant. The gap between the non-connected string and the toy measured 5 cm. The toy was placed out of the reach of the infant, at 38 cm away from the near end of the board. The toys used were coloured plastic ducks, which are the toys that the infants tested in our lab usually express the most interest in. A different duck was used on each trial to avoid decrease in motivation. A digital video camera was positioned behind the table, to one side of the experimenter, to record the infant's active behaviour during the task, and to allow rough off-line coding of looking behaviour.

2. Vision task *(figure 1b, c, d)*

The scene for this task was laid out on the same carton board as in the action task. The board was again placed in front of the infant, but at a distance of approximately 70 cm away from the infant, and inclined horizontally at an angle of 9° with respect to the table to facilitate gaze measurement with the eye-tracker. The same strings were used as in the action task, but the gap between the toy and the non-connected strings was larger (10 cm). This distance was calculated based on Thales' theorem, taking into account the larger distance between the board and the infant, and the inclination of the board. A Tobii X120 eye-tracker was placed on a table slightly below the board, around 60 cm away from the infant's eyes and at an angle of 20° from the table. A digital video camera ("front camera": see Fig. 1b) was positioned behind the board, facing the infant, to check its looking behaviour outside the cardboard scene, when the eye-tracker cannot track the infant's gaze. A USB camera ("scene camera": see Fig. 1c and 1d) linked to the Tobii system, was placed just over the infant's head. The image from this camera, representing the subject's view and including the carton board or looking scene, was calibrated inside the system as the scene camera. The five calibration points used were the four corners and the centre of the board. Gaze direction was measured and recorded using the Tobii Studio program.

Procedure

The action task was always presented first, to ensure that the infants had understood the task when measuring their looking behaviour during the vision task. Before being tested with four strings, each infant was tested with only one string, connected to the out-of-reach toy. This was to make sure that all participants were able and motivated to use the string as a means to retrieve the toy. In both tasks, each trial was prepared behind an opaque screen, to keep the subject from seeing the connection through a simultaneous movement of the toy and the connected string. The test began when the mask was removed.

In the action task, the board was first presented out of the infants' reach, to prevent them from pulling any string at random without even looking at the toy. After the infant had looked at the board for at least 1 second, the board was moved toward the infant, stopping at a distance of 5-10 cm. If the infant pulled the correct string and thus grasped the toy, he was allowed to play with it for about one minute. If he pulled one or several of the wrong string(s), the board remained in position until the infant had pulled the connected string and retrieved the object.

During the vision task, the parent whose lap the infant sat in was asked to wear strong sunglasses to prevent the Tobii from tracking his/her eyes instead of those of the infant. Because infants often leaned toward the scene to get closer to the object, making it difficult for the eye-tracker to keep registering their gaze, the parents were also asked to stabilize their infant by gently holding their chest and arms during the task (see Fig. 1b). Again, each trial was prepared besides an opaque screen. For each trial, the board was then placed at the calibrated position described in the previous section. During this transporting phase of the board, the object and its connection to one of the four strings were covered by a mask to prevent infants from seeing the connection before the cardboard was in the calibrated position. Then, the experimenter went to the child's left side and removed the mask. The experimenter's position (left or right) relatively to the side of the infant could not be randomized because of the lack of space on the right side, due to the presence of the USB camera stander. For this reason, we controlled for the presence of an effect of side of presentation in the analyses of the vision data at each position of the connected string. After the removal of the mask, the infant's attention was driven to the out-of-reach toy with phrases such as "*Look at the duck! Do you see the duck? How can I get it? Which string should I pull?*". After a mean time of 11.4 seconds (SD = ±3.39s, min = 2.03s; max = 32.69s; depending on infants' attention toward the scene), the experimenter approached her hand toward the connected string and pulled it to bring the object within reach, giving it to the infant. The cardboard was then pulled away and the next trial was prepared behind the opaque screen.

During both tasks the participants sat in the lap of one of their parents, in front of the test table. An attractive toy was always presented at the same position on the board, out of the reach of the subject, and attached to one of four strings. Four consecutive trials (one at each possible position of the string) were presented in each of the two tasks. The position of the connected string (see Fig. 1d for the numbering of the strings) was randomized between the four trials across all subjects, so that all orders of presentations were tested at least once in vision and once in action. The infants never saw the same order of presentation for the action and the vision tasks consecutively. Each experimental session lasted about 30 minutes. A laterality test was performed to assess infants hand preference (see Fagard & Marks, 2000) in order to control for any effect of side in the action task.

Data Analysis

1. Action task

The infants' behaviours were coded from the video recordings. As infants could pull several strings at the same time, and as they could pull any string until they got the toy, independently of their actual understanding of the physical relations between the strings and the toy, it was sometimes difficult to code in terms of true success versus failure. We attributed a behavioural category to each trial. A score of 1 was given when infants apparently pulled the strings randomly without looking at the out-of-reach toy. An intermediate score of 2 was given when infants looked at the toy before and while pulling a string, but did not pull the connected string first. This score was also attributed when infants pulled two strings simultaneously with both hands (one of which was connected to the object), making difficult to code whether this success was intentional or not. A score of 3 was given when infants looked at the toy before and while pulling directly on the connected string. The scores for each infant were averaged over the four trials. We then assigned infants into one of three groups based on performance: Group 1 (mean score 1 to 1.5), the failure group; Group 2 (mean score >1.5 to <2.5), the intermediate group; and Group 3 (mean score 2.5 to 3), the success group. This coding was independent of the infants' age (16, 18 or 20 months). Even though more of the 20-month-olds suceeded at the task than in the younger infants, there was a great deal of age variability in each performance group (as we will see in the Results section). Moreover, the purpose of this work was not to evaluate the age differences in action capacities between these ages. We thus preferred to compare the looking strategies of the different performance groups rather than the age groups.

A second observer coded 18 infants (44%) independently to assess inter-observer reliability. Reliability between the two observers was 80%.

2. Vision task

We analysed infants' visual behaviour from the moment when the object and the connection area were uncovered by the mask to the moment when the experimenter began to reach for the connected string. We could thus record the infant's exploration of the scene before pulling the string. Three areas of interest (AOIs) were defined for each of the four strings (see Fig. 1d): 1) the whole string (area F, from one end to the other end of each string); 2) the connection area (area C), corresponding either to the gap between the string and the toy, or to the connection between the string and the toy, in the case of the connected string; 3) the end of the string (area E), where the strings are usually grasped when being pulled. As the two external strings were longer than the strings in the mid-position, the AOIs F and E were of the same size for the external strings (strings 1 and 4), and for the strings in the middle (strings 2 and 3), but the two pairs differed from each other. We defined these three AOIs to explore possible differences in looking strategies toward the connected versus non-connected strings between the performance groups. We used the fixation duration (FD) for each AOI. The choice to use the FD over the visit duration (VD, corresponding to the FD with, in addition, saccades within the AOIs), was motivated by the literature. Aslin (2012) suggested that not all saccades inside the AOI constitute relevant information, as they might only “fly over” the AOI without processing any information. All data were taken separately for each trial. Due to different scene duration in each trial, the FD data were transformed into percentages of looking (fixation) time at the entire scene (the area inside the cardboard). After that, the data were averaged across the three non-connected strings to obtain the mean looking percentage toward non-connected strings. This value was then subtracted from the percentage of looking time spent looking at the connected string. If the value is positive, this means that the infant looked more at the connected string than at the non-connected strings.

Results

I. Action task

Mean performance as a function of age

A regression analysis on mean performance (averaged over the four trials), as a function of age (in days, min = 478d ; max = 619d) showed a significant increase in performance with age ($R = .31$, $F(1,39) = 4.14$, $p < .05$).

As mentioned in the Methods section, the aim of our study was to focus on the differences between performance groups, rather than on the differences betweenages. In the following section we give the mean age for each group.

Mean age by performance group

An Anova on the performance groups with age as the dependent variable showed no significant age differences between the three groups ($F_{2,38} = 2.57$, $p = .09$, $\eta^2 = .12$, table 1). Thus, if different looking strategies are observed between the performance groups, age should not have directly influenced them, as the age distribution did not significantly differ between the groups.

Table 1. Mean age, mean score and number of subjects in each performance group. SE = standard error.

Group	N	Mean Age	SE	Mean score	SE
1	15	17.33	0.42	1.42	.40
2	13	17.69	0.50	1.88	.50
3	13	18.77	0.48	2.67	.50

Distribution of handedness in each group

Right-handed infants could have expressed a bias toward the string that was positioned closer to their preferred hand. Thus, we analysed the infants' performance by the position of the connected string and by their handedness.

Table 2. Distribution of handedness by group

Group	N	Left-handed	Non-lateralized	Right-handed
1	15	1	7	7 (46.7%)
2	13	2	5	6 (46.1%)
3	13	0	4	9 (69.2%)

A chi-squared analysis of handedness across the performance groups showed no significant difference in the distribution of handedness between the three groups ($N = 41$, $dof = 2$, $\chi^2 = 1.86$, $p = .40$; Table 2). This absence of difference is important as hand preference could affect which string the infant pulls first. For example, right-handed infants might express a bias toward the string at Position 3 (see Fig. 1). Thus, a difference in such bias between groups (as we will see below), should not be caused by differences in handedness between the groups.

Mean performance for each position of the connected string

A repeated measures ANOVA on mean performance with the position of the connected string (1, 2, 3 and 4; see Fig. 1) as a within-subjects factor showed a significant effect of the position of the connected string ($F_{3,120} = 4.86$, $p < .01$, $\eta^2 = .11$) $m_{S1} = 1.82$; $m_{S2} = 2.02$; $\mathbf{m_{S3} = 2.22}$; $m_{S4} = 1.79$). A post hoc analysis indicated that mean performance was greater when the connected string was on Position 3 than when it was in Position 1 and 4.

It is worth noting that the third position is the closest position to the right hand. Thus, higher performance for connected strings at the third position could have been explained by the fact that a majority of infants was right-handed (54% of infants) or non-lateralized (39%). At least right-handed infants, and possibly most non-lateralized infants might have shown a tendency to pull this string first, independently of which string is actually connected to the toy, because it was the closest to their right hand. If this were true, infants performance would likely appear greater when the connected string was in Position 3 than when it was in the other positions. In fact, the infants' first choice was directed to the string in Position 3 (with or without pulling another string at the same time) in 66.46% of trials, which corresponds to more than two out of the four trials per infant in this task. A breakdown of this bias toward the third position by handedness showed that overall, right-handed infants selected this string first on 62.5% of their initial attempts, and non-lateralized infants on 76.56%, whereas the three left-handed infants chose it on 41.67% of their initial attempt.

Beyond the main effect of the position of the connected string on mean performance, there could be further significant differences between performance groups. At least in the third group (success group), infants should not show this bias toward the third position but should perform equivalently at each string position. Figure 2 illustrates the performance of infants from each group by string position.

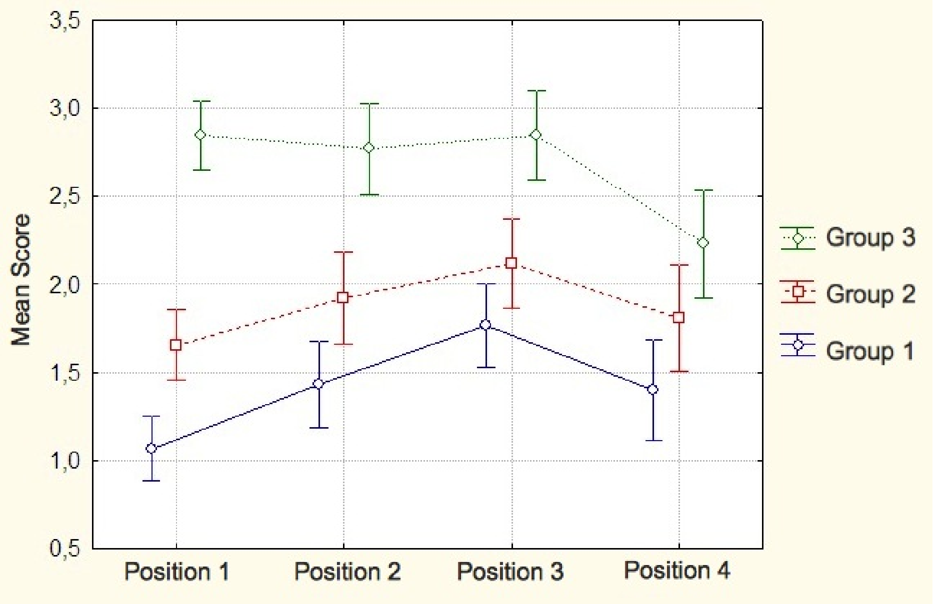

Figure 2. Mean score for each position of the connected string by group. Error bars give standard error.

The most important observation from Figure 2 is that the performance difference when the connected string was in Position 3 as compared to 1 and 4 only seems to have occured in Groups 1 and 2. It is also worth noting that Groups 1 and 2 show the same performance pattern, that is, greater performance when the connected string is in Position 3, and a comparative decrease in performance for Positions 1, 2 and 4. In contrast, Group 3 seems to have performed equally at least for Positions 1 to 3. Repeated measures ANOVAS on each group with string position as a within-subjects factor indicated that this performance difference in favour of the string in Position 3 was only significant in Group 1 ($F_{3,42} = 4.94$, $p < .01$, $\eta^2 = .26$). As the distribution of handedness between groups was not significantly different, this result suggests that the infants in Group 1 had a bias toward the string on the third position, which would explain their higher performance when the connected string was in Position 3. Indeed, infants in Group 1 pulled the string in Position 3 on their first attempt on 83.33% of trials, the infants in Group 2 on 63.46% of trials, and infants in Group 3 on 50%

of trials.

Finally, in Group 3, there was a significant performance difference when the string was in Position 4 compared to the other positions ($F_{3,36} = 6.18$, $p < .01$, $\eta^2 = .34$), for which we have no particular explanation.

Mean performance by trial

To control for a possible effect of the repetition of the task with successive trials, independently of the position of the string, we performed a repeated-measures ANOVA on mean performance across trials. There was no significant difference in performance across trials ($F_{3,120} < 1$; $m_{t1} = 1.94$; $m_{t2} = 1.93$; $m_{t3} = 2.07$; $m_{t4} = 1.90$). There was also no significant interaction between trials and groups ($F_{6,114} < 1$).

II. Vision

The mean Fixation Duration (FD) toward the scene was 3.78s (*SD* = ±1.87s, min = 0, max = 11.48s). At other times infants looked outside the scene, mostly at the experimenter, at their parent or visually exploring the room. As mentioned in the Methods section, infants who looked at the scene for less than 20% of the total trial time were not included in the final sample. Mean FD was 2.69s for the toy area (69% of the looking time at the scene; *SD* = 1.54, min = 0; max = 11.40), and 0.46s for the string area (12.44% of the looking time at the scene; *SD* = .36, min = 0; max = 2.46). For further analysis, all FDs for the toy, string and gap areas were converted into percentages, based on looking time at the scene in each trial.

III. Comparison between vision and action

In this section we compare the looking strategies of the three performance groups from the action task: failure, intermediate and success. In the first paragraph we analyze the differences in the mean percentage of looking time at the whole scene, at the toy area, and at the string area.

For all further analyses in the other paragraphs of Section III, the dependent variable is the <u>difference</u> between the percentage of fixation furation (%FD) toward the AOIs (F, E and C) of the connected string and the mean %FD toward the three non-connected strings (see Table 3). The performance group was integrated as aa betwee-subjects variable. To control for a side-effect due to the left-position of the experimenter, the position of the string was added as an intra-subject variable.

Table 3. Mean %FD difference (±SE) between connected and non-connected areas of interest, by group. Significance level: * <.05, ** <.01, ***<.001.

Area of Interest (Difference between connected and mean of non-connected areas)	Performance group		
	1	2	3
F: Whole String area	.02 (±1.09)	-.36 (±1.17)	**4.23 (±1.17) ***
C: Connection area	-.73 (±.86)	.78 (±.92)	.46 (±.92)
E: Extremity area	.52 (±1.34)	.67 (±1.44)	**10.04 (±1.44) *****

Looking time at the scene as a function of performance group

The mean fixation duration on the scene was not significantly different between the groups ($F_{2,38} = 1.84$, $p = .17$, $\eta^2 = .09$). However, an ANOVA on the mean %FD on the scene revealed a significant difference in the proportion of looking time at the scene between the groups ($F_{2,38} = 3.27$, $p = .05$, $\eta^2 = .15$). A post hoc analysis indicated that infants in Group 3 looked significantly less toward the whole scene (mean $FD_{scene} = 26.68\%$ of the total scene duration) than infants in Group 1 (39.39%). Group 2 had an intermediate looking percentage of 34.94%.
The mean %FD for the toy area differed by group ($F_{2,38} = 6.76$, $p < .01$ $\eta^2 = .26$). A post hoc analysis indicated that infants in Group 3 looked significantly less at the toy (mean $FD_{toy} = 26.68\%$ of total scene duration) than infants in Groups 1 (77%) and 2 (71.51%).
The mean %FD on the four strings (independently of their connection with the toy) differed by group ($F_{2,38} = 4.48$, $p < .05$ $\eta^2 = .19$). A post hoc analysis indicated that infants in Group 3 looked significantly more at the strings (mean $FD_{strings} = 16.96\%$ of the total scene duration) than did infants in Group 1 (8.64%). Infants in Group 2 had an intermediate looking percentage of 12.3% at the strings, not significantly different from the other groups.

Mean percentage difference in looking time at connected versus non-connected strings (Area F, see Fig. 1d)

A repeated measures ANOVA on the mean %FD difference between connected and non-connected strings showed a significant difference in looking strategies between groups ($F_{2,38} = 4.80$, $p<.05$, $\eta^2 = .20$; Table 3, Fig. 3). A post hoc analysis indicated a significant difference between Group 3 (mean $\%FD_{diff} = 4.23$), and the two other groups (mean

$\%FD_{diff} = .02$ for Group 1 and -.36 for Group 2). Thus, infants in Group 3 looked more at the connected string than the non-connected strings, unlike the two other groups (see Fig. 3). An ANOVA on the mean %FD difference between connected versus non-connected strings by group (n = 3) with the positions of the connected string as a repeated measure (n = 4) showed no significant effect of string position ($F_{3,114} = 1.98$, $p = .12$, $\eta^2 = .05$), and no significant interaction between group and string position ($F_{6,114} < 1$). This result indicates that there was no looking bias toward some of the strings, despite the asymmetry of the experimental setup (experimenter positioned to the left of the infant). Also, contrary to the action task, there was no bias toward the third string position. This confirms that this bias in the action task was related to the infants' right-hand preference.

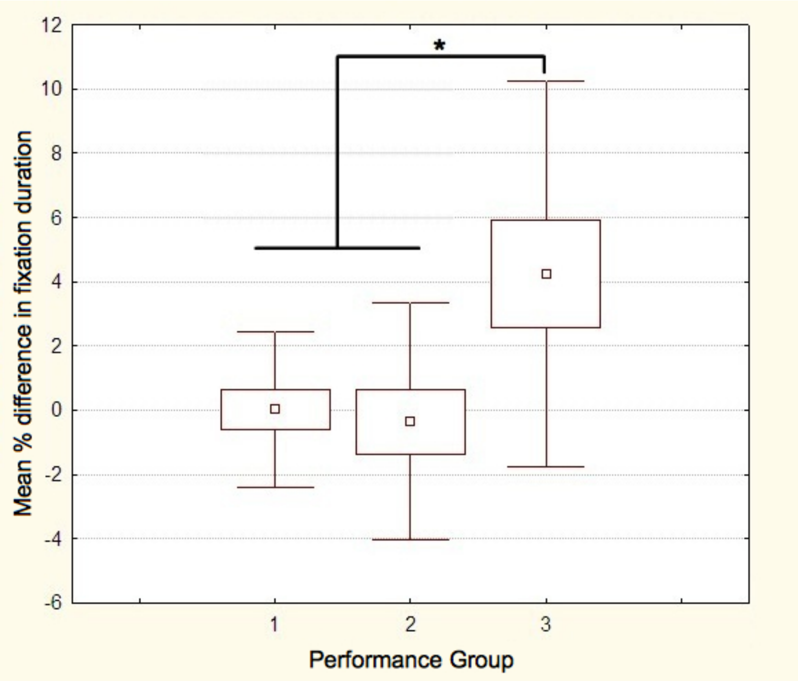

Figure 3. Mean percentage fixation duration difference between connected and non-connected whole strings, by group. Dots correspond to mean, boxes to standard error, and whiskers to standard deviation.

Mean percentage difference in looking time at the connection versus the spatial gaps (Area C, see Fig. 1d)

A repeated measures ANOVA on the mean %FD difference between the connection area versus the gap areas showed no significant difference in looking times between groups ($F_{2,38} < 1$; Table 3). There was no significant difference in the string position ($F_{3,114} = 2.56$, p = .06, $\eta^2 = .06$), and no significant interaction between group and string position ($F_{6,114} = 1.27$, $p = .28$, $\eta^2 = .06$).

Mean percentage difference in looking time at the end area between connected and non-connected strings (Area E, see Fig. 1d)

A repeated measures ANOVA on the %FD difference between the end of connected and non-connected strings showed a significant difference in looking strategies between groups ($F_{2,38} = 14.70$, $p < .001$, $\eta^2 = .44$). A post hoc analysis indicated a significant difference was significantly different between Group 3 and the two other groups (see values in Table 3). Infants in Group 3 looked more at the end of the string that was connected than at the end of the non-connected strings, unlike the two other groups (see Fig. 4). Again, there was no significant effect of string position ($F_{3,114} < 1$), and no significant interaction between group and string position ($F_{6,114} < 1$).

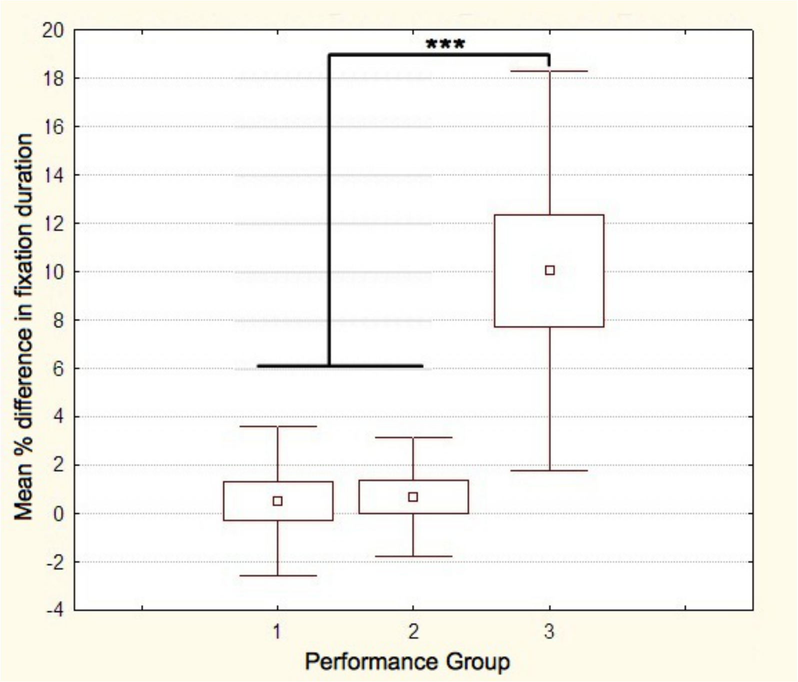

Figure 4. Mean %FD difference between the connection and gap areas, by group. Dots correspond to mean, bowes to standard error, and whiskers to standard deviation.

Mean difference between trials for each AOI

In order to see whether infants' looking strategies differed from one trial to another, we conducted a repeated measures ANOVA on mean %FD difference between connected versus non-connected string areas with trial (from 1 to 4) as a within-subjects factor. We found no differences between trials ($F_{3,114} = 1.98$, $p = .12$, $\eta^2 = .05$), and no significant interaction between groups and trials ($F_{6,114} < 1$). There was also no significant difference in the looking strategies between trials for the connection versus gap areas ($F_{3,114} = 1.25$, $p = .29$, $\eta^2 = .03$), and no significant interaction between groups and trials ($F_{6,114} = .59$, $p = .74$, $\eta^2 = .03$). Finally, there was also no significant difference in looking strategies for the ends of the connected versus non-connected strings with trials ($F(3,114) < 1$), and no significant interaction between groups and trials (($F(6,114) < 1$).

These results indicate that there was no difference in visual strategies across trials for the connected string versus the non-connected strings, connected versus non-connected string ends, and gap versus connection areas.

Discussion

The aim of the present study was to investigate the factors that influence infants' performance on the multiple-string task. The spontaneous behaviours of 16- to 20-month-old infants' in the task are discussed first, followed by the differences in visual behaviours between performance groups.

Infants' performance on the multiple-string task

The results of the “action” part of the study showed that efficient performance of the multiple-strings task does indeed develop in the late second year of life. Overall, performance improved with age. However, the ages of infants were equally distributed between the performance groups (failure, intermediate and success).

A first interesting result is the general bias toward the third position of the strings, independently of the position of the connected string, but not of the infant’s handedness. Such a position bias has already been found in similar multiple-strings tasks by Richardson (1932) with young infants aged 6.5 to 12 months, and by Köhler (1925) with adult chimpanzees. In our study, this bias progressively decreased from Group 1 to Group 3. Moreover, it increased infants' performance when the connected string was at this position, relative to the other positions. This was significant only in Group 1, however, athough infants in Group 2 showed the same tendency. This result is very similar to what has been found in some tool use studies on infants' planning abilities. Studies on the development of spoon-feeding showed that handedness influenced infants' spoon grasping, but that the ability to use the non-preferred hand when it could lead to a more efficient use of the spoon increased until 19 months of age (Claxton, McCarty & Keen, 2009; McCarty et al., 1999, 2001). Another tool study, involving the use of a rake to retrieve an out-of-reach object, showed the same kind of trade-off between hand preference and task asymmetry (Rat-Fischer, O'Regan & Fagard, 2012b). In this study, the authors found that between 16 and 22 months, infants became increasingly able to use their non-preferred hand when it made success at the task easier due to the position of the tool relative to the object. These results were interpreted in terms of infants' ability to anticipate the outcome, as a function of the movement that needed to be performed and the infants' handedness. In the present study, it seems that the infants in Group 1 were not able to inhibit their motor response with the right hand. The same tendency might explain the results of Group 2, which present patterns similar to Group 1. On the contrary, the performance of Group 3 was similar for the various positions of the connected strings. This requires inhibiting their spontaneous motor response toward the string closest to their preferred hand in order to pull the string that is connected to the toy. The present results thus suggest that the differences between infants who succeed and those who fail at the multiple-strings task are due to different levels of inhibitory control toward the preferred hand.

Besides these differences in inhibitory control, other factors might influence infants response to the multiple strings problem. A way to verify this is to compare infants' visual behaviours between the groups when someone else performs the task at some distance from the infants, so that they are not motorically involved in the task. If inhibitory control is the only factor, then infants should display similar visual patterns, independently of their own performance.

Comparision between vision and action

a. Differences in visual patterns between groups

The results from the visual task showed differences in visual patterns between groups. Overall, infants in Group 3 looked more at the connected strings than at the non-connected strings, unlike the two lower performance groups. The difference was even greater for the end of the connected string compared to the other, non-connected strings. This result was not due to a decrease in infants attention toward the scene, as infants in Group 3 looked less at the scene in proportion to the total scene duration than did infants in the other groups. This highlights the fact that infants in Group 3 correctly discriminated *which* string should be pulled in order to retrieve the object, but also that they anticipated *where* on the string by the experimenter should pull. As mentioned by von Hofsten (2013) in his review of the development of action in infancy, an actor's control of actions is closely linked to the anticipation ofthe outcome, which is "based on knowledge of the rules and regularities that govern events" (von Hofsten, 2013, p. 274). This corresponds to the "ideomotor principles", first introduced by James (1890). According to this theory, anticipating actions is essential in order to be able to plan and perform goal-directed actions. The ability to anticipate of one's own actions develops very early in infancy. Infants as young as four month old perform successful intentional grasping behaviours (von Hofsten & Rönnqvist, 1988), and progressively learn to adapt their hand opening according to object properties. Thus, our results suggest that only infants in Group 3, who visually anticipated the action, have a solid representation of the action that has to be performed to retrieve the object.

One noteworthy observation is the absence of differences in looking time at the connection compared to the spatial gap, independent of performance groups. Moreover, overall looking time in this area was very low in all groups (5.77% of the looking time at the scene). However, this quantitative result does not mean that infants did not look at the connection area at all. This area was very close to the toy (between 0 and 10 cm from the toy), which was the area of the scene that all the infants looked at the most. Also, because of the almost horizontal scene that we used, our 3-D design was probably not precise enough to precisely distinguish looking at these two areas, which were very close together. It is thus highly probable that the infants identified the connection using peripheral vision during the visual exploration of the toy area, fact that could not be recorded by the eye-tracker. However, the fact that we were not able to establish confident measurement of the infants' looking behaviour toward the connection area per se does not impair the validity of our main results, as in any case, only infants in group 3 made sense of the information about the connection. We cannot determine whether the infants in the other groups actually looked at the connection or not.

b. Is inhibition sufficient to explain the patterns in the infants' performance?

As discussed above, the results of the action task suggest that there were differences in infants' performance according to their level of inhibitory control toward their preferred hand, generally the right. However, the comparison between vision and action suggests that inhibitory control was not the only factor influencing infants' performance of the task. Indeed, in the vision task, where infants were not motorically involved (and thus where inhibitory control should not influence infants' looking behaviours), we found that the performance groups used different looking strategies. Thus, while the motor inhibitory hypothesis gives one factor that may have an impact on infants performance on the string-pulling task, it is not sufficient to explain why infants failed to solve the task on the first attempt. The absence of anticipatory looking behaviour in Groups 1 and 2 suggest that these infants did not have the necessary representations of connectedness to solve the task, or at least, that these representations are not strong enough to overcome other factors that influenced their performance on the task. In our experiment, only infants who effectively solved the task in action, also visually anticipated which string another agent who was performing the same task should pull.

This result is in line with recent findings from studies using predictive gaze to investigate infants' ability to anticipate the outcome of observed actions (e.g., Biro, 2012, Gredebäck & Kochukhova, 2010, Falck-Ytter, Gredebäck & von Hofsten, 2006). Gredebäck and Kochukova (2010), for example, found that only toddlers who were manually able to solve a puzzle task also visually anticipated the goal when observing similar actions by another agent. More generally, our results provide additional experimental evidence for the direct matching hypothesis formulated by Rizzolatti and Fadiga (2005) and first demonstrated experimentally by Flanagan and Johansson (2003). The direct matching hypothesis postulates observers understand actions on the basis of motor knowledge. In other words, our understanding of actions that we observe is based on mapping this action onto motor representations of the same action. In their experiment, Flanagan and Johansson (2003) showed that (1) when subjects observed a block-stacking task, their gaze at the actor's hand was predictive of the actor's action, and that (2) this coordination between the gaze and the hand was similar when the subjects performed the task themselves. As formulated by Biro (2012), the direct matching hypothesis specifies that infants need to be able to perform the actions themselves to anticipate the goals of similar actions by others. Although previous experimental studies with infants also support this hypothesis, our study is the first, to our knowledge, to show such an effect by comparing an action task with a 3-dimensional, live observational task. In contrast, previous studies, such as those of Biro (2012), Gredebäck and Kochukova (2010), and Falck-

Ytter, Gredebäck and von Hofsten (2006) have compared infants' performance on a given task with their predictive looking behaviour at a performance of that task by a videotaped agent.

It is important to stress the fact that the visual differences between groups wer not due to differences in the infants' visual abilities. First of all, infants of all ages were present in the three groups, making very unlikely that there were systematic differences in the maturation of the visual systems of the groups. Moreover, one-year-old infants already possess a highly advanced visual system. They are able to identify object properties very efficiently (see Atkinson & Braddick, 2013, for a review), track visual moving targets with smooth pursuit in an adult-like manner at the middle of their first year of life (von Hofsten & Rosander, 1997), even with fast-moving objects (von Hofsten, 2013). Thus, the observed differences in visual patterns between groups should not be due to differences in the maturation of the infants' visual systems.

c. Effect of repeated trials

Another interesting result, although minor in the present context, is the absence of behavioural and visual changes across trials. This means that, on the four action trials, the infants did not learn from their success (as all trials lasted until the infants had pulled the correct string and retrieved the object). Thus, infants who failed to immediately identify the connected string also failed to learn from successive trials which element would help to solve the task. In the vision task, even on seeing several demonstrations of the successful performance of task, infants did not change their attentional behaviours toward the scene.

This result might again be compared with infants' behaviours with tools in the same age-period. Infants younger than two years of age rarely solve a tool task in which the tool is spatially separated from the toy (Rat-Fischer, O'Regan & Fagard, 2012a; O'Regan, Rat-Fischer & Fagard, 2011). Even if they happen to succeed in retrieving the toy at random, infants are not able to reproduce this action to succeed at the task on the next trial (O'Regan, Rat-Fischer & Fagard, 2011). The absence of attentional change after demonstration might be explained in telation to infants' very low rate of observational learning of tool use (between 0 and 30% of observational learning between 16-20 months: Esseily, Rat-Fischer, O'Regan & Fagard, 2013; Rat-Fischer, O'Regan & Fagard, 2012a). While Esseily et al. (2013) found no observational learning of tool use in 16-mont-olds, when the demonstrator's intention was shown prior to the demonstration it helped the infants make the link between the tool and the toy. Thus, infants as young as 16 months were able to broaden their focus of attention to encompass both the tool and the toy. It seems plausible that adding such information during the demonstration of the string-pulling task could have a similar effect on infants' performance of the task.

General conclusion

This work aimed to understand what factors influenced infants' problem-solving behaviours on the multiple-strings task. Our results show that the performance of infants differs as a function of their level of inhibitory control. Moreover, these results are in line with the direct matching hypothesis (Rizzolatti & Fadiga, 2005), formulating that infants predictive behaviour on an observed actions is only present if infants are able to perform that actions themselves.

A striking aspect of study of the string task in general concerns the notion of connectedness. Infants are able to solve the string problem as early as 12 months when only one string is present, suggesting that they have acquired the notion of spatial connectedness between objects. The same concept has also been reported in studies involving composite objects, where infants can act on one part of an object to retrieve another part of this object (e.g., Fagard, Florean, et al., in prep; Rat-Fischer, O'Regan & Fagard, 2012a). However, infants do not seem to use information about connectedness between objects to solve the multiple-string task. Our results contribute to the debate on infants' knowledge of concepts and their actual use of this knowledge in action. As Schlottmann (2011) pointed out, infants' difficulties solving tasks requiring causal understanding have often been attributed to a lack of knowledge of the concepts related to the task. Schlottmann defended a different view, arguing instead that causal structure can be based on several levels of perception and underlying knowledge, and that failure to solve a task can be due to difficulties coordinating the different levels rather than lack of knowledge. On to this view, infants' failure to solve the multiple-strings task might be due to such difficulties with coordinating the different levels required for the task. Thus, even if the notion of connectedness is present earlier in infants' development, they may need time and experience to integrate this notion and use it in more complex tasks.

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References

Aguiar, A., & Baillargeon, R. (2000). Perseveration and problem-solving in infancy. *Advances in Child Development and Behavior, 27,* 135-180.

Aslin, R. N. (2012). Infant Eyes: A window on cognitive development, Infancy, 17(1), 126-140.

Atkinson, J., & Braddick, O. (2013). Visual development (Chapter 12). In Zelazo, P.D. (Ed.) *The Oxford Handbook of Developmental Psychology, Vol. 1: Body and Mind*. Oxford University Press.

Baillargeon, R. (1994). How do infants learn about the physical world? *Current Directions, 3,* 133-140.

Bates, E., Carlsonluden, V., & Bretherton, I. (1980). Perceptual Aspects of Tool Using in Infancy. *Infant behaviour & Development, 3*(2), 127-140.

Brown, A. L. (1990). Domain-Specific Principles Affect Learning and Transfer in Children. *Cognitive Science, 14(1),* 107-133.

Chen, Z., & Siegler, R. S. (2000). Across the great divide: bridging the gap between understanding of toddlers' and older children's thinking. *Monographs of the Society for Research in Child Development, 65 (2)*, i-vii, 1-96.

Claxton, L. J., McCarty, M. E., Keen, R. (2009). Self-directed action affects planning in tool-use tasks with toddlers. *Infant Behavior & Development, 32,* 230-233.

Diamond, A. (1991). Neuropsychological insights into the meaning of object concept development. In S. Carey & R. Gelman (Eds.), *The epigenesis of mind: Essays on biology and cognition* (The Jean Piaget Symposium series, pp. 67–110). Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.

Esseily, R., Rat-Fischer, L., O'Regan, J.K., & Fagard, J. (2013). Understanding the experimenter’s intention improves 16-month-olds’ observational learning in a novel tool use action. *Cognitive Development, 28(1),* 1-9.

Fagard, J., Florean, C., Rat-Fischer, L., & O'Regan, J.K. *(in prep*). When do infants understand that the parts of composite objects move together ?

Fagard, J., & Marks, A. (2000). Unimanual and bimanual and the assessment of handedness in toddlers. *Developmental Science, 3(2),* 137-147.

Franchak, Kretch, Soska, & Adolf (2011). Head-Mounted Eye Tracking: A New Method to Describe Infant Looking. *Child Development, 82,* 1738-1750.

Hespos, S.J., Baillargeon, R. (2001). Infants’ knowledge about occlusion and containment events : A surprising discrepancy. *Psychological Science, 12 (2),* p 141-147.

James, W. (1890). *The principles of psychology,* Vols. I, II. Cambridge, MA: Harvard University Press.

Köhler, W. (1925). *The mentality of apes.* London: Kegan Paul, Trench, & Trubner.

Leslie, A. M. (1988). Some implications of pretense for mechanisms underlying the child's theory of mind. In J. W. Astington, P. L. Harris, & D. R. Olson (Eds.), *Developing theories of mind* (pp. 19-46). New York: Cambridge University Press.

Leslie, A.M., & Keeble, S. (1987). Do six-month-olds perceive causality? *Cognition, 25,* 265-288.

O'Regan, J.K., Rat-Fischer, L., & Fagard, J. (2011). Mechanisms leading to tool use: A longitudinal study in human infants. In *Front. Computer Neuroscience Conference Abstract: IEEE ICDL-EPIROB 2011* http://dx.doi.org/10.3389/conf.fncom.2011.52.00014

Piaget, J. (1952). *The origins of intelligence in children* (M. Cook, Trans.). New York: Norton. (Original work published 1936).

Rat-Fischer, L., O'Regan, J. K., & Fagard, J. (2012a). The Emergence of tool use during the second year of life. *Journal of Experimental Child Psychology, 113(3),* 440-446.

Rat-Fischer L, O'Regan JK, & Fagard J. (2012b). Handedness in infants' tool use. *Developmental Psychobiology,* in press.

Richardson, H. M. (1932). The growth of adaptive behaviour in infants: An experimental study at seven age levels. *Genetic Psychology Monographs, XII*, 195-357.

Rizzolatti, G. & Fadiga, L. (2005). The mirror-neuron system and action recognition. In Freund, H.J., Jeannerod M., & Hallett M. (Eds.). *Higher-order motor disorders: from Neuroanatomy and Neurobiology to Clinical Neurology*. New York: Oxford University Press.

Schlesinger, M., Langer, J. (1999). Infants'developing expectations of possible and impossible tool-use events between ages 8 and 12 months. *Developmental Science, 2 (2),* 195-205.

Schlottmann, A. (2011). Perception versus knowledge of cause and effect in children : when seeing is believing, *Current directions in psychological science,* 111-115.

Spelke, E., Breinlinger, K. Macomber, J., Jacobson, K. (1992). Origins of Knowledge. *Psychological Review, 99 (4),* p 605-632

Spelke, E. (1985). Preferential looking methods as tools for the study of cognition in infancy, in Gottlieb, C., and Krasnegor, N. (Eds.). *Measurement of Audition and Vision in the First Year of Postnatal Life.* Ablex, Norwood, N.

Sommerville & Woodward (2005). Pulling out the intentional structure of action: the relation between action processing and action production in infancy. Cognition, 95, p. 1-30.

Uzgiris, I. C., & Hunt, J. M. V. (1975). *Assessment in infancy : ordinal scales of psychological development*. Urbana: University of Illinois Press.

van Leeuwen, L., Smitsman, A., & van Leeuwen, C. (1994). Affordances, perceptual complexity, and the development of tool use. *Journal of Experimental Psychology: Human Perception and Performance, 20(1)*, 174-191.

von Hofsten, C. (2013). Action in Infancy: A foundation for Cognitive Development. In W. Prinz, M. Beisert, & A. Herwig (Eds.), *Action science: Foundations of an emerging discipline* (pp. 255-280). Cambridge, MA: MIT Press.

von Hofsten, C., & Rönnqvist, L. (1988). Preparation for grasping an object: a developmental study. *Journal of Experimental Psycholology: Human Perception and Performance, 14,* 610-621.

von Hofsten, C., & Rosander, K. (1997) Development of smooth pursuit tracking in young infants. *Vision Research, 37,* 1799–810.

Willatts, P. (1999). Development of means-end behavior in young infants: pulling a support to retrieve a distant object, *Developmental Psychology, 35(3),* 651–667.

Willatts, P. (1984). The Stage-IV infant's solution of problems requiring the use of supports. *Infant Behavior and Development, 7,* 125-134.

Chapter 5. Observational learning

1. General introduction

The longitudinal and cross-sectional studies presented in chapter 3 show that infants learn to use tools to retrieve an out-of-reach object by observation starting at the age of 18 months. One study even reported some observational learning of a tool use action involving using a rake to retrieve an object at 15 and 18 months of age (Esseily, Nadel & Fagard, 2010; Fattori, Breveglieri, Bosco, Marzocchi, Esseily & Fagard, 2008). However, in our tool use study, the success rate was remarkably low (about 30%). This is striking, as we know that infants start to learn other means-end actions by observation by the end of the first year of life (Esseily, Nadel & Fagard, 2010; Fagard & Lockman, 2010). One of the difficulties that infants may have is perceiving the actions demonstrated as goal directed. Thus, we investigated whether adding some cues to the demonstration would help infants understand that the action with the tool is related to the goal of retrieving the object, and thereby to learn this action by observation.

1.1. Effect of additional cues during demonstration

Recent work on infants' observational learning capacities have shown that adding cues to demonstrations can help infants reproduce the target action. For example, Sage and Baldwin (2011) showed that adding some pedagogical cues prior to demonstration, such as eye contact, name referral or gaze shifting, helped infants aged 8-10 months to perform a simple tool action involving using a hook to retrieve an out-of-reach object standing within the crook of the hook (see also Csibra & Gergely, 2006, for a review of the effect of pedagogical cues in observational learning). In the same line, infants aged 24 months were more likely to imitate the exact actions required to open a box from a live model than from a videotaped TV model (Nielsen, Simcock & Jenkins, 2008). In this study, Nielsen et al. (2008) also showed that even with two models seen via video, infants were more likely to imitate the modelled action when the TV model provided socially interactive feedback to the infant (with help of a closed-circuit TV-system), than when the TV model was videotaped in advance. Another study showed that the presence of the model during the test session improves 14-month-old infants' capacity to learn a tool-use action (using a magnetic ball to retrieve an object placed inside) by imitation, as compared to a situation where the model is absent (Kiràly, 2009). Moreover, imitative learning was even better when the experimenter showed a failed attempt prior to the demonstration. This kind of information may facilitate infants' capacity to identify the goal of the model. Indeed, Carpenter, Call and Tomasello (2002) showed that two-year-old infants were more likely to learn a complex task by observation, such as opening a complex box to get an object, when the experimenter provided information about the goal prior to the demonstration.

From the results of the two last studies, one hypothesis to explain infants' difficulty learning tool use actions by observation might be that infants do not understand the goal that the models are attempting to achieve. However, to be able to understand the goal of a demonstrator's action, infants have to be able to identify the intention behind it.

1.2. Brief review: the emergence of intention attribution in infancy

The ability to identify the intention of an agent emerges early in infancy. Habituation experiments using looking time paradigms have shown that by 3-6 months of age, infants can represent the relational structure of events. For example, 5-month-old infants showed a stronger novelty preference when an agent changed goals (i.e., chose a novel toy in the test phase, compared to the familiarisation phase), than when the agent changed actions (i.e,. chose the same toy, but at the other side of the screen; e.g., Guajardo & Woodward, 2004; Biro & Leslie, 2007; see Woodward, Sommerville, Gerson, Henderson & Buresh, 2009, for a review). In action studies, infants have been shown to identify the agent's intention by 7 months of age. For example, infants systematically grasped the same goal-object as an agent when the latter acted in an intentional way (grasping an object), whereas they did not grasp this goal-object when the agent acted in an ambiguous manner toward it (statically touching it; Hamlin, Hallina, & Woodward, 2008). By 10 months of age, infants can extract and reproduce the goal of a novel tool-action (such as grasping an object with a claw) when at the same time they are given the opportunity to compare this novel action with a familiar action (grasping the object with the hand; Gerson and Woodward, 2012). By 13 months of age, infants are able to infer the agent's intentional attitude (unwilling versus unable to give a toy to the infant; Legrain, Destrebecqz & Gevers, 2012). By 14 months of age, infants are able to discriminate an intentional action from an accidental action. Carpenter, Akhtar and Tomasello (1998) presented infants aged 14 to 18 months with several test objects that produced an effect by two different means. Figure 1 shows an example of these test objects, in which a light could be switched on either by turning a spinner, or by pushing a button. The experimenter performed both types of actions, and provided verbal information about her intention to perform this action: “*There*” in case of an intentional action and “*Oops*” in case of an accidental action. The authors found that all infants imitated almost twice as many of the experimenter's intentional actions as they did of her accidental actions.

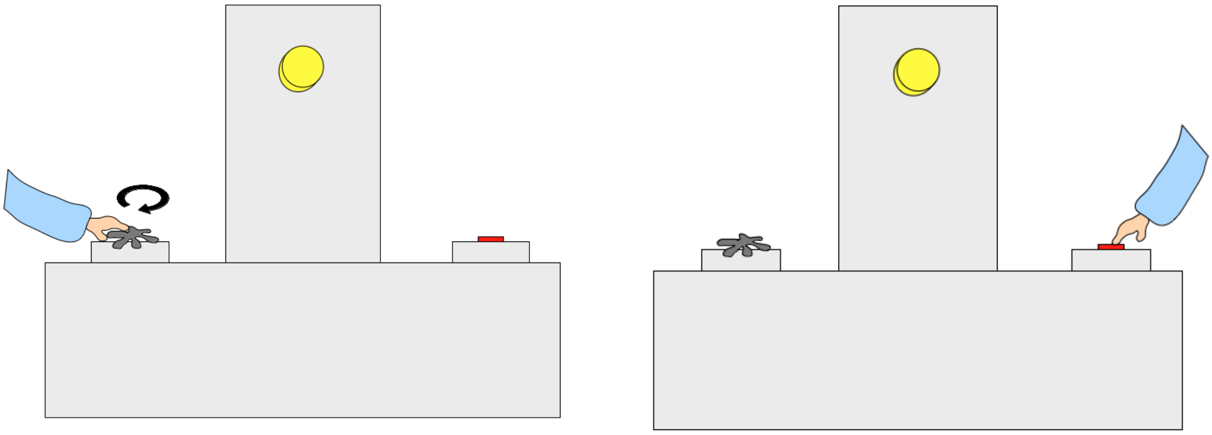

Fig 1. One of the test objects used to test infants' intentional understanding (pictures adapted from Carpenter, Akhtar & Tomasello, 1998).

Finally, by the middle of the second year of life, infants can produce an entire target action by observing an agent's failed attempt to attain a goal, thus showing understanding of the agent's goal despite failure (Meltzoff, 1995).

1.3. Aim of the present study

It is clear from this brief overview that infants are able to identify the intention of an agent quite early in the development. One possible way to explain infants' failure to learn the tool action by observation in the studies presented in chapter 3, is that in these “classical” demonstrations, the demonstrator's intention might not have been very clear. During classical demonstrations, the tool action is performed twice without any systematic information about the action or the goal being provided. Thus, in such demonstrations, infants may have encountered some difficulties understanding the demonstrators' goal in using the tool, making them less likely to learn this action by observation. In the present study, we investigate this issue by comparing several groups of 16-month-old infants presented with either (1) no demonstration, (2) classical demonstrations, (3) demonstrations preceded by an explicit demonstration of the experimenter's intention, or (4) two additional conditions to control for stimulus enhancement and motor resonance (Esseily, Rat-Fischer, O'Regan & Fagard, 2013, *Cognitive Development*).

1.4. Contributions to the study

This study was designed by all authors of the paper. All the subjects were tested at the Laboratoire Psychologie de la Perception, by R. Esseily and L. Rat-Fischer. Both experimenters also coded and interpreted the data. Statistical analyses were conducted by R. Esseily and V. Huet. The paper was written by R. Esseily, who also presented the results at two international conferences (ICIS, Minneapolis, 2012; Dagstuhl Seminar 13072, Dagstuhl, 2013).

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Understanding the experimenter's intention improves 16-month-olds' observational learning of the use of a novel tool

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ABSTRACT

Our aim was to investigate why 16-month-old infants fail to master a novel tool-use action via observational learning. We hypothesized that 16-month-olds' difficulties may be due to not understanding the goal of the observed action. To test this hypothesis, we investigated whether showing infants an explicit demonstration of the goal of the action before demonstrating the action would improve observational learning compared with a classic demonstration of the target action. We examined 16-month-old infants who observed a tool-use action consisting of grasping a rake-like tool to retrieve an out-of-reach toy, under five conditions. Only when infants were shown the goal of the action before demonstration did they show some success.

Infants' capacity to imitate simple object-directed actions as early as 6 months has been demonstrated in many studies (for reviews see Elsner, 2007; Elsner, Hauf, & Aschersleben, 2007; Poulson, Nunes, & Warren, 1989). Generally, however, the simple actions involved in these studies were actions already in the infant's motor repertoire. Few studies, however, have investigated situations in which infants acquire an action not already in their repertory via observational learning. Most such studies involve means-end actions and show that infants become very good at observational learning of novel actions in their second year of life. At 12 months, for instance, infants can learn by observation how to bimanually manipulate a rolling drum to produce music (Fagard & Lockman, 2010). At 15 months,

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infants can learn by observation how to turn a bottle upside down to retrieve a small peg inserted in it (Esseily, Nadel, & Fagard, 2010). Also at 15 months, infants can learn a complex action connecting means (e.g., pushing on a button) and end (e.g., producing music; Elsner & Aschersleben, 2003).

When the means-end action involves tool use (e.g., use of a rake to retrieve a desired object), however, infants are able to learn by observation only after about 18 months (O'Regan, Rat-Fischer, & Fagard, 2011; Rat-Fischer et al., 2012). Chen and Siegler (2000) showed that even well after 18 months, infants may still be unable to learn how to use a tool following observation. Between 18 and 35 months, some infants used the tool appropriately to retrieve a toy after observation, but others still used indirect strategies such as reaching with their hands, asking for their mother's help or simply staring at the toy without trying to reach for it.

What is special about tool use that makes it so much harder to learn by observation compared to other types of observational learning? When infants observe performance of this means-end action, they must form a representation of what connects the tool and object. The two are spatially separated, likely making the task of relating means and end difficult for an infant (Bates, Carlson-Luden, & Bretherton, 1980; Rat-Fischer et al., 2012; van Leeuwen, Smitsman, & van Leeuwen, 1994). Few studies have taken into account the problem of understanding the goal when infants observe tool use. Here we propose the hypothesis that younger infants do not understand that the model's goal is to retrieve the toy. If infants do not understand the goal, they may not be able to relate the action they have observed to that goal and thus are unable reproduce it.

This hypothesis may seem surprising, since the ability to understand goals has been shown to arise very early in infants. Evidence from violation-of-expectation studies, using looking time measures, suggests that from 6 months on, infants perceive actions in terms of the intended goal of the agent (Csibra, 2008; Kamewari, Masaharu, Takayuki, Hiroshi, & Kazuo, 2005; Southgate, Johnson, & Csibra, 2008; Woodward, 1998, 1999). For instance, in Csibra's study, infants are familiarized with a box moving by itself from A to B. Infants thus attribute to the box the goal of reaching location B. Infants then see the box move either with an obstacle present in its path or not. Infants are surprised if the box makes a detour to reach location B when no obstacle is present. The authors conclude that infants perceive actions in terms of their goals.

Imitation studies also provide evidence of infants' ability to interpret an action as goal-directed (Carpenter, Call, & Tomasello, 2005; Gergely, Bekkering, & Kiràly, 2002). Meltzoff (1995) showed that when 18-month-olds observed an experimenter who was trying unsuccessfully to separate a dumbbell-shaped object into two halves, they performed the experimenter's intended action as often as those who saw the target action successfully performed. Bellagamba and Tomasello (1999) replicated these results with 12-month-olds. Carpenter, Akhtar, & Tomasello (1998) showed that infants are able to differentiate between intended actions and accidental actions. Infants saw an experimenter perform two actions that can lead to the same goal. While performing the actions, the experimenter said either "There" to show that her action was intentional or "Oops" to show that her action was accidental. The infants reproduced twice as many intentional actions as accidental ones.

These studies show that infants below 18 months can understand that an agent performing an action intends to achieve a goal. But in some situations, when the task is complex, it is necessary for the experimenter to explicitly indicate the goal prior to the demonstration in order for the infant to benefit. Thus, Carpenter, Call, and Tomasello (2002) showed two-year-olds an experimenter performing a target action in order to open the door of a box. Before the demonstration, the experimenter either provided information about her intention to open the box, gave no information at all, or gave other irrelevant information. Infants opened the door more often if they had been informed about the experimenter's intention. Southgate, Chevallier, and Csibra (2009) showed that when information about the goal of the action is provided before demonstration, infants no longer imitate the means used by the model, but use their own means to attain the same goal, thus imitating the goal but not the action itself.

Tool use is thus a complex task because it entails a means-end action and means and the end are spatially separated. Infants must simultaneously pay attention to tool and object, and relate them to each other. In contrast in other means-end actions, the two objects involved are often spatially connected. Thus, our hypothesis appears plausible: one of the reasons infants do not learn tool use via observation before 18 months of age is that they are unable to understand the model's goal. In the present study, we examine the effect of providing intention cues to infants before demonstrating a tool-use action. We hypothesized that such intention cues will improve performance. We presented 16-month-olds a tool-use task that we knew infants could accomplish without demonstration around the end of the second year, and at 18 months with demonstration (O'Regan et al., 2011; Rat-Fischer et al., 2012). The task consisted in using a rake-like object to retrieve an out-of-reach toy. There were five groups of infants: a spontaneous group, a classic demonstration group, a prior intention group and two other groups controlling for stimulus and local enhancement. Our hypothesis was that infants would produce the target action or at least show comprehension of the connection between the tool and the toy only in the prior intention group and that infants' performance would be similar in the other four groups.

1. Method

1.1. Participants

Seventy infants (mean age = 16 months, 7 days; range = 16–16 months, 14 days; 34 females) participated. Six additional infants (three females) were excluded due to technical problems ($N = 3$) or fussiness ($N = 3$). Infants were recruited from a list of local families who expressed interest in participating in studies of infant development. Families were middle- to upper-middle class.

1.2. Materials

Materials included a toy and a tool. The toy consisted of a small yellow car 3 cm long, 2 cm high and 2 cm wide. The car could be easily rolled along the table, so that the experimenter could roll it away from her and then retrieve it with the tool. If the infants did not show interest in the car, we replaced it with another attractive toy of the same size that could easily move on the table. The tool was constructed for this experiment and consisted of a rake-like T-shaped object made of white cardboard. The handle was 20 cm long and the head 20 cm wide. The rake was visually quite plain, so as to not distract infants.

1.3. Procedure

Testing took place in the university laboratory. Infants were seated on the parent's lap in front of a table. Parents were asked to remain quiet. All sessions were videotaped. Infants were randomly assigned to one of the five groups.

Phase 1 (familiarization) was the same for all conditions. Experimenter 1 (E1) gave the car to the infant for 30 s, during which period the infant was free to manipulate it. E1 then took the car back and gave the infant the rake for 30 s of manipulation. This prior familiarization with the experimental materials was included so that the novelty of the objects would not lead infants to focus only on one or the other exclusively.

In each of the conditions, Phase 2 began with E1 giving the toy to Experimenter 2 (E2) and placing the rake near E2's hand, with the handle oriented toward E2. E2 played with the toy for a few seconds and then rolled it along the table in front of her until it was out of her reach. The *classic demonstration* condition, E2 took the rake with her right hand and used it to bring the toy closer. She then reached with her left hand for the toy, grasped it, and gave it to E1. The demonstration was repeated twice. E2 then gave the toy to E1.

In the *prior intention* condition, once the toy was out of reach E2 stretched her arm and hand out toward the toy, obviously trying to grasp it and said, "I can't get it." E2 then used the tool to retrieve the toy. The sequence was repeated twice. E2 then gave the toy to E1.

In the *hand enhancement* condition, once the toy was out of reach E2 stretched her hand toward the location (now empty) where the toy had been during the demonstration, as if reaching for something, and said, "I can't get it." E2 then grasped the toy, rolled it away from her and used the tool to retrieve it as in the other demonstration conditions. The sequence was repeated twice. E2 then gave the toy to E1. This condition was included to control for the possibility that success was due only motor matching or "motor resonance" (Paulus, Hunnius, Vissers, & Bekkering, 2011), i.e., to attention being attracted by the movement of the hand itself (twice as frequent in this condition compared with the prior intention condition).

In the *stimulus enhancement* condition, once the toy was out of reach E1 then made the car move by itself for a few seconds by manipulating a magnet under the table. E2 then performed the demonstration as in the other demonstration conditions. The sequence was repeated twice. E2 then gave the toy to E1. This condition was included to control for the possibility that success was due only to attention being attracted to the toy rather than to understanding of the experimenter's intention.

In the *spontaneous* condition, infants did not participate in phase 2.

Phase 3 (test) was the same across all conditions. E1 was seated in front of the infant on the opposite side of the table, whereas E2 was seated to the right of the infant and to the left of E1. E1 always looked at E2 during the demonstration to encourage the infant to do the same. E1 placed the toy in front and out of reach of the infant, at a distance of approximately 70 cm from the infant. E1 then placed the rake near the infant's hand. Thus, from the infant's point of view, the toy was behind the rake. E1 said "Look at the yellow car; do you want to play with it? How can you get it?" If the infant failed to retrieve the toy, the test ended 60 s after a period starting when the infant first touched the rake or stretched his or her hand out toward the toy. If, within this test period, the infant became discouraged after having tried to retrieve the toy and failed, E1 encouraged the infant once by touching the car and saying "Go ahead; how can you get that car?" If the infant threw the rake away, E1 placed the rake near the infant once more and another 60-s test period began. If the infant successfully retrieved the toy using the rake, the same toy was placed again in the same location for a new trial to insure that the success was repeated, which it was in all cases. Parents were asked to restrain their infants if they tried to crawl onto the table to get the toy.

2. Results

2.1. Coding

Videos of 25 infants (35%) were coded independently by a second observer to assess inter-observer reliability. Reliability between the two observers was found to be 100%.

Because full success was rare, a score from 0 to 4 was assigned for each action based on whether the infant did or did not manipulate one or both objects, made a connection between the toy and the rake without necessarily retrieving the toy; and ultimately retrieved the toy using the rake.

Score 0: *No try.* In actions in this category, the infant grasped the tool, discarded it, looked at the toy, looked at the tool, and/or looked at the adult, doing nothing more.

Score 1: *Interested mainly in toy or tool alone.* In actions in this category, (a) the infant pointed to the toy refusing or ignoring the tool; (b) pointed to the toy then grasped tool (either spontaneously or encouraged by the experimenter), then pointed again toward toy with other hand; (c) grasped tool, discarded it and pointed to the toy; (d) pointed to toy, then grasped tool and played with it (put into mouth or rubbed, swiped, hit on table); (e) grasped tool and played with it; (f) grasped tool, swiped table with it, and swept toy away by accident; (g) grasped tool, played with it and then rejected it, possibly interested in toy again.

Score 2: *Interested in tool in connection with toy.* In actions in this category, the infant grasped tool (spontaneously or encouraged by the experimenter) and touched or pushed toy with it; or the infant pointed to the toy, then grasped tool and touched or pushed toy with it.

Score 3: *Interested in tool for retrieval: trial and error, difficult or partial success.* In actions in this category, the infant (a) grasped tool, moved tool, tried to bring back toy, but failed; (b) grasped tool after being encouraged (after pointing first to toy or not), moved tool and retrieved toy with it; (c) grasped tool (after first pointing to toy or not), made awkward movements to bring toy to hand, and succeeded; (d) grasped tool (after pointing first to toy or not) and retrieved toy after several attempts.

Score 4: Interested in tool for retrieval: Intentional full success. Infant grasped tool directly, moved tool behind the toy to retrieve it, and succeeded.

Mean number of actions per infant was 2.9 (SD = 1.5). Recorded were the score for the first action, the score of the highest action and the mean score of all actions. Given the relatively small number of

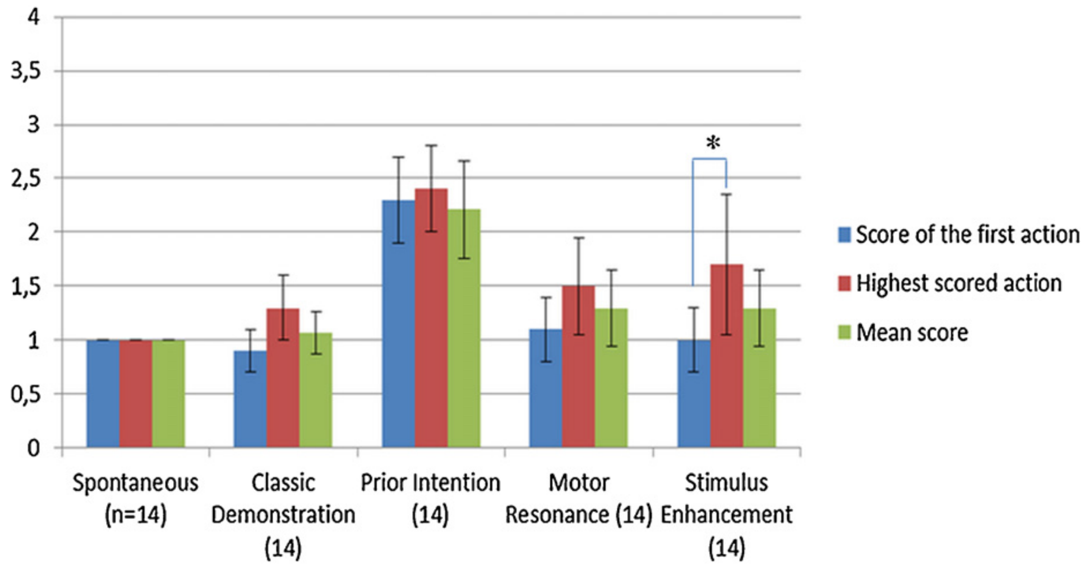

Fig. 1. The score of the first action, highest action and the mean score of all actions as a function of condition. The maximum score each infant can have is 4. $N = 14$ in each condition.

infants within each group ($N = 14$), we categorized scores into two categories and statistical analyses were conducted only on these two categories. The first category included scores 0 and 1, and the second category included scores 2, 3 and 4 (connection between the tool and the toy).

We also coded alternative strategies infants used in addition to or instead of using the tool. One was pointing. Pointing was coded each time the infant stretched his or her hand toward the toy either with an index finger or with the whole hand opened. Recorded were (1) the total number of infants who pointed at least once in each condition, and (2) mean number of pointings per infant for each condition (some infants pointed more than once). Other behaviors were coded but not included in the analyses because not frequently observed, such as asking parents for help (4 instances) or trying to climb onto the table (2 instances).

2.2. Mean and highest scores

Fig. 1 presents the score of the first action, the highest scored action and the mean score of all actions by condition. An analysis of variance (ANOVA) for first action, highest scored action and the mean score of all actions produced within the 60-s test period showed a significant effect of condition for each measure. For first action, $F(4, 63) = 12.24$; $p < .0001$, for highest scored action, $F(4, 63) = 4.9$; $p < .01$, and for mean score of all actions, $F(4, 63) = 3.3$; $p < .0001$. Post hoc LSD tests showed that for all measures, there was no difference between the spontaneous condition, the classic demonstration condition and the two control conditions (hand and stimulus). The effect was due to the difference between the prior intention group and all other groups. Cohen's d indicates that the effect is large for the first action (0.77), the highest scored action (0.75), and the mean action (0.68). Infants used the rake in connection with the toy significantly more often in the prior intention condition than in all three other conditions.

We compared the score of the first action and the mean score of all actions, and the score of the first action and the score of the highest scored action, in each condition, to learn whether infants' scores improved over the session. A t-test conducted for each condition, separately comparing the score of the first action and the mean score showed no significant difference for any conditions. A t-test conducted for each condition separately comparing the score of the first action and the score of the highest scored action shows a significant effect only in the stimulus enhancement condition, $t(13) = -2.5$; $p < .05$.

Table 1 presents the distribution of the first and highest scored actions for each of the two scoring categories for each condition. For the first action, the prior intention group is the only one in

Table 1
Distribution of the first and highest scored action for each of the two scoring categories as a function of condition (in bold, significant differences). Category 1 includes scores 0 and 1 (no connection between tool and toy); category 2 includes scores 2, 3 and 4 (at least some connection between tool and toy).

	First action		Highest action	
	Category 1	Category 2	Category 1	Category 2
Spontaneous	14	0	14	0
Classic demonstration	13	1	10	4
Prior intention	**2**	**12**	**2**	**12**
Hand enhancement	12	2	11	3
Stimulus enhancement	11	3	**7**	**7**

which there are many more infants who obtained scores in category 2 than scores in category 1 (two infants obtained score 1, seven infants obtained score 2, three infants obtained score 3 and two infants obtained score 4). In all other groups, more infants obtained scores in category 1 than in category 2. In the spontaneous condition, all infants obtained score 1, except one infant who obtained score 0; in the classic demonstration condition, two infants obtained score 0, 11 infants obtained score 1 and one infant obtained score 2; in the hand enhancement condition, one infant obtained score 0, 11 infants obtained score 1, one infant obtained score 2 and one obtained score 3; in the stimulus enhancement condition, three infants obtained score 0, eight obtained score 1 and three obtained score 2. A contrast of category distribution by condition was significant in showing a difference only for the prior intention group, χ^2 (4, $N = 70$) = 34.8, $p < .001$.

For the highest scored action, the prior intention group is again the only one in which there are many more infants who obtained scores in category 2 than in category 1 (the distribution of scores did not change from that of the first action except for one infant who improved his score from 2 to 3). In the stimulus enhancement group, infants were equally distributed between categories (two infants obtained score 0, five obtained score 1, three score 2, two score 3 and two score 4); in all other groups, infants mostly obtained scores in category 1. The distribution did not change in the spontaneous condition. In the classic demonstration condition, 10 infants kept their scores of 0 or 1 and three improved their scores from 1 to 2. In the hand enhancement condition, 12 infants kept their scores of 0 or 1 and only one improved his score from 1 to 2. The contrast of category distribution by condition showed a difference for the prior intention group, χ^2 (4, $N = 70$) = 23.8, $p < .001$ and marginally significant difference for the stimulus enhancement group, χ^2 (3, $N = 56$) = 9.01, $p = .05$. Thus, only infants in the prior intention group showed some understanding of tool use.

2.3. Pointing behavior

Table 2 presents the total number of infants who pointed in each condition as well as the mean number of pointings per infant in each condition. Fewer infants pointed in the prior intention condition, compared to all other conditions. A significant difference across conditions appears only if the prior intention condition is included, χ^2 (4, $N = 70$) = 18.1, $p < .01$. The overall effect of condition is significant, $F(4, 65) = 4.6$; $p < .01$. Mean number of pointings per infant is lowest in the prior intention group. A post hoc LSD test showed no significant differences between spontaneous condition, classic demonstration

Table 2
Total number of infants who pointed and mean number of pointing per infant as a function of condition (in bold, significant differences).

	N	Mean (SD)
Spontaneous (*N* = 14)	13	1.4 (0.1)
Classic demonstration (*N* = 14)	13	1.3 (0.1)
Prior intention (*N* = 14)	**5**	**0.4** (**0.1**)
Hand enhancement (*N* = 14)	12	1.1 (0.1)
Stimulus enhancement (*N* = 14)	11	0.9 (0.1)

condition and the two enhancement conditions (hand and stimulus). The effect was thus due to the difference between the prior intention condition and all other conditions. Cohen's *d* (0.9) indicates that the effect is large. Thus, not only did fewer infants point in the prior intention condition but those who pointed did so significantly less than infants in other conditions.

3. Discussion

We investigated whether understanding the experimenter's intention enables 16-month-olds to use observation to perform a tool use task that infants are known to succeed at spontaneously around the end of the second year of life. Infants were assigned to a spontaneous condition (no demonstration) or to one of four demonstration conditions. In all of the demonstration conditions, infants saw an adult demonstrating how to use a tool to retrieve an out-of-reach toy. What infants saw before the demonstration differed across conditions. Infants who were presented with information about the adult's intention before the demonstration made a connection between the tool and the toy significantly more frequently than did those not presented with this information. Infants did equally poorly in all demonstration conditions in which no information was provided about the adult's intentions (whether they received no information before the demonstration or saw an action that was uninformative with regard to the adult's goal), thus ruling out a possible alternative explanation of the results based on differences in attention.

Although infants in the groups gaining no information about the adult's intentions saw a full demonstration of the target action, they were as unsuccessful as infants who saw no demonstration (the spontaneous group). In addition, infants who made the connection between the tool and the toy in the prior intention group did so as their first action directly after observation: There was no significant difference between infants' first action and their behavior across the 60-s test period. Apart from a few infants in one condition (stimulus enhancement), most infants did not improve their performance over the session and the first action reflected well their overall performance.

Even when infants were provided with information about intentions before demonstration, learning was not perfect. Only two infants from the intention group successfully retrieved the toy by using the rake almost immediately (and none did so in the other conditions). Other infants in the intention group used the tool to push the toy away from them, swiped the tool laterally on the table to make the toy fall off the side of the table, or banged on the toy with the rake. It may be that infants were exploring other aspects of the connection between the tool and the rake.

Another hypothesis as to why learning was less than perfect is that infants may understand the experimenter's intention but understand less well how to use the tool. Tool use is a complex task requiring several steps: infants have to put the tool behind the toy and then simultaneously apply two forces to the tool, one vertical toward the table and the other horizontal toward themselves. When faced with this complex task, infants might simply decide to do something with the rake that is more commensurate with their motor capacities, e.g., swiping or banging.

Connections between the rake and the toy were almost exclusively observed in the prior intention condition and not in the other conditions. Thus, we can conclude that understanding prior intention enabled infants to gain at least some understanding of new tool affordances at 16 months of age. These results do not imply that this is the only case in which infants show understanding of a tool's affordances. There are a few examples in the literature showing that infants younger than 16 months can understand tool affordances but these examples mainly concern familiar tools such as the spoon (Connolly & Dalgleish, 1989; McCarty, Clifton, & Collard, 2001). However spoon use and rake use differ for at least two reasons. First they differ regarding their novelty: Infants have observed others using a spoon before using it themselves, whereas infants likely never saw a rake before. Second, spoon use can be considered as a self-directed action, whereas in this experiment the tool has first to be directed away from the self. Self-directed actions have been shown to be easier to plan and execute than other-directed actions (Claxton, McCarty, & Keen, 2009; McCarty et al., 2001). Thus, for both these reasons, infants may understand the spoon affordances much earlier than those of a novel tool such as the rake used in our study.

Our results are in accordance with another study showing that even 14-month-old infants were more likely to imitate a novel tool-use action (using a magnetic ball to retrieve a small box placed inside a bigger box), when they were shown a failed attempt prior to the demonstration of the target action, thus revealing the adult's intention (Kiraly, 2009). Indeed, existing data (Chen & Siegler, 2000; O'Regan et al., 2011; Rat-Fischer et al., 2012) as well as ongoing experiments in our laboratory show that some 18-month-olds infants learn a novel tool use via observation without an explicit demonstration of intention. Infants of this age may be able to grasp the adult's main goal while observing the adult's actions without considering each of the different steps leading to the goal. Thus, it seems that 16–18 months constitute a critical period for tool use understanding.

One explanation of what might be happening at 16 months is suggested by the theory of goal-directed imitation (GOADI) (Bekkering, Wohlschlager, & Gattis, 2000). Infants might represent each of the action steps leading to the main goal as a goal itself. Given that tool use involves multiple steps, the representation of the main goal might be difficult to extract without a hint. Showing the experimenter's intention beforehand may help infants orient their attention to the main goal of the task. We thus postulate that what is developing at 18 months is the ability to extract the main goal when observing an adult perform the action even when the means comprise multiple actions.

An alternative explanation of the difference in performance between the prior intention condition and the other conditions in our study could be that in the prior intention condition, the adult shows the infants a failed attempt by stretching her arm toward the toy and being unable to retrieve it. Thus the fact that the adult's action looked like the mistake most of the infants made in the spontaneous condition may have helped the infants learn what they should not do, rather than what they should do. This alternative explanation can also account for the lower frequency of pointing behavior in the prior intention group. Indeed, the fact that infants in the prior intention group used fewer alternative strategies such as pointing toward the toy suggests that because infants in the prior intention condition observed the experimenter reach for the toy without success, they avoided using the pointing strategy themselves and thus paid more attention to more efficient strategies such as using the rake. This possibility may also apply to other studies involving failed attempts to reveal the intention behind the use of a novel tool (Kiraly, 2009).

In conclusion, the present study is the first one to show that 16-month-olds only learn from demonstration of a complex tool-use task when the intention of the experimenter is emphasized. This finding raises the question of whether studies investigating observational learning of tool use may be underestimating infants' true capacities.

References

Bates, E., Carlson-Luden, V., & Bretherton, I. (1980). Perceptual aspects of tool using in infancy. *Infant Behavior and Development*, *3*, 127–140.

Bekkering, H., Wohlschlager, A., & Gattis, M. (2000). Imitation of gestures in children is goal-directed. *Quarterly Journal of Experimental Psychology A*, *53*(1), 153–164.

Bellagamba, F., & Tomasello, M. (1999). Re-enacting intended acts: Comparing 12- and 18-month-olds. *Infant Behavior and Development*, *22*(2), 277–282.

Carpenter, M., Akhtar, N., & Tomasello, M. (1998). Fourteen- through 18-month-old infants differentially imitate intentional and accidental actions. *Infant Behavior and Development*, *21*(2), 315–330.

Carpenter, M., Call, J., & Tomasello, M. (2002). Understanding "prior intentions" enables two-year-olds to imitatively learn a complex task. *Child Development*, *73*(5), 1431–1441.

Carpenter, M., Call, J., & Tomasello, M. (2005). Twelve- and 18-month-olds copy actions in terms of goals. *Developmental Science*, *8*(1), 13–20.

Chen, Z., & Siegler, R. S. (2000). Across the great divide: Bridging the gap between understanding of toddlers' and older children's thinking. *Monographs of the Society for Research in Child Development*, *65* (2, Serial No. 261).

Claxton, L., McCarty, M. E., & Keen, R. (2009). Self-directed action affects planning in tool-use tasks with toddlers. *Infant Behavior and Development*, *32*(2), 230–233.

Connolly, K., & Dalgleish, M. (1989). The emergence of a tool-using skill in infancy. *Developmental Psychology*, *25*(6), 894–912.

Csibra, G. (2008). Goal attribution to inanimate agents by 6.5-month-old infants. *Cognition*, *107*(2), 705–717.

Elsner, B. (2007). Infants' imitation of goal-directed actions: The role of movements and action effects. *Acta Psychologica*, *124*(1), 44–59.

Elsner, B., & Aschersleben, G. (2003). Do I get what you get? Learning about the effects of self-performed and observed actions in infancy. *Consciousness and Cognition*, *12*(4), 732–751.

Elsner, B., Hauf, P., & Aschersleben, G. (2007). Imitating step by step: A detailed analysis of 9- to 15-month-olds' reproduction of a three-step action sequence. *Infant Behavior and Development*, *30*(2), 325–335.

Esseily, R., Nadel, J., & Fagard, J. (2010). Object retrieval through observational learning in 8- to 18-month-old infants. *Infant Behavior and Development*, *33*(4), 695–699.

Fagard, J., & Lockman, J. (2010). Change in imitation for object manipulation between 10 and 12 months of age. *Developmental Psychobiology*, *52*, 90–99.

Gergely, G., Bekkering, H., & Kiràly, I. (2002). Rational imitation in preverbal infants. *Nature*, *415*(6873), 755.

Kamewari, K., Masaharu, K., Takayuki, K., Hiroshi, I., & Kazuo, H. (2005). Six-and-a-half-month-old children positively attribute goals to human action and to humanoid-robot motion. *Cognitive Development*, *20*(2), 303–320.

Kiraly, I. (2009). The effect of the model's presence and of negative evidence on infants' selective imitation. *Journal of Experimental Child Psychology*, *102*(1), 14–25.

McCarty, M. E., Clifton, R. K., & Collard, R. R. (2001). The beginnings of tool use by infants and toddlers. *Infancy*, *2*(2), 233–256.

Meltzoff, A. N. (1995). Understanding the intentions of others: Re-enactment of intended acts by 18-month-old children. *Developmental Psychology*, *31*(5), 838–850.

O'Regan, K., Rat-Fischer, L., & Fagard, J. (2011). Mechanisms leading to tool use: A longitudinal study in human infants. In *Front. Computer Neuroscience Conference Abstract: IEEE ICDL-EPIROB 2011* http://dx.doi.org/10.3389/conf.fncom.2011.52.00014

Paulus, M., Hunnius, S., Vissers, M., & Bekkering, H. (2011). Imitation in infancy: Rational or motor resonance? *Child Development*, *82*(4), 1047–1057.

Poulson, C. L., Nunes, L. R., & Warren, S. F. (1989). Imitation in infancy: A critical review. *Advances in Child Development and Behavior*, *22*, 271–298.

Rat-Fischer, L., O'Regan, K., & Fagard, J. (2012). The emergence of tool-using during the second year of life. *Journal of Experimental Child Psychology*, *113*(3), 440–446.

Southgate, V., Chevallier, C., & Csibra, G. (2009). Sensitivity to communicative relevance tells young children what to imitate. *Developmental Science*, *12*(6), 1013–1019.

Southgate, V., Johnson, M. H., & Csibra, G. (2008). Infants attribute goals even to biomechanically impossible actions. *Cognition*, *107*(3), 1059–1069.

van Leeuwen, L., Smitsman, A., & van Leeuwen, C. (1994). Affordances, perceptual complexity, and the development of tool use. *Journal of Experimental Psychology: Human Perception and Performance*, *20*(1), 174–191.

Woodward, A. L. (1998). Infants selectively encode the goal object of an actor's reach. *Cognition*, *69*(1), 1–34.

Woodward, A. L. (1999). Infants' ability to distinguish between purposeful and non-purposeful behaviors. *Infant Behavior and Development*, *22*(2), 145–160.

Chapter 6. General discussion and future directions

Despite growing interest in the development of tool use, very few studies have investigated how this ability is acquired in infancy. The aim of the work presented in this thesis was to study the cognitive, perceptual and motor bases of the acquisition of tool use in infants. To this end, we studied infants' spontaneous use of a tool during the second year of life. Our task was the use of a rake-like tool to retrieve an out-of-reach attractive object. Given the importance of social learning during the second year of life, we also explored the development of the learning of tool use by observation. Finally, we investigated the extent to which perceptual factors influence infants' performance in means-end tasks such as the tool and the multiple-string tasks.

In Chapter 1, I defined what was meant by tool use behaviours, based on the existing literature on tool use in human and non human animals. In Chapter 2, I briefly reviewed the literature on the early development of infants' manual interactions with objects, and described the experimental literature on tool use activities in infants, such as self-feeding with spoons and object retrieval with rigid straight tools (such as sticks, rakes and hooks).

In the experimental part, I presented three main studies. The aim of the first study was to investigate infants' tool use behaviours at different ages during the second year of life (Chapter 3). We designed the tool task used in this study on the basis of a precursor longitudinal study, using five conditions differing by the spatial relationship between the tool and the toy. In addition, we investigated whether infants who failed in some conditions would succeed after demonstration. We analysed infants' planning abilities on the basis of the hand they chose to grasp the rake given the respective positions of the rake and toy. On the basis of the results of this first study, we further investigated several issues that we hypothesized could have an impact on the development of tool use, such as the perceptual and social aspects of tool use learning, as described below.

The second study we conducted was driven by a noteworthy observation from the first cross-sectional and longitudinal studies, namely the facility with which young infants solved the task when the object was attached to the tool (Chapter 4). Our explanation for this finding was that infants have acquired the notion of composite object before the end of the first year of life. A preliminary experiment conducted in our lab showed that 8-month-old infants can use the notion of connectedness to indirectly act on an out-of-reach part of a composite object by directly acting on its reachable part. Starting at 8 months of age, infants looked at the out-of-reach part of a composite object before and while grasping the handle part of the object. In addition, they often looked surprised when the object did not come along with the handle. Other studies from the literature have shown that around 12 months of age, infants can retrieve an out-of-reach object by pulling on the reachable part of a string connected to the object. However, we were surprised to observe that when presented with a choice of strings, only one which is connected to the object, infants did not use the notion of connectedness to choose the correct string, but instead pulled strings at random. Because spatial configuration influences infants' performance in the tool tasks, we shought to explore this issue with the string task. Thus, in the second experimental study conducted during this thesis, we investigated why most infants did not use connectedness information to solve a multiple-string task at 16, 18 and 20 months of age.

The third study presented in this manuscript concerns infants' capacity to learn a tool use action by observation (Chapter 5). Infants are known to learn new actions by observation starting the end of the first year of life. We thus wondered why infants fail to learn to use a tool by observation before the age of 18 months and later. Chapter 5 presents a study on infants' observational learning at 16 months of age, and particularly the effect of adding information about the demonstrator's intention before the demonstration on learning.

One of the most important results from the systematic examination of infants' use of a rake-like tool to retrieve an out-of-reach toy was their difficulty using the tool when the toy was not attached to it until late in the second year of life. Young infants were actually able to use the tool in a situation where the toy was not attached to the tool, but only when the object stood in the trajectory of the rake (conditions C2 and C3, Chapter 3). However, we argue that such early successes were not based on a functional understanding of the tool, as the infants were unable to figure out what to do with the rake when the object was not placed directly in the trajectory between the rake's initial position and the infant (conditions C4 and C5). An observation that supports this view was the fact that the mean success rate in the conditions where the toy lay in the tool's trajectory did not surpass 50% before 18 months of age, meaning that even in such “apparently easier” conditions success was not systematic. More importantly, before 18 months of age, when infants failed to retrieve the toy with the tool on their first attempt, they almost never tried to replace the tool behind the toy in the same trial.

Thus, contrary to what has been claimed in the literature (e.g., Bates et al., 1980), we argue that the spatial relationship between the tool and the toy is not the essential factor influencing infants' understanding of tools. In our view, the presence of a gap is essential for gaining insight about infants' understanding of tools, because in such conditions, infants cannot succeed by chance. For this reason, the discussion that follows will focus only on conditions with a gap.

Two main questions arise from the preceding conclusions. The first question is the following: Why do infants fail to spontaneously solve the tool problem before 18 months of age (longitudinal study, Chapter 3, Appendices 2 and 3) and sometimes even later (cross-sectional study, Chapter 3)? The second question concerns the relatively late stage in development at which infants begin to benefit from demonstrations of a tool use action, compared to other means-end actions: Why are such demonstrations ineffective before 18 months of age, or even later for some infants? I try, in the following paragraphs, to provide some elements of discussion on these two questions, in light of the two additional studies we presented in Chapter 4 and 5, along with some preliminary results from recent studies by our team and some recent findings from different fields of research.

Why do infants fail to solve the tool problem before at least 18 months of age? In other words: what makes the tool problem so difficult to solve?

One important factor explored in the present work was infants' action planning abilities. Action planning is a crucial mechanism in executive control, along with other skills such as inhibitory control and goal setting (see Stoet & Snyder, 2012, for a short review of the role of executive control in tool use). Planning skills consist in the capacity to determine a series of steps necessary to reach a goal, along with the memory and dynamic error monitoring capacities. In the tool task, infants had to (1) set the goal of retrieving the toy, (2) grasp the tool, and (3) perform a movement allowing them to successfully retrieve the toy—that is, placing the rake behind the toy and bring it across the surface of the table toward themselves. In the second paper, presented in Chapter 3, we investigated infants' planning strategies in phase 2 (grasping the tool), as we observed that hand choice for grasping strongly influenced the movement that the infants performed with the tool, and thus influenced the outcome. Our results showed that, when grasping the tool, 16-month-old infants were more influenced by their hand preference than older infants, who were better at anticipating the most successful strategies and choosing the hand that would allow them to perform an easy raking movement to retrieve the toy. This result suggests that the ability to perform a tool use action such as the rake task requires advanced planning abilities which might not be mature before the second half of the second year of life. Tool use is a complex action in the sense that it is composed of several phases or segments (Claxton, Keen & McCarty, 2003). As stressed by Cox and Smitsman (2006a), such multi-step actions require planning at a more advanced level than simple actions involving only one phase (e.g., grasping an object). One example of planning a multi-step action comes from the study of Claxton, Keen and McCarty (2003), who tested the ability of 10.5-month-old infants to prepare an action (phase 1 – grasping a ball), as a function of the required precision (phase 2 – either throwing the ball or inserting it into a tube). They observed that the 10.5-month olds took more time to grasp an object in a task context requiring high precision (inserting the ball into the tube) than in a task context with low precision requirements (throwing the ball). The only studies thus far on infants' planning abilities in multi-step tasks involving the use of tools before the end of the second year of life have investigated spoon use (McCarty et al., 1999; 2001). These studies found that infants begin to manage to adjust their grip adequately before grasping the spoon at 19 months of age. Thus, even when it comes to a familiar tool action such as self-feeding with a spoon, for which infants have the opportunity both to observe others practising in everyday life and to practice themselves for some time, it seems that efficient planning develops rather late in the second year of life. In our tool use task, infants started to efficiently plan their grasping independently of their hand-preference at approximately the same age. Thus, infants' difficulties using tools might be partly caused by limitations in their capacity to plan complex tasks involving the use of tools.

As mentioned above, another important mechanism involved in executive functions is the inhibitory control of prepotent motor responses. In our study on the multiple-strings problem (Chapter 4), we showed that most 16- to 20-month-old infants who failed at the task had difficulty inhibiting their grasping response with the preferred right hand toward the nearest string. Thus, although inhibitory motor control is known to develop between 8 and 12 months of age in simple tasks, such as object retrieval and detour reaching (Diamond, 1991), it is possible that infants' inhibitory control skills are not strong enough before the end of the second year of life to allow them to inhibit prepotent behaviours in more complex tasks such as the multiple-strings task. What about inhibitory motor control in the tool task? This issue was not explicitly discussed in the papers presented in Chapter 3. However, the cross-sectional study did not provide some behavioural elements. One way to investigate infants' inhibition skills in the tool task is to look at their very first behaviour when presented with the out-of-reach toy and the tool. As mentioned above, the first behaviour that infants have to perform when using a tool to retrieve an out-of-reach object is to grasp the tool. However, the desire for the object might elicit another, spontaneous behaviour, which is a pointing gesture toward the toy. In the cross-sectional study, we quantified all pointing gestures toward the toy and, in particular, all the trials in which the pointing behaviour was the infants' first behaviour. A figure in Appendix 1 shows the percentage of trials in which pointing was the infants' first behaviour by age and spatial condition. As can be seen in the graph, the quantity of trials in which infants first pointed toward the object seems to have increased with the difficulty of the condition: the more space there was between the rake and the toy, the more infants tended to point first. What is interesting here is that this pointing pattern does not seem to vary with age. On half of the trials in condition C4 (i.e., object to the side of the rake, at about 20 cm to the left or right), infants first pointed toward the toy, independently of age. Even at 22 months of age, where infants successfully started to use the tool spontaneously, infants often grasped the tool only after first having pointed toward the toy. Thus, even at 22 months, when infants know how to use the rake, they seem to have difficulties inhibiting the first spontaneous behaviour of pointing toward the toy. This may add an argument in favour of the hypothesis that inhibitory control might not be strong enough to suppress prepotent behaviours in complex tasks such as tool use and retrieval by pulling in a multiple-string context.

To sum up, our findings highlight two executive mechanisms, planning and inhibition, whose immaturity may contribute to infants' difficulties using tools before the end of the second year of life. From this conclusion arises the question of whether executive functions are the only factors essential to the emergence of tool use, or whether other factors may also play a role. To answer this question, let us invert it: are advanced executive functions such as well-developed planning and inhibitory control skills sufficient for tool use to emerge? I will look here at two points from different research fields that do not support this hypothesis.

The first element comes from comparative studies in human and non-human animals. Vaesen (2012), in his review of the cognitive bases of human tool use, argued in favour of particular, humanique, executive functions, which other animal species lack. However, Patterson and Mann (2012) stressed in their response to Vaesen's argument, we lack comparative studies investigating analogous behaviours and, in particular, studies that are ecologically and socially adapted to the tested species. Several studies have already demonstrated that some species of birds and monkeys have highly developed planning and inhibitory control abilities (e.g., Weiss, Chapman, Wark & Rosenbaum, 2012; Taylor & Clayton, 2012). Coming back to the tasks used in the present thesis, we had the opportunity to compare infants' ability on the multiple strings task with those of two monkey species: baboons (*Papio anubis*) and macaques (*Macaca mulatta;* Rat-Fischer, Meunier, O'Regan & Fagard, unpublished data). We tested the ability to solve the multiple-strings task in 16 baboons (11 adults and 5 juveniles aged 5 to 8 months), and 15 macaques (12 adults and 3 subadults aged approximately 2 years). Baboons and macaques are both non-tool-using species (see for example Fattori et al., 2008 for a study on means-end tasks in macaques), unless they are extensively trained in tool use situations for several weeks (e.g., Macellini, Maranesi, Bonini, Simone, Rozzi, Ferrari & Fogassi, 2012; Ishibashi, Hihara, Iriki, 2000). We presented a series of trials, each containing between one and four strings, with only one string being connected to an out-of-reach piece of food. In the condition with four strings, we observed a high mean success rate in adult and subadult individuals (66.17% for the baboons; 72.67% for the adult and subadult macaques), as well as in juvenile baboons (66.3%). Interestingly, this mean percentage is higher than the 40% success that we observed at 16 months of age in a preliminary study on 14 infants (see Chapter 5, Section 2). Contrary to human infants who very often bimanually retrieved two strings at the same time, the primates' high success rate was not due to bimanual retrieval (only 1.9% of the trials with bimanual retrieval in primates). I will not delve further into the results of the non-human primate study, as they are not the focus of this discussion. However, it is worth noting that baboons (including juveniles) and macaques performed better at the multiple-strings task than did young infants. This study gives evidence that non-tool-using species are capable of solving complex problems involving planning (pulling the correct string in order to retrieve a piece of food) and inhibitory control abilities (identifying the correct string rather than pulling the strings at random). This first study suggests that executive functions are not the only factor involved in tool use abilities.

Another, more convincing argument against the hypothesis of the sufficiency of executive functions for the development of tool use comes from neuropsychology. Problem solving has long been linked to executive/frontal functions (e.g., Duncan & Owen, 2000). However, some recent work has shown that patients with frontal lobe lesions or dysexecutive syndrome are not impaired in one-step problem-solving skills, whereas they have great difficulties performing tasks requiring multi-step planning (e.g., Goldenberg, Hartmann-Schmid, Sürer, Daumüller & Hermsdörfer, 2007). Another very recent study investigated problem-solving strategies in patients with left brain damage leading to apraxia of tool use (i.e., impairment of the ability to use familiar tools) but without impairment of executive functions (Osiurak, Jarry, Lesourd, Baumard & Le Gall, 2013). These patients had no particular difficulty solving problems involving planning abilities, but had great difficulty solving tool tasks involving the choice of an unfamiliar tool to use to open a box. According to the results of this study, factors other than planning abilities in particular, and executive functions in general, are responsible for the difficulties of such left-brain-damaged patients with using tools. The authors performed a qualitative analysis of the patients' behaviours in order to draw inferences about the strategies that they used when trying to solve the tool task. Interestingly, they often observed that patients tended to express behaviours categorized as "perplexity" behaviours, which they defined as "any action that does not involve the interaction of a tool with an object such as either 'doing nothing', or handling a tool or an object in isolation" (Osiurak et al., 2013, p. 2). They opposed such "perplexed" behaviours to trial-and-error behaviours, in which the subjects combine a tool with the target object in attempts to discover the solution. Osiurak et al. explained the patients' tendency to express perplexity behaviours in terms of their inability to identify the affordances of tools and other objects, and/or their difficulties representing the actions needed to proceed with the task. This last aspect is very interesting with respect to our results on young infants, who tended to orient their behaviours either toward the toy (pointing and begging for the toy), or toward the tool (manipulating the tool in itself, discarding the tool), rather than combining the tool and the toy. In addition, even when combining the tool and the toy, infants mostly seemed to switch the goal of retrieving the toy to another goal, which was to play with the rake itself (i.e., raking/banging on the table or toward the object, etc). Thus, it is possible that the infants encountered some difficulty to identifying the affordance of the tool (e.g., the rake part of the tool can be used to bring the object into reach), and/or representing the actions needed to proceed with the task (e.g., orienting the tool toward the object, moving the rake part of the tool behind the toy, etc), and/or keeping the goal of retrieving the object in mind.

Besides the factors discussed above, related to executive functions and the identification of tool affordance and task operators, another factor could explain infants' difficulty using tools before 18 months of age: motor limitations. Did younger infants struggle due to lack of motor skills? Indeed, motor components have been identified as an important factor in the capacity to use tools successfully, along with perceptual and representational components (Greif & Needham, 2011). In our tool task, several movements had to be performed: grasping the tool, possibly placing the tool behind the toy in some conditions (C4-C5), and pulling the tool closer. Grasping the tool is obviously no longer a problem at 12 months of age, as efficient and planful grasping behaviours are in place very early in the first year of life. We know from the observations of condition C1 that 12 and 14-month-olds can perform the required pulling movements without difficulty. The movement consisting in placing the tool behind the toy, it is true that it might pose a problem for infants of these ages. However, several observations seem to contradict the notion that this element alone explains the infants' failure to use the tool. First, in the longitudinal and cross-sectional studies, we observed that when infants obviously knew that the tool could be used to retrieve the toy, it took them only a few trials to overcome the motor problem (for instance by placing the tool further out). Secondly, in two recent studies that we conducted in our lab, but which are not described in the present thesis, we observed that under some visual demonstration conditions with this task, 18 month-olds (Esseily, Rat-Fischer, O'Regan & Fagard, in prep), and even 16 month-olds (Somogiy, Ara, Rat-Fischer, O'Regan & Fagard, subm.) were able to retrieve the out-of-reach object with the rake very efficiently, without any kind of motor training, as will be described below. Finally, even if infants had difficulties performing the correct sequence of movements in order to retrieve the toy, had they understood the rake's functionality, they should at least have tried to connect the tool and the toy. However, such connections between tool and toy were rarely observed before 18 months of age. Thus, on our view, motor limitations are not sufficient to explain infants' difficulty with this tool use task. However, it is possible that a load on the infants' processing capacities created by such motor difficulties limited their cognitive processing of the task. Examples of such motor-cognitive tradeoffs in problem solving have been shown in infants (Boudreau & Bushnell, 2000).

In the three preceding paragraphs, I have discussed the contributions of planning and inhibition, as well as detection of tool affordance, the representation of actions needed to proceed with the task, and motor components, which might explain why infants below a certain age are not able to use a tool to retrieve an out-of-reach object in normal, spontaneous conditions. However, it is important to note that, in certain conditions, these limitations do not prevent infants from learning to use a tool at such an earlier age. Indeed, developmental processes are known to be embedded within a complex dynamic system due to the multicausality of such processes (Smith & Thelen, 2003). Thus, any change in the environment might lead to a sudden change in infants' capacity to use tools.

An exemple of tool use learning by infants earlier in development comes from a series of studies conducted in our team lab. They first conducted a preliminary longitudinal observation on one infant starting at 9 months of age, who was visually familiarized with the function of the tool between 9 and 12 months of age (i.e., his father often retrieved his glass with a rake-like object before grasping it at dinner, while the infant was watching him, without any comment and without the infant being given the rake-like object). This infant showed an exceptionally early capacity to use the tool to retrieve objects as compared to the other infants in the longitudinal study described in Chapter 3.1. He achieved true success in condition where the toy and the tool were separated in space at 12 months. These results were then replicated in a systematic longitudinal study on 9 infants, who were regularly visually familiarized with the tool's functionality between the ages of 14 and 16 months (Somogiy, Ara, Rat-Fischer, O'Regan & Fagard, subm.). Similarly, these infants performed better at the task of using these tools at 16 months than infants who had not been familiarized with them. The main reason for presenting these preliminary results is to point out that infants can develop tool use behaviours before the age at which they normally display such behaviours when they are familiarized with them. Thus, the rate of development of planning, inhibitory control and other components discussed previously may be affected by shifts due to external factors such as repeated observations of the target action. One reason why infants do not learn to use a tool before the end of the second year may be the lack of opportunity to watch others use it. Hence, the second part of our discussion looks at observational learning in tool use.

Why do infants fail to learn to use a tool to retrieve out-of-reach objects by observation before 18 months of age?

The second part of our discussion on infants' difficulty using tools before the end of their second year of life focuses on observational learning abilities. We have shown that observing someone demonstrating the tool action improved infants' performance in a tool use task only starting at 18 months of age. We decided to investigate why infants begin to learn from demonstrations so late by adding some cues about the demonstrator's intention. We tested whether infants would be more likely to reproduce the tool action if the demonstrator explicitly showed her intention to retrieve the toy prior to the demonstration, by stretching her arm toward the toy before using the tool. The result was an improvement in infants' overall performance at 16 months as compared to infants who saw only a classical demonstration. It is worth noting that these infants rarely reproduced the tool action perfectly. Out of the 14 infants tested, only two used the tool perfectly to retrieve the toy, while most other infants either pushed the toy away with the rake, banged on the toy with the rake, or swiped the rake on the table until the toy fell from the table. Though infants seemingly understood the *why* of the experimenter's intention in using the rake, they may not have been clear as *how* to use the rake. Possibly the infants needed some training after demonstration before they could efficiently reproduce this tool action. This was the first time that we observed most 16-month-olds making the connection between the toy and the rake at 16 months, even if they did not perfectly succeed. In another recent study on the observational learning of tool use at 18 months, we even observed some perfectly successful instances of tool use after a demonstration. In this study, we compared a group of infants who saw a classical demonstration of the tool action with a group of infants who observed the experimenter retrieving the toy with the tool and who then, rather than playing with it, grasped it and let it fall to the floor, while saying "*oops*" (incongruous demonstration group). A comparison of the classical demonstration group with the incongruous demonstration group revealed no significant differences in performance between the groups. However, we observed that some infants in the incongruous demonstration group found the situation very funny and laughed during the demonstration. A comparison of the performance of infants who laughed and infants who did not laugh within this group revealed a great difference in success rates, with approximately 30% success in the non-laughing group and 100% success in the laughing group. With the results of this study, we show that even without training, the 18-month-old infants in the laughing group were able to reproduce the tool action with a perfect motion, that is, carefully placing the rake-part of the tool behind the toy and pulling it closer in a straight-line movement (Esseily, Rat-Fischer, O'Regan & Fagard, in prep). We have several hypotheses to explain why laughing infants performed better than non-laughing infants, which will not be developed here. Control groups and further analyses will be needed to assess what behavioural differences between the two groups during and after the demonstration might explain the difference in performance (e.g., attentional differences, communicative differences toward the adults, etc). The main point we raise with this study is that even without prior training, 18-month-old infants were able to reproduce the action with perfect movements. Such skilful performances were surprising, as the successful performances we observed in the studies presented in Chapter 3, either spontaneously or after demonstration, were often very clumsy even at 22 months of age. Lack of training may thus not suffice to explain why infants around 16-18 months have difficulty faithfully reproducing this demonstrated tool action. It would be interesting to investigate whether this "laughing effect" can be observed at a younger age in the tool task and other complex tasks.

A final issue in this discussion of the learning og tool use by demonstration concerns the need for pedagogical cues. We have discussed above that when infants observe two demonstrations of the tool action with the demonstrator explicitely showing her intention improved 16-month olds' preformance. However, the study by Somogyi et al. (submitted) discussed above suggest that the observation of an action performed without pedagogy, where the demonstrators had to use the tool in a natural context without providing any pedagogical cues, also has an effect on infants' performance. This situation resembles to the first experience that infants have with the spoon, where they have many opportunities to observe people using it, before using it themselves. Thus we argue that in everyday life, repeated observations of an action performed in a natural context is important for infants to learn this action. One possibility to explain that infants learn so late in development to use tools to retrieve out-of-reach objects, is that they rarely observe others performing such actions in their everyday life.

How does tool use emerge in infancy? Developmental perspectives on the emergence of tool use

So far, we have tried to explain what factors might be responsible for infants' difficulties using tools either spontaneously or by observation before the age of 18 months. We suggested that before a certain stage in development, infants' executive functions, their motor abilities and possibly their abilities to keep the main goal in mind, to perceive the tool's affordances and/or to represent the actions needed to solve the problem are limited. When seeing a demonstration of the target action, young infants need some additional clues about the demonstrator's intention in order to successfully learn to solve the tool problem by observation. Additionally, according to the results of the longitudinal study described above on infants' visual familiarization with the tool's function, it seems that infants can learn to solve the problem without the need for exeperience manipulating rake-like objects, and without the presence of pedagogical cues during the demonstration, if this visual familiarization is provided repeatedly and during a sufficient amount of time.

In the debate on the emergence of tool use in infancy, as described in Chapter 2, Section 2.3, here is a temptation to conclude that this ability tends to emerge in an abrupt and discontinuous fashion, as the cognitive perspective suggests. However, from a dynamic systems point of view, it could be argued that this apparently abrupt change is the result of a myriad of tiny changes in parameters both within the infants themselves (e.g., increases in manipulatory skills) and in the environment (e.g., the opportunities to watch tool use). This is why any deviation from infants' normal experience may trigger an earlier emergence of tool use (for instance, repeatedly seeing an adult using a rake to grasp faraway objects).

Even though the longitudinal study exploring visual versus manual familiarization with the tool suggest that manual familiarization with the tool is not usefull to learn how to use it, we do not contend that personal manipulation of objects is not important in infant’s tool use development. In particular, infants may progressively gather knowledge from their everyday experience with objects and from observing their caregivers’ use of objects during their two first years of life, a process that is difficult to evaluate quantitatively or even qualitatively. We know from the developmental literature that object play and practice is essential for infants' discovery of the properties of objects and how they can be manipulated (e.g., Baumgartner & Oakes, 2013: Björklund, 2011). Such behaviours can later serve as substrates or precursors for later tool use behaviours (Lockman, 2000). For example, early object banging has been reported to serve as a precursor of later percussive behaviours in tool use actions such as hammering (Kahrs, Jung & Lockman, 2012). Another example of behaviours described as precursors to functional tool use is object-object combinations (Kenward et al., 2011; Hayashi & Matsuzawa, 2003; Torigoe, 1985; Vauclair & Bard, 1983). For example, a longitudinal study on object manipulation in three infant chimpanzees showed that the first tool use behaviours appeared at approximately 1 year and 9 months of age, four months after a dramatic increase in object-object combinatory behaviours (Hayashi & Matsuzawa, 2003). New Caledonian crows also show an increasing tendency to combine objects before the period when they begin to use tools to reach for food (Kenward et al., 2011).

It is worth noting that non-tool-using species also manipulate and combine objects. For instance, common ravens (*Corvus corax*), which do not routinely use tools, spend as much time in manipulating objects during their early development as New Caledonian crows (Kenward et al., 2011). However, this comparative study showed a significant difference in the persistence of combinatory behaviours, which significantly decreased and almost disappeared across development in common ravens, whereas they significantly increased in the tool-using crows. This increase in combinatory behaviours was not directly correlated with food extraction (functional tool use), as it began several weeks before the first use of twigs as a tool to reach inaccessible food. Thus, in tool-using crows, the emergence of tool use involves an inherited internal motivation to combine objects without any external reward. For non-tool-using birds, combinatory behaviours might be present first as an exploratory behaviour, and then be replaced during development by other, more functional behaviours (e.g., food caching).

Considering the importance of object-combinatory behaviours, one possible direction for continuing this work on tool use in infants would be to examine longitudinally human infants' propensity to perform such behaviours. In the same line, tool use might be hypothesized to emerge earlier in the development of infants who perform more combinatory behaviours with objects. Thus, a second possible way to investigate the importance of combinatory behaviours in the emergence of tool use would be to evaluate the role of repeated demonstrations of combinatory behaviours. We hypothesize that early familiarization to various types of combinations by another individual will increase the infants' propensity to combine objects, which should in turn lead to an earlier emergence of tool use.

In conclusion, the present work examined the question of the emergence of infants' use of a tool to retrieve out-of-reach objects. In it I described the developmental steps in tool use learning during the second year of life and proposed some basic mechanisms that are likely to influence infants' capacity to use tools, such as inhibitory, planning and observational learning mechanisms. This is pioneering work in the sense that until now the developmental trajectory of tool use learning in infants had not been clearly defined. However, there is still much work left to do in this field, in particular to better understand the mechanisms responsible for the emergence of tool use. Longitudinal studies, which are more appropriate than cross-sectional studies to gain insight on how complex behaviours such as tool use develop in infancy, are of particular importance (Keen, 2011). One challenge for developmental psychologists investigating the emergence of tool use is to work in close collaboration with developmental roboticists. Developmental roboticists have recently been seeking to design artificial systems autonomously develop tool use abilities (see for example the pioneering thesis work of Alexander Stoytchev, 2007, and the survey on the ontogeny of tool use for cognitive developmental roboticists of Frank Guerin et al., 2013). Findings on development may offer insights into how robots can learn such complex abilites with minimal inputs from the programmers. In return, developmental robotics can use artificial systems to test the hypothetical learning mechanisms extracted from experimental work with infants in order to verify their coherence.

References

Abravanel, E., Levan-Goldschmidt, E., & Stevenson, M. B. (1976). Action Imitation: The Early Phase of Infancy. *Child Development, 47,* 1032-1044.

Ambrose, S. H. (2001). Paleolithic technology and human evolution. *Science, 291,* 1748-1753.

Baldwin, J. M. (1896). A new factor in evolution. *The American Naturalist*, 30, 441 451.

Bard, K. A., Vauclair, J., (1984). The communicative context of object manipulation in ape and human adult-infant pairs. *Journal of Human Evolution 13 (2),* 181-190.

Barrett, E., Davis, E., Needham, A. (2007). Learning about tools in infancy. *Developmental Psychology, 43(2)*, 352-368.

Bates, E., Carnaioni, L., & Volterra, V. (1975). The acquisition of performatives prior to speech. *Merrill-Palmer Quarterly*, *21,* 205-224.

Bates, E., Carlsonluden, V., & Bretherton, I. (1980). Perceptual Aspects of Tool Using in Infancy. *Infant Behavior & Development, 3(2),* 127-140.

Baumgartner, H. A. and Oakes, L. M. (2013), Investigating the Relation Between Infants' Manual Activity With Objects and Their Perception of Dynamic Events. Infancy. doi: 10.1111/infa.12009

Beck, B. B. (1980). *Animal tool behavior*. NewYork: Garland.

Bentley-Condit, V., Smith, E. O. (2010) Animal tool use: Current definitions and an updated comprehensive catalog. *Behaviour, 147,* 185-221.

Biro, S., & Leslie, A. M. (2007). Infants’ perception of goal-directed actions: Development through cue-based bootstrapping. *Developmental Science, 10*(3), 379–398.

Björklund, D. F. (2011). Cognitive development: An overview. In P. Zelazo (Ed.), *Handbook of Developmental Psychology*. Oxford, UK: Oxford University Press.

Breuer, T., Ndoundou-Hockemba, M. & Fishlock, V. (2005). First observation of tool use in wild gorillas. *PLoS Biology, 3,* 2041-2043.

Brown, A. L. (1990). Domain-Specific Principles Affect Learning and Transfer in Children. *Cognitive Science, 14(1),* 107-133.

Boudreau, J. P., & Bushnell, E. W. (2000). Spilling thoughts: Configuring attentional resources in infants' goal-directed actions. *Infant Behavior & Development, 23*(3-4), 543-566.

Bushnell, E. W., & Boudreau, J. P. (1998). Exploring and exploiting objects with the hands during infancy. In K. J. Connolly (Ed.), *The psychobiology of the hand* (pp. 144-161).

London NW3 5RN, England: Mac Keith Press.

Bushnell, E. W., Sidman, J., & Brugger, A. E. (2006). Transfer according to the means in human infants: The secret to generative tool-use? In V. Roux, & B. Bril (Eds.), *Stone knapping: The necessary conditions for a uniquely hominid behaviour* (pp. 303–317). Cambridge, UK: McDonald Institute Monograph Series.

Carpenter, M., Call, J., & Tomasello, M. (2002). Understanding "prior intentions" enables two-year-olds to imitatively learn a complex task. *Child Development, 73(5),* 1431-1441.

Carpenter, M., Akhtar, N., & Tomasello, M. (1998). Fourteen- through 18-month-old infants differentially imitate intentional and accidental actions. *Infant Behavior and Development, 21*(2), 315–330.

Carpenter, M., Nagell, K., & Tomasello, M. (1998). Social cognition, joint attention, and communicative competence from 9 to 15 months of age. *Monographs of the Society for Research in Child Development, 63(4),* i-vi, 1-143.

Chen, Z., & Siegler, R. S. (2000). Across the great divide: bridging the gap between understanding of toddlers' and older children's thinking. *Monographs of the Society for Research in Child Development, 65(2)*, i-vii, 1-96.

Cheng, C.K., & Schmuckler, M.A. (2008, March). Action-perception progress in tool use development. Paper presented at the *15th Biennial International Conference on Infant Studies*, Vancouver, BC.

Chevalier-Skolnikoff, S. & Liska, J. O. (1993). Tool use by wild and captive elephants. *Animal Behaviour, 46,* 209-219.

Claxton, L. J., Keen, R., McCarty, M. E. (2003). Evidence of motor planning in infant reaching behavior. *Psychological Science, 14,* 354-56.

Claxton, L. J., McCarty, M. E., Keen, R. (2009). Self-directed action affects planning in tool-use tasks with toddlers. *Infant Behavior Development, 32*, 230-233.

Connolly, K., & Dalgleish, M. (1989). The emergence of a tool-using skill in infancy. *Developmental Psychology, 25(6),* 894-912.

Corbetta, D., & Bojczyk, K. E. (2002). Infants return to two-handed reaching when they are learning to walk. *Journal of Motor Behavior, 34(1),* 83–95.

Corbetta, D., & Thelen, E. (1996). The developmental origins of bimanual coordination: a dynamic perspective. *Journal of Experimental Psychology: Human Perception and Performance, 22(2),* 502-522.

Cox, R. F. A., & Smitsman, A. W. (2006a). Action planning in young children’s tool use. *Developmental Science*, *9,* 628–641.

Cox, R. F. A., & Smitsman, A. W. (2006b). Hand-use perseveration in young children’s use of a spoon: a dynamic model.

Cox, R. F. A., & Smitsman, A. W. (2006c). The planning of tool-to-object relations in young children’s use of a hook. *Developmental Psychobiology, 48,* 178–186.

Craig, C. M. and Lee, D. N. (1999). Neonatal control of sucking pressure: evidence for an intrinsic tau-guide. *Experimental Brain Research, 124,* 371-382.

Cisbra, G., & Gergely, G. (2006) Social learning and social cognition. The case for pedagogy. In Munakata (ed.). *Processes of Change in Brain and Cognitive Development. Attention and Performance* XXI (pp. 249-274). Oxford, UK: Oxford University Press.

Deecke, V. (2012). Tool-use in the brown bear (*Ursus arctos*). *Animal Cognition, 15 (4),* 725-730.

Duncan, J., & Owen, A. M. (2000). Common regions of the human frontal lobe recruited by diverse cognitive demands. *Trends in Neurosciences, 23*, 475–483.

Elsner, B. (2007). Infants' imitation of goal-directed actions: the role of movements and action effects. *Acta Psychologia (Amst), 124(1)*, 44-59.

Emery, N.J., & Clayton, N.S. (2009). Tool use and physical cognition in birds and mammals. *Current Opinion in Neurobiology, 19(1)*, 27-33.

Esseily, R., Nadel, J., & Fagard, J. (2010). Object retrieval through observational learning in 8- to 18-month-old infants. *Infant Behavior & Development, 33(4),* 695-699.

Esseily, R. (2010). *Observatinal learning of new manual skills in the first two years of life*. Ph.D. dissertation, Université Paris Descartes.

Esseily, R., Rat-Fischer, L., O'Regan J. K., & Fagard, J. (in prep). Laughing babies do it!

Fagard, J., Florean, C., Rat-Fischer, L., & O'Regan, J.K. (in prep). When do infants understand that the parts of composite objects move together ?

Fagard, J., & Jacquet, A. Y. (1989). Onset of Bimanual Coordination and Symmetry versus Asymmetry of Movement. *Infant Behavior and Development, 12*, 229-236.

Fagard, J., & Lockman, J. J. (2010). Change in imitation for object manipulation between 10 and 12 months of age. *Developmental Psychobiology, 52(1)*, 90-99.

Fagard, J., & Marks, A. (2000). Unimanual and bimanual and the assessment of handedness in toddlers. *Developmental Science, 3(2)*, 137-147.

Fagard, J., & Pezé, A. (1997). Age Changes in Interlimb Coupling and the Development of Bimanual Coordination. *Journal of Motor Behavior, 29(3)*, 199-208.

Fagard, J., Rat-Fischer, L., & O'Regan, J.K. (2012). Comment le bébé accède-t-il à la notion d'outil? *Enfance, 64*(1), 73-84.

Fattori, P., Breveglieri, R., Bosco, A., Marzocchi, N., Esseily, E. & Fagard, J. (2008). Observational learning of tool-use in human infants and macaques. *Academy Press* viewed on 26/02/10 @ http://www.ics.forth.gr/mathesis/Papers/paperIEEE2008.pdf

Fragaszy, D. M., Liu, Q., Wright, B. W., Allen, A., Brown, C. W., & Visalberghi, E. (2013). Wild Bearded Capuchin Monkeys (*Sapajus libidinosus*) Strategically Place Nuts in a Stable Position during Nut-Cracking. *PLoS ONE, 8(2)*, p. e56182.

Gerson, S. A. & Woodward, A. L. (2012). A claw is like my hand: Comparison supports goal analysis in infants. *Cognition, 122,* 181-192.

Gesell, A. and Ilg, F. L. (1943) *Infant and Child in the Culture Today. The Guidance of Development in Home and Nursery School*. New York: Harper and Brothers Publishers.

Gibson, E. J. (1988). Exploratory behavior in the development of perceiving, acting and the acquiring of knowledge. *Annual Review of Psychology,* 39, p 1-41.

Gibson, J. J. (1966). *The senses considered as perceptual systems*. Boston: Houghton-Mifflin.

Gibson, J. J. (1979). *The ecological approach to perception*. Hillsdale, NJ: Lawrence Erlbaum Associates

Gibson, E. J. & Pick, A. D. (2000), *An Ecological Approach to Perceptual Learning and Development*, Oxford University Press, New York.

patients and healthy participants who have difficulties in tool use

Goldenberg, G., Hartmann-Schmid, K., Sürer, F., Daumüller, M., & Hermsdörfer, J. (2007). The impact of dysexecutive syndrome on use of tools and technical devices. *Cortex, 43*, 424–435.

Goodall, J. (1986). *The chimpanzees of Gombe. Cambridge*, MA: Belknap Press, Harvard University.

Greif, M. L., & Needham, A. (2011). The development of human tool use in early life. In McCormack, T. (Ed.). *Tool use and causal cognition*, (pp. 51-68). Oxford, UK: Oxford University Press.

Grenier, A. (1981). La "motricité libérée" par fixation manuelle de la nuque au cours des premières semaines de la vie. *Archives Françaises de Pédiatrie*, *38,* 557-562.

Guajardo, J. J., & Woodward, A. L. (2004). Is agency skin-deep? Surface features influence infants' sensitivity to goal-directed action. *Infancy, 6*, 361–384.

Guerin, F., Krüger, N., & Kraft, D. (2013). A Survey of the Ontogeny of Tool Use: From Sensorimotor Experience to Planning. *IEEE T. Autonomous Mental Development, 5(1),* 18-45.

Gerson, S. A. & Woodward, A. L. (2012). A claw is like my hand: Comparison supports goal analysis in infants. *Cognition, 122*, 181-192.

Hamlin, J. K., Hallinan, E. V., & Woodward, A. L. (2008). Do as i do: &-month-old infants selectively reproduce others' goals. *Developmental Science, 11*(4), 487–494.

Hayashi, M. & Matsuzawa, T. 2003. Cognitive development in object manipulation by infant chimpanzees. *Animal Cognition, 6,* 225-233.

Hepper, P. G., Wells, D. L., & Lynch, C. (2005). Prenatal thumb sucking is related to postnatal handedness. *Neuropsychologia, 43(3),* 313-315.

Hespos, S. J., Baillargeon, R. (2001). Infants' knowledge about occlusion and containment events : A surprising discrepancy. *Psychological Science, 12 (2),* 141-147.

Hespos, S. J. & Baillargeon, R. (2006). Décalage in infants' reasoning about occlusion and containment events: Converging evidence from action tasks. *Cognition, 99,* B34-B41.

Hunt, G. R. 1996. Manufacture and use of hook-tools by New Caledonian crows. *Nature, 379,* 249-251.

Inoue-Nakamura, N. & Matsuzawa, T. 1997. Development of stone tool use by wild chimpanzees (*Pan troglodytes*). *Journal of Comparative Psychology, 111,* 159-173.

Ishibashi, H., Hihara, S. & Iriki, A. (2000). Acquisition and development of monkey tool-use: Behavioral and kinematic analyses. *Canadian Journal Physiology Pharmacology, 78*, 958–966.

Kahrs, B. A., Jung, W. P., & Lockman, J. J. (2012). What is the role of infant banging in the development of tool use. *Experimental Brain Research, 218,* 315-320.

Keen, R. (2011). The development of problem solving in young children: a critical cognitive skill. *Annual Review of Psychology, 62,* 1-21.

Kenward, B., Schloegl, C., Rutz, C. Weir, A. S., Bugnyar, T. & Kacelnik, A. (2011). On the evolutionary and ontogenetic origins of tool-oriented behavior in New Caledonian crows (*Corvus moneduloides*). *Biological Journal of the Linnean Society. 102(4),* 870-877.

Kenward, B, Rutz, C, Weir, A A S & Kacelnik, A (2006). Development of tool use in New

Caledonian crows: inherited action patterns and social influence. *Animal Behaviour 72,* 1329-1343.

Kimmerle, M., Mick, L.A., Michel, G.F (1995). Bimanual role-differentiated toy play during infancy. *Infant Behavior & Development, 18*, 299-307.

Kiràly, I. (2009). The effect of the model's presence and of negative evidence on infants' selective imitation. *Journal of Experimental Child Psychology, 102(1),* 14-25.

Köhler, W. (1925). *The mentality of apes.* London: Kegan Paul, Trench, & Trubner.

Lefebvre, L., Nicolakakis, N., & Boire, D. (2002). Tools and brains in birds. *Behaviour, 139,* 939-973.

Legrain, L., Destrebecqz, A., & Gevers, W. (2012). The role of goal-directed behavior in attention attribution in children. *Journal of Experimental Child Psychology, 112*, 351-359.

Lockman, J. J. (2000). A perception-action perspective on tool use development. *Child Development, 71(1),* 137-144.

McCormack, T., Hoerl, C., & Butterfill, S. A. (2011). *Tool use and causal cognition*. Oxford: Oxford University Press.

Mann, J., Sargeant, B.L., Watson-Capps, J.J., Gibson, Q.A., Heithaus, M.R., Connor, R.C., and Patterson, E. (2008). Why do dolphins carry sponges? *PLoS ONE, 3*, e3868.

Fruth, B., & Hohmann, G. (1996). Nest building behavior in the great apes: the great leap forward? In McGrew, W.C., Marchant, L.F., & Nishida, T. (Eds.) *Great Ape Societies*, (pp. 225-240). Cambridge, UK: Cambridge University Press.

Macellini S., Maranesi M., Bonini L., Simone L., Rozzi S., Ferrari P.F., Fogassi L. (2012). Individual and social learning processes involved in the acquisition and generalization of tool-use in macaques. *Philosophical Transactions of the Royal Society, B. 367*, 24-36.

Matheson, E. (1931). A study of problem solving in preschool children. *Child Development, 2*, 242-262.

McCarty, M. E., Clifton, R. K., & Collard, R. R. (1999). Problem solving in infancy: the emergence of an action plan. *Developmental Psychology, 35(4),* 1091-1101.

McCarty, M. E., Clifton, R. K., & Collard, R. R. (2001). The beginnings of tool use by infants and toddlers. *Infancy, 2,* 233-256.

McGrew, W. (1992). *Chimpanzees material culture: Implications for human evolution*. Cambridge University press, Cambridge.

McGrew, W.C., Marchant, L.F. & Nishida, T. (1996). *Great Ape Societies*, Cambridge University Press (328 pp), Cambridge.

Meltzoff, A. N. (1988). Infant imitation and memory: nine-month-olds in immediate and deferred tests. *Child Development, 59,* 217–225.

Meltzoff, A. N. (1995). Understanding the intentions of others: Re-enactments of intended acts by 18-month-old children. *Developmental Psychology, 31*, 838–850.

Moro, E., & Freundenberg, E. (1921). Der Morosche Umklammerungs-reflex und das Brudzins-kische Nachkenzeichen als Reflexe des Seuglingsalters. *Münchener Medizinische Wochen-schrift, 68.*

Nabeshima, C., Kuniyoshi, Y., & Lungarella, M. (2006). Adaptive body schema for robotic tool-use. *Advanced Robotics, 20(10)*, 1105-1126.

Nagell, K., Olguin, R. S., and Tomasello, M. (1993). Processes of social learning in the tool use of chimpanzees (*Pan troglodytes*) and human children (*Homo sapiens*). *Journal of Comparative Psychology, 107*(2), 174-186.

Nielsen, M., Simcock, G., & Jenkins, L. (2008). The effect of social engagement on 24-month-olds' imitation from live and televised models. *Developmental Science, 11(5),* 722-731.

Osiurak, F., Jarry, C., Lesourd, M., Baumard J., & Le Gall, D. (2013). Mechanical problem-solving strategies in left-brain damaged patients and apraxia of tool use. *Neuropsychologia,* http://dx.doi.org/10.1016/j.neuropsychologia.2013.06.017.

Patterson, E. M. & Mann, J. Look, no hands! Open peer commentary to Vaesen, K. The cognitive bases of human tool use. *Behavioral and brain sciences, 35*, 203–262.

Piaget, J. (1952). *The origins of intelligence in children* (M. Cook, Trans.). New York: Norton. (Original work published 1936).

Rat-Fischer, L., O'Regan, J. K., & Fagard, J. (2012a). The Emergence of tool use during the second year of life. *Journal of Experimental Child Psychology, 113(3),* 440-446.

Rat-Fischer L, O'Regan JK, & Fagard J. (2012b). Handedness in infants' tool use. *Developmental Psychobiology*, in press.

Rat-Fischer, L., O'Regan, J. K., & Fagard, J. Visual attention in a means-end task: the case of multiple strings (*submitted*).

Richardson, H. M. (1932). The growth of adaptive behavior in infants: An experimental study at seven age levels. *Genetic Psychology Monographs*, XII, 195-357.

Sage, K. D., & Baldwin, D. A. (2011). Disentangling the social and the pedagogical in infants' learning about tool-use. *Social Development, 20*, 825-844.

Schlesinger, M., & Langer, J. (1999). Infants'developing expectations of possible and impossible tool-use events between ages 8 and 12 months. *Developmental Science*, *2(2)*, 195-205.

Schmuckler, M. A. (2011). Perceptual-motor relations in obvious and non-obvious domains: A history and review. In P. Zelazo (Ed.), *Handbook of Developmental Psychology*. Oxford, UK: Oxford University Press.

Seed, A. M., & Byrne, R. W. (2010). Animal tool use. *Current Biology, 20,* 1032-1039.

Smith, L.B., Thelen, E. (2003). Development as a dynamic system. *Trends in Cognitive Sciences, 7*, 343–348.

Smitsman, A. W., & Cox, R. F. A. (2008). Perseveration in tool use: A window for understanding the dynamics of the action-selection process. *Infancy, 13(3)*, 249-269.

Smitsman, A. W., & Corbetta, D. (2010). Action in infancy: Perspectives, concepts, and challenges. In G. Bremner & T. Wachs (Eds.), *Blackwell Handbook of Infant development (2nd edition)*. Blackwell.

Sommerville & Woodward (2005). Pulling out the intentional structure of action: the relation between action processing and action production in infancy. *Cognition*, *95*, p. 1-30.

Somogyi, E., Ara, C., Rat-Fischer, L., O'Regan, J. K., & Fagard, J. (subm.). Infants benefit more from Function familiarization than object familiarization when learning to use a tool. A longitudinal study.

Spelke, E., Breinlinger, K. Macomber, J., Jacobson, K. (1992). Origins of Knowledge. *Psychological Review, 99 (4)*, p 605-632

Spelke, E., & Van de Walle, G. (1993). Perceiving and reasonning about objects: insights from infants. In N. Eilan, W. Brewer & R. McCarthy (Eds.), *Spatial representation* (pp. 132-161). Oxford: Blackwell.

Spencer, J. P., Vereijken, B., Diedrich, F. J., & Thelen, E. (2000). Posture and the emergence of manual skills. *Developmental Science, 3(2)*, 216-233.

St. Amant, R. & Horton, T. (2008). Revisiting the definition of animal tool use. *Animal Behaviour, 75*, 1199-1208.

Stoet, G. & Snyder, L. H. The role of executive control in tool use. Open peer commentary to Vaesen, K. The cognitive bases of human tool use. *Behavioral and brain sciences, 35*, 203–262.

Stoytchev, A. (2007). *Robot tool behavior: A developmental approach to autonomous tool* *use.* Ph.D. dissertation, College of Computing, Georgia Institute of Technology.

Tomasello, M. & Call, J. (1997). *Primate Cognition*. New York: Oxford University Press.

Tomasello, M. (1999). *The Cultural Origins of Human Cognition*. Harvard University Press.

Torigoe, T. (1985). Comparison of object manipulation among 74 species of non-human primates. *Primates, 26*, 182–194.

Uzgiris, I. C., & Hunt, J. M. V. (1975). *Assessment in infancy : ordinal scales of psychological development*. Urbana: University of Illinois Press.

Vaesen, K. (2012). The cognitive bases of human tool use. *Behavioral and Brain Sciences*, *35(4)*, 203-218.

van Leeuwen, L., Smitsman, A., & van Leeuwen, C. (1994). Affordances, perceptual complexity, and the development of tool use. *Journal of Experimental Psychology: Human Perception and Performance, 20(1)*, 174-191.

van Roon, D., Van Der Kamp, J., Steenbergen, B. (2003). Constraints in children's learning to use spoons. In: Savelsbergh, G., Davids, K., van der Kamp, J., Bennett, S. (Eds.). *Development of Movement Coordination in Children: Applications in the Field of Ergonomics, Health Sciences and Sport*, (pp. 75–93). London, UK: Routledge.

Vauclair, J. & Bard, K. A. (1983). Development of manipulations with objects in ape and human infants. *Journal of Human Evolution, 12*, 631-645.

Vauclair, J. (1993). Tool use, hand cooperation and the development of object manipulation in human and non-human primates. In A. Kalverboer, B. Hopkins & R.H. Geuze (Eds.), *Motor development in early and later childhood: Longitudinal approaches* (pp. 205-216). Cambridge : Cambridge University Press.

Visalberghi, E., & Limongelli, L. (1994). Lack of Comprehension of cause-effect relations in tool-using capuchin monkeys (*Cebus apella*). *Journal of Comparative Psychology, 108*,15–22.

von Hofsten, C. (2013). Action in Infancy: A foundation for Cognitive Development. In W. Prinz, M. Beisert, & A. Herwig (Eds.), *Action science: Foundations of an emerging discipline* (pp. 255-280). Cambridge, MA: MIT Press.

von Hofsten, C., Rönnqvist, L. (1988). Preparation for grasping an object: a developmental study. *Journal of Experimental Psycholology: Human Perception and Performance*, *14*, 610-621.

von Hofsten, C. (2007). Action in development. *Developmental Science, 10 (1)*, 54-60.

von Hofsten, C. (2004). An action perspective on motor development. *Trends in Cognitive*

Science, 8, 266–272.

von Hofsten, C. (1984). Developmental changes in the organization of pre-reaching movements. *Developmental Psychology, 20*, 378–388.

Willatts, P. (1999). Pulling a support to retrieve a distant object. *Developmental Psychology*, *35(3)*, 651-667.

Willats, P. (1984). The Stage-IV infant's solution of problems requiring the use of supports. *Infant Behavior and Development, 7,* 125-134.

Wolff, P. H., (1968). The serial organization of sucking in the young infant. *Pediatrics*, *42(6)*, 943-956.

Woodward, A. L., Sommerville, J.A., Gerson, S., Henderson, A. M. E., & Buresh, J. S. (2009). The emergence of intention attribution in infancy. In B. Ross (Ed.) *The Psychology of Learning and Motivation*, 51, 187-222. Academic Press.

Zoia, S., Blason, L., D'Ottavio, G., Bulgheroni, M., Pezzetta, E., Scabar, A. & Castiello, U. (2007). Evidence of early development of action planning in the human foetus: a kinematic study. *Experimental Brain Research, 176(2)*, 217-226.

Appendices

Appendix 1 – Pointing gestures in the tool task

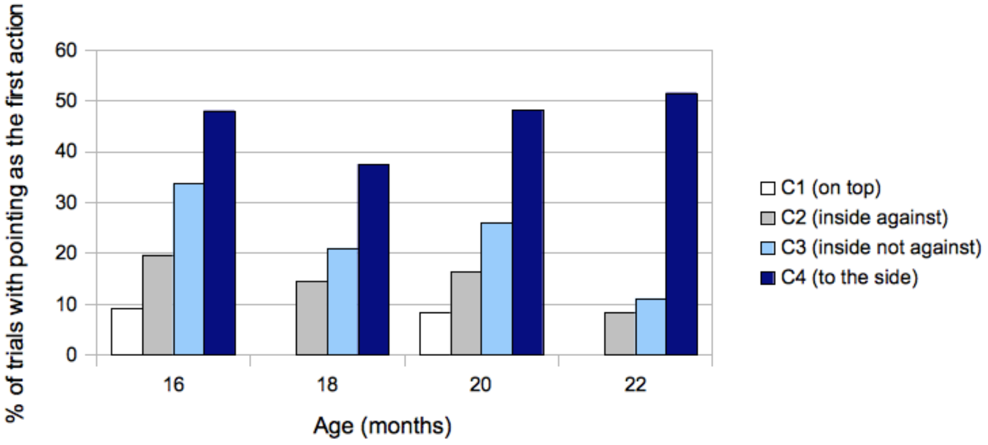

Fig A1. Proportion (%) of trials in which the pointing gesture toward the toy was the first action of the trial, as a function of condition and age (data from the study in paper 1 « The Emergence of Tool Use During the Second Year of Life », Rat-Fischer, O'Regan & Fagard, 2012).

Appendix 2 – Comment le bébé accède-t-il à la notion d'outil ?

(Enfance, 2012)

Comment le bébé accède-t-il à la notion d'outil ?

Jacqueline FAGARD[1], Lauriane RAT-FISCHER[1]
et Kevin O'REGAN[1]

RÉSUMÉ

L'utilisation d'un outil permet de dépasser les limites de son propre corps pour interagir avec l'environnement. Après avoir appris à contrôler sa main pour prendre des objets, le bébé découvre peu à peu qu'un objet peut permettre d'agir sur un autre objet. Dans cet article nous nous intéressons à la fonction particulière de l'outil qui permet de rapprocher un objet présenté hors de portée. Nous passons d'abord en revue les comportements précurseurs de cette habileté, comme l'utilisation de moyens intermédiaires pour atteindre un but secondaire (*means-end*), ainsi que les premières études consacrées à l'utilisation d'outil pour rapprocher un objet. Dans un deuxième temps nous posons la question des mécanismes sous-jacents à la découverte de cette utilisation de l'outil à partir des résultats d'une étude où nous avons suivi quatre bébés pendant près d'un an à partir de 12 mois en leur présentant un jouet hors de portée et un râteau à portée de main. Nos résultats montrent que les bébés mettent plusieurs séances avant de comprendre l'utilité du râteau, séances pendant lesquelles soit ils explorent le râteau, soit ils quémandent le jouet, soit ils associent le râteau et le jouet mais pas pour essayer de rapprocher le jouet. Ce n'est que vers 18 mois, relativement soudainement, que les bébés ont semblé comprendre que le râteau pouvait leur permettre de rapprocher le jouet. Au vu des résultats, nous concluons que les mécanismes « essai-erreur » et apprentissage par observation nécessitent un certain niveau d'intuition de la solution pour être efficaces, mais que l'intuition elle-même nécessite une longue phase d'exploration qui permet dans un premier temps à la fois d'améliorer la manipulation du râteau (qui devient un prolongement de la main ?) et d'en découvrir les affordances.

MOTS CLÉS : UTILISATION DE L'OUTIL, COMPORTEMENT « MOYEN-BUT », DÉVELOPPEMENT PRÉCOCE, MÉCANISMES

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ABSTRACT

How do infants acquire the concept of tool?

Tools allow one to overcome the limits of one's body in interacting with the environment. After learning to control their hands to grasp objects, babies gradually discover that one object can be used to act on other objects. In this article we shall discuss specifically the use of those tools that allow far-off objects to be brought into range. We shall first describe studies of behaviours that are precursors to this skill, in particular means-end behaviours that require invoking an intermediate means to attain a final end. We shall then describe the existing studies of the use of a tool to bring an object closer. In the second part of the article we ask what the mechanisms are that might underlie the discovery of this kind of tool use. We shall appeal to results of a study in which we followed four infants starting at age 12 months for about a year, and in which they had to attain an out-of-reach toy with a rake. Our results show that the infants needed several months before understanding the use of the rake. During this period they explored the rake, begged for the toy, played with toy and rake together but without trying to bring the toy closer. Only around age 18 months did the infants, somewhat suddenly, come to understand that the rake could be used to attain the toy. We conclude that in order to be helpful, trial and error, as well as observational learning, require the child to have a degree of intuition concerning the solution. This intuition itself requires a long period of exploration which may contribute both to improving the child's ability to manipulate the rake (perhaps becoming an extension of the hand) and to improving the child's knowledge of the rake's affordances.

KEY-WORDS: TOOL USE, MEANS-END BEHAVIOURS, EARLY DEVELOPMENT, MECHANISMS

INTRODUCTION

Utiliser un outil pour agir sur un objet permet de dépasser les limites de son corps (longueur, force ou mode de fonctionnement des organes préhensiles, par exemple) pour interagir plus efficacement avec son environnement. Malgré quelques études pionnières comme celle de Piaget (1936), ce n'est que très récemment qu'on s'intéresse à l'émergence de l'utilisation de l'outil au cours des premières années de la vie. Ceci est d'autant plus étonnant que l'utilisation de l'outil a longtemps été considérée comme un marqueur fondamental de l'évolution en général (van Schaik, Deaner, & Merrill, 1999) et de l'intelligence humaine en particulier (Wynn, 1985). Notons qu'après avoir longtemps cru qu'il s'agissait d'une habileté propre à l'homme, on sait maintenant que de nombreuses espèces animales utilisent des outils et parfois les façonnent, primates non humains mais aussi oiseaux, éléphants, poissons, etc. (voir Seed & Byrne, 2010). Dans cet article nous ferons une revue des études existantes sur l'utilisation de l'outil chez le bébé humain, incluant les nôtres, afin de donner quelques jalons sur l'émergence de cette capacité au cours des deux premières années de vie, puis nous tenterons d'extraire quelques principes permettant d'évaluer les mécanismes sous-jacents à ce développement.

QU'ENTEND-ON PAR OUTIL ?

Si on définit l'utilisation de l'outil comme la capacité d'utiliser un objet pour agir sur un autre objet, faut-il que les deux objets soient spatialement déconnectés pour que l'un soit considéré comme un « outil » servant à modifier l'autre ? On pourrait ainsi considérer que l'utilisation d'un outil spatialement indépendant de l'objet sur lequel il agit n'est que l'extrême d'un continuum qui commencerait dès que le bébé attrape un objet par un bout quand c'est l'autre bout qui l'intéresse, le hochet par exemple. L'utilisation d'un objet pour explorer l'environnement pourrait également être considérée comme un précurseur de l'utilisation d'outil (Lockman, 2000 ; voir aussi Kahrs & Lockman, ce numéro thématique d'*Enfance*). Parmi d'autres comportements qui pourraient impliquer une notion d'outil, on pourrait énumérer : se servir d'un objet pour rapprocher un deuxième objet posé dessus, tirer une ficelle au bout de laquelle est attaché un objet, appuyer sur un endroit précis d'un objet pour obtenir un effet se produisant à l'autre bout de l'objet ou ailleurs. Si ces comportements, plus généralement appelés « moyen-but », ont été amplement étudiés chez le bébé, comme nous le verrons, ils ne sont pas considérés comme de vraies conduites d'utilisation d'outil. Dans cet article nous nous centrerons principalement sur l'émergence de l'utilisation de l'outil au sens restreint d'un objet indépendant servant à agir sur un autre objet, et plus particulièrement servant à mettre à portée de main un objet hors de portée. Nous commencerons néanmoins par un bref rappel des conduites « moyen-but » servant à rapprocher un objet.

PREMIÈRES CONDUITES « MOYEN-BUT » POUR RAPPROCHER UN OBJET HORS DE PORTÉE

On définit comme « moyen-but » un comportement qui implique l'exécution délibérée et planifiée d'une séquence d'actions pour arriver à un but dans une situation où un obstacle empêche la réalisation du but (Willatts, 1999). Pour y arriver, le bébé doit mettre de côté un but inatteignable immédiatement et exécuter une action intermédiaire. Par exemple, lorsqu'un bébé a très envie d'un objet sur un support, avant d'avoir accès aux comportements « moyen-but », il tend la main vers l'objet pour l'obtenir. Le stade « moyen-but » consiste à regarder la scène, à percevoir que l'objet est posé sur un support, à tirer le support pour s'emparer de l'objet dès qu'il est suffisamment rapproché. Les conduites « moyen-but » représentent le cinquième stade piagétien, et dans la terminologie piagétienne, à ce stade l'enfant ne se contente plus d'appliquer des schèmes d'action primaires comme prendre, secouer, frotter mais il devient capable d'inventer des schèmes nouveaux pour répondre à son projet. Comme pour les stades précédents, le nouveau schème peut être découvert par hasard, lors de l'expérimentation active de l'enfant avec l'objet : pour reprendre notre exemple, à un stade intermédiaire le bébé va renoncer à prendre l'objet hors de portée, prendre le support qui est le seul objet disponible, tirer dessus souvent pour le mettre à la bouche et s'apercevoir que cela fait venir l'objet. Piaget donne ainsi de nombreux exemples de tels comportements chez ses enfants, vers la fin de la première année (9-12 mois) (Piaget, 1936).

Les conduites « moyen-but » ont été étudiées systématiquement sur un plus grand nombre de bébés par plusieurs auteurs (Bates, Thal, Fenson, Whitesell, & Oakes, 1989 ; Willatts, 1999). Willatts a ainsi comparé le comportement de 16 bébés vus longitudinalement à 6, 7 et 8 mois. Le jouet était posé, hors de portée, sur un tissu placé à portée de main. En analysant les séquences temporelles entre le regard et l'action, l'auteur a codé le comportement selon l'intention de prendre l'objet : sans intention, avec une intention « partielle » (stade « transitionnel » selon Piaget), ou avec une intention claire. Les auteurs codaient la conduite comme intentionnelle si les bébés tiraient le tissu et prenaient le jouet directement sans autres conduites exploratoires. Les résultats montrent qu'à 6 mois le comportement est transitionnel tandis qu'à 7 mois les bébés semblent résoudre le problème de façon clairement intentionnelle. Un autre comportement « moyen-but » noté par Piaget et fréquemment étudié depuis est celui de la ficelle. Dans ce cas, l'objet intéressant et hors de portée est attaché au bout d'une ficelle. L'étude de la conduite de la ficelle remonte à des travaux très anciens, les premières études de Gesell (1928) ayant sans doute elles-mêmes été inspirées de travaux anciens sur les singes et autres animaux (Thorndike, 1898 ; Köhler, 1927) mais aussi sur les bébés humains (voir Richardson, 1932, pour une revue de ces travaux anciens). L'étude de Richardson ainsi que quelques études plus récentes (Bates, Carlsonluden, & Bretherton, 1980 ; Chen, Sanchez, & Campbell, 1997) avaient pour but de tester le degré réel de compréhension de la notion de connectivité en comparant les configurations perceptuelles pour lesquelles l'enfant réussissait à prendre la bonne ficelle. Le consensus actuel est que ce type de tâche est réussi vers la fin de la première année.

Un autre exemple de conduite « moyen-but » est donné par l'étude de Koslowski et Bruner (1972) dans laquelle les auteurs ont mis devant des bébés de 12 à 24 mois un levier sur lequel est accroché un jouet. Pour attraper le jouet les enfants doivent pousser le levier. Les auteurs considèrent ce levier comme un outil primitif. Les résultats montrent que le problème est résolu avec des stratégies de plus en plus efficaces avec l'âge. Les bébés apprennent à maîtriser individuellement les différentes composantes de l'action en les exerçant pour elles-mêmes de façon variée (tirer-pousser-lever le levier, par exemple). Lorsqu'une composante est maîtrisée et « modularisée », c'est-à-dire intégrée dans une séquence d'actions, le bébé peut alors être attentif à l'effet de son geste sur l'objet à rapprocher et réussir la tâche, ce qu'il fait entre 16 et 24 mois.

Dans l'échelle de développement d'Uzgiris et Hunt (1975), les conduites du support et de la ficelle sont considérées comme représentatives de l'âge de 10 mois. Par contre l'utilisation de l'outil correspond à un item typiquement réussi à partir de 18 mois. Pourquoi un tel décalage ?

UTILISATION DE L'OUTIL AU COURS DES DEUX PREMIÈRES ANNÉES

Les premiers outils du bébé dirigés vers lui

Le premier outil au sens restreint dont le bébé apprend à se servir systématiquement est la cuillère. L'utilisation de la cuillère a fait l'objet d'une étude longitudinale portant sur deux groupes de bébés de 11 et 17 mois vus tous les mois pendant une période de six mois (Connolly & Dalgleish, 1989). Les auteurs ont cherché à observer les progrès dans l'utilisation de la cuillère en ce qui concerne la main utilisée, le type de prise, la trajectoire jusqu'à la bouche. Leurs résultats montrent un changement dans les stratégies qui deviennent de plus en plus efficaces avec l'âge. L'utilisation de la cuillère a fait l'objet d'une autre étude, celle de McCarty, Clifton, & Collard (1999). Dans cette étude les auteurs ont donné à des bébés de 9, 14 et 19 mois une cuillère remplie de nourriture et présentée de telle sorte que soit le manche soit le bol de la cuillère contenant de la compote était du côté de la main préférée du bébé. Les résultats montrent qu'à 9 mois les bébés prennent avec leur main préférée le bol de la cuillère à pleine main, que ceux de 19 mois prennent le manche de la cuillère directement avec leur main non préférée, et que le groupe intermédiaire utilise des stratégies compliquées pour corriger leur prise initiale du manche de la cuillère avec la main préférée. Ces deux études mettent en évidence l'amélioration avec l'âge de la planification motrice de l'utilisation de l'outil, et sont une investigation de l'aspect moteur, plus que de l'aspect conceptuel de l'utilisation d'outil.

Une hypothèse intéressante concernant la précocité de la capacité d'utiliser une cuillère ou une brosse à dent (outre la familiarité de ces outils) a été proposée par McCarty, Clifton, & Collard (2001 ; voir aussi Claxton, McCarty, & Keen, 2009). Ces auteurs suggèrent qu'il est plus facile de contrôler une action vers soi (comme utiliser une cuillère pour mettre la nourriture dans la bouche) qu'une action vers l'extérieur.

L'utilisation d'outil pour rapprocher un objet placé hors de portée

La conduite du bâton, qui consiste à rapprocher un objet situé hors de portée à l'aide d'un bâton à portée de main, fut décrite en premier par Piaget (1936) sur son fils Laurent vers la fin de la première année. Les premières études systématiques de ce type se sont focalisées sur le rôle des facteurs perceptifs, plus précisément de la relation spatiale entre deux objets, pour comprendre qu'un objet peut servir à rapprocher l'autre (van Leeuwen, Smitsman, & van Leeuwen, 1994 ; Brown 1990 ; Bates, Carlsonluden, & Bretherton, 1980). Dans l'étude de Bates *et al.* (1980), on a présenté à 40 bébés de 10 mois un jouet hors de portée placé à côté de différents outils (mini-cerceau, crochet ou bâton). Le jouet était posé à différentes positions par rapport au cerceau (dedans contre ou au milieu) et au crochet (à l'intérieur de sa partie courbe ou à côté) et il était placé à côté du bâton. Dans deux conditions supplémentaires le jouet était posé sur un tissu ou attaché au bout d'une ficelle fine ou épaisse. Les résultats montrent que le pourcentage de réussite est le plus élevé lorsque l'objet et l'« outil » sont connectés de façon indissociable (tissu et ficelles), un peu moins élevé lorsqu'ils sont connectés de façon dissociable (jouet contre l'outil), et très rarement réussi en l'absence de connexion (jouet à côté de l'outil).

Dans leur étude de 1994, van Leeuwen *et al.* ont utilisé un crochet à portée de main et une balle hors de portée située à différents endroits par rapport au crochet et ils ont testé 57 enfants entre huit mois et 3 ans 8 mois. Ils concluent de leurs résultats que ce n'est pas seulement la discontinuité spatiale mais aussi le nombre d'étapes impliquées dans l'action qui influence la réussite.

Dans une de nos études longitudinales nous avons également observé un succès plus précoce en condition de contiguïté spatiale qu'en condition de non-contiguïté mais nos conclusions sont différentes (O'Regan, Rat-Fisher, & Fagard, 2011). Dans cette étude nous avons suivi quatre bébés tous les mois entre 12 et 20 mois, en leur présentant un jouet attrayant hors de portée et un râteau en carton à portée de main. Le jouet était soit attaché sur le râteau, soit à l'intérieur du râteau, soit à distance du râteau (voir Figure 1).

Notre codage spécifiait si le bébé avait réussi à rapprocher le jouet, mais également si le rapprochement était clairement intentionnel ou non. Lorsque le jouet est attaché sur le râteau, le succès est immédiat dès l'âge de 12 mois, apparaît clairement intentionnel, et ne change pas avec l'âge. Lorsque le jouet est à l'intérieur et contre le râteau, le taux de succès, très élevé à 12 mois, diminue aux séances suivantes avant de remonter à partir de 15 mois. Le succès lorsque le jouet est à distance du râteau est très rare avant 18 mois (voir Figure 2). Une ANOVA sur le pourcentage de succès en fonction de la condition (x3, jouet

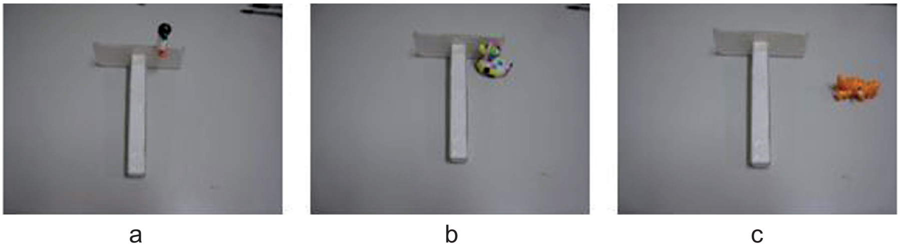

Figure 1.
Jouet présenté sur le râteau (a), à l'intérieur du râteau (b) ou à distance du râteau (c)

attaché, à l'intérieur du râteau ou à distance du râteau) et de la séance (x6) montre un effet significatif de la condition (F(2,6) = 110,6 ; p < 0,0001), et de la séance (F(5,15) = 4,3, p < 0,02) mais pas d'interaction entre les deux. Un test post-hoc de Tukey montre que les trois conditions diffèrent significativement, et que la séance 6 diffère de toutes les autres séances sauf de la séance 5. L'absence d'interaction est sans doute liée au petit nombre de sujets car il semble bien que le succès évolue très différemment avec la séance suivant les conditions.

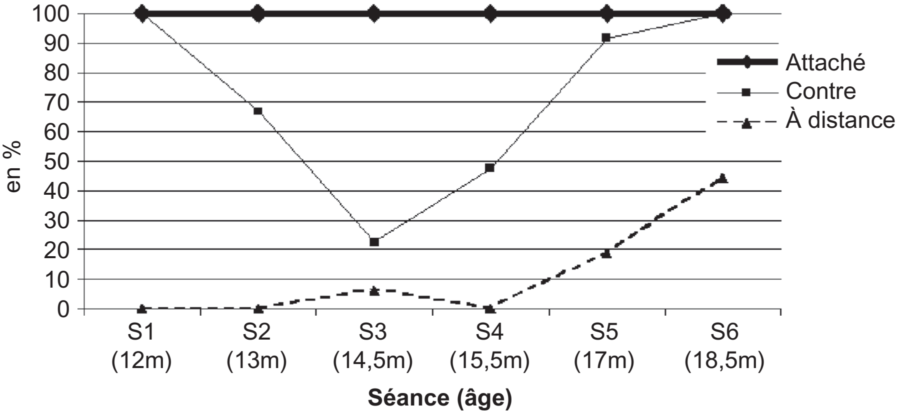

Figure 2.
Pourcentage de réussite en fonction de la séance et de la condition

Il nous a semblé que les premières réussites dans la condition où l'objet est à l'intérieur du râteau surviennent non pas parce que le bébé a compris la fonction de l'outil mais parce que le jouet vient par contingence spatiale dès que l'enfant tire l'outil, qui est l'objet le plus proche (pour cette raison nous appelons ces succès « ambigus »). Plusieurs observations nous ont amenés à cette conclusion : le fait que les premiers succès à 12 mois passent parfois inaperçus par les bébés qui rapprochent l'objet mais ne s'en emparent pas ; que ces premiers succès sont suivis aux deux ou trois sessions suivantes (c-à-d. jusque vers 16-17 mois) de nombreux échecs au cours desquels les bébés montrent à la fois leur désir d'obtenir le jouet et leur refus d'utiliser l'outil, soit en jetant l'outil sur la table ou par terre après lui avoir fait contourner le jouet, soit en ignorant l'outil (voir Figure 3) ; enfin le fait que lorsque le geste de tirer l'outil n'a pas permis de rapprocher suffisamment le jouet, les bébés ne font jamais une deuxième tentative pour aller replacer l'outil derrière le jouet. Nous avons donc conclu que, même si la contiguïté spatiale peut favoriser la compréhension de la fonctionnalité de l'outil au bout de plusieurs sessions, il ne faut pas surinterpréter les premiers succès qui semblent dus à la contingence entre l'action de tirer le premier objet à portée de main et le rapprochement du jouet contigu plus qu'à l'action intentionnelle de rapprocher le jouet avec l'outil.

Figure 3.
Jusqu'à 18-20 mois le bébé ignore souvent l'outil et quémande le jouet.

MÉCANISMES SOUS-JACENTS À L'UTILISATION DE L'OUTIL

La plupart des études précitées ont cherché à décrire les progrès dans l'habileté manuelle à utiliser un outil, ou encore les facteurs influençant la réussite comme la relation spatiale entre l'outil et l'objet à rapprocher. Une question plus intéressante est celle de savoir comment se développe la *compréhension de la fonctionnalité de l'outil* en tant que moyen d'étendre la portée de son bras. En effet, jusqu'au milieu de la deuxième année, le problème du bébé n'est pas vraiment de savoir *comment* utiliser l'outil pour rapprocher un objet car il ne semble même pas avoir l'idée que l'outil peut lui permettre de le faire. La question intéressante est donc celle posée par Piaget (1936, p. 290) : « Comment expliquer la transition entre essai et erreur et invention, entre schème moteur et schème représentatif ». Pour répondre à cette question il faut déterminer les mécanismes qui sous-tendent la compréhension progressive de la fonctionnalité de l'outil.

Notre étude longitudinale déjà citée (O'Regan *et al.*, 2011) avait ce but ; pour cela nous avons analysé tous les comportements observés aux séances successives chez les quatre bébés suivis de 12 à 20 mois. Un premier résultat notable est que les premiers succès quand le jouet est contre le râteau, succès que nous avons qualifiés d'« ambigus », n'ont néanmoins pas permis aux bébés d'apprendre que le râteau peut effectivement servir à rapprocher le jouet puisqu'ils sont suivis d'échec dans les autres conditions ainsi que dans la même condition aux séances suivantes. Lorsque le râteau et le jouet sont spatialement séparés, ce n'est que vers la 5e ou 6e séance (entre 17 et 20 mois) que les bébés cherchent à mettre en contact le râteau et le jouet avec le but évident de rapprocher le deuxième en utilisant le premier (voir Figure 2). Jusqu'à la 5e séance, il semble donc que le bébé n'a pas appris de l'observation de l'effet de ses actions pour comprendre l'utilité du râteau. Pour la condition « à distance du râteau », le parent ou l'expérimentateur faisait deux démonstrations au bébé s'il avait échoué spontanément. Les démonstrations se faisaient selon la perspective du bébé. La démonstration par un adulte n'entraîne ni succès ni changement de comportement avant la séance 5[1], ce qui montre que le bébé n'a pas appris non plus de l'observation de l'action réussie de l'autre dans cette situation d'utilisation d'outil. Nous avons conclu que ces deux mécanismes (essai-erreur et apprentissage par observation) nécessitaient un certain niveau d'intuition de la solution pour être efficaces.

Comment émerge cette intuition ? Pour le comprendre nous avons analysé en détail les comportements précédant le stade d'intuition de la fonctionnalité du râteau. Ceux-ci sont très variés : les bébés soit se focalisent sur l'outil (le mettent à la bouche, frottent la table avec, etc.) ou sur le jouet (tendent la main vers lui), soit connectent les deux sans chercher à rapprocher le jouet (tapent sur le jouet avec le râteau, par exemple). Contrairement à notre attente, nous n'avons pas observé une augmentation de ces comportements de connexion entre le râteau et le jouet au fur et à mesure des séances : ces comportements sont observés dès 12 mois et ils alternent avec les autres comportements pendant toutes les premières séances, de façon variée suivant les enfants. Ce n'est qu'au cours des séances 5 et 6 (entre 17 et 20 mois) que les bébés commencent à montrer qu'ils comprennent que le râteau peut servir à rapprocher le jouet. Ils ne le rejettent plus et ont leurs premiers comportements « essai-erreur ». Il est fort probable que cette intuition résulte des explorations qui l'ont précédée, la manipulation du râteau ayant sans doute permis aux bébés d'augmenter leurs connaissances des affordances non spécifiques du râteau avant d'entraîner la compréhension de l'affordance qui

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[1] Notons que quelques études ont montré une capacité plus précoce d'apprendre par observation à utiliser un outil, soit dans des conditions plus simples d'utilisation d'outil (Brown, 1990 ; Sommerville, Hildebrand, & Crane, 2008), soit dans un contexte pédagogique de démonstration (contact oculaire, référence au prénom, etc.)(Sage & Baldwin, 2011).

consiste à rapprocher le jouet vers soi. On peut également penser que le bébé ayant appris à manipuler le râteau, il devient plus disponible pour imaginer la possibilité d'une nouvelle affordance (voir Schlesinger & Langer, 1999, et Sommerville, Hildebrand & Crane, 2008, pour une discussion sur l'influence de l'action sur la perception). Si par exemple le râteau est ressenti comme un prolongement de la main, la possibilité d'aller chercher l'objet avec s'impose peut-être tout naturellement au bébé.

En conclusion, il semble que tant que le bébé n'anticipe pas les conséquences de son action, tant qu'il ne tire pas le râteau *pour* rapprocher un objet dont il sait qu'il est indépendant, il ne perçoit pas que le rapprochement du jouet est directement lié à son geste de tirer le râteau. De même, tant qu'il n'anticipe pas l'intention de l'adulte, il ne voit pas le lien entre l'action de l'adulte et le résultat sur le jouet rapproché, et en conséquence, il n'imite pas l'adulte. Cette absence d'imitation contraste avec les observations que les bébés peuvent imiter des actions simples dès la deuxième moitié de la première année (Meltzoff, 1988 ; Barr, Dowden, & Hayne, 1996), mais concordent avec l'observation que la complexité d'une tâche influence fortement l'imitation, même chez des enfants de 5 ans (Wang, Fu, Zimmer, & Aschersleben, sous presse).

Un facteur important qui permet au bébé d'approcher l'intuition de la fonctionnalité de l'objet semble être la variabilité des comportements spontanés, telle l'exploration du râteau, seul ou en relation avec le jouet mais pas pour le rapprocher. De la compréhension des affordances variées du râteau, mais sans doute aussi de la maîtrise croissante à manipuler le râteau, émerge assez brutalement vers l'âge de 18 mois (lorsque le jouet est à distance de l'outil) l'intuition que le râteau pourrait rapprocher le jouet. Dès que le bébé possède cette intuition, il devient capable de tirer parti de ses tentatives partiellement réussies (essais-erreurs) ou de la démonstration d'un adulte pour arriver à utiliser le râteau avec succès.

Ces conclusions concordent avec la distinction de deux composantes dans l'apprentissage de l'utilisation de l'outil : une composante cognitive (compréhension de la fonctionnalité de l'outil) et une composante motrice (habileté à manier l'outil) (Greif & Needham, 2007). Au vu de nos résultats, on pourrait dire que la première met plusieurs séances avant d'apparaître relativement soudainement, suivie des progrès rapides de la deuxième au cours des deux dernières séances. Cependant, cette distinction est à relativiser et il y a tout lieu de penser avec Greif & Needham (2007) que les deux composantes interagissent dynamiquement : par exemple, les explorations qui précèdent l'intuition de la fonctionnalité du râteau servent sans doute autant la composante cognitive que la composante motrice de cette habileté.

Enfin on peut poser la question de savoir si un seul mécanisme suffit à expliquer ce qui donne l'impression d'un changement abrupt vers 18 mois. L'augmentation des connaissances des affordances de l'outil et celle de l'habileté dans le maniement du râteau peut, à un certain moment, atteindre un niveau suffisant pour permettre un changement qualitatif. Des exemples de transitions abruptes correspondant à des changements de phase ont été décrits pour certains comportements, la prise d'objet par exemple (Wimmers, Savelsbergh, Beek, & Hopkins, 1998). Une autre possibilité serait qu'un mécanisme nouveau entre en jeu soit grâce à la maturation du système nerveux, soit grâce au développement d'autres systèmes. Un tel mécanisme nouveau pourrait être lié à un progrès dans la capacité de mémoire à court terme, ou bien à la capacité de relier deux événements spatialement et temporellement séparés (Diamond, 1983) ou de visualiser un point de contact potentiel bien qu'absent de la scène visuelle (Brown, 1990), ou encore à une augmentation dans la capacité d'anticiper les conséquences de son action sur un objet. Il semble que la compréhension de la notion de causalité *per se* ne soit plus en cause aux âges étudiés (Leslie & Kibble, 1987).

Pour savoir si la familiarisation progressive au cours de plusieurs mois lors de sessions successives avec leurs explorations variées suffit à elle seule à expliquer le changement brutal à 18 mois, nous sommes en train de comparer ces résultats longitudinaux portant sur quatre bébés avec les résultats obtenus dans une étude transversale en cours portant sur un plus grand nombre de bébés âgés de 12 à 22 mois.

BIBLIOGRAPHIE

Barr, R., Dowden, A., & Hayne, H. (1996). Developmental changes in deferred imitation by 6- to 24-month-old infants. *Infant Behavior and Development*, *19*(2), 159-170.

Bates, E., Carlsonluden, V., & Bretherton, I. (1980). Perceptual Aspects of Tool Using in Infancy. *Infant Behavior & Development*, *3*(2), 127-140.

Bates, E., Thal, D., Fenson, L., Whitesell, K., & Oakes, L. (1989). Integrating Language and Gesture in Infancy. *Developmental Psychology*, *25*(6), 1004-1019.

Brown, A. L. (1990). Domain-Specific Principles Affect Learning and Transfer in Children. *Cognitive Science*, *14*(1), 107-133.

Chen, Z., Sanchez, R. P., & Campbell, T. (1997). From beyond to within their grasp: the rudiments of analogical problem solving in 10- and 13-month-olds. *Dev Psychol*, *33*(5), 790-801.

Claxton, L. J., McCarty, M. E., & Keen, R. (2009). Self-directed action affects planning in tool-use tasks with toddlers. *Infant Behav Dev*, *32*(2), 230-233.

Connolly, K., & Dalgleish, M. (1989). The emergence of a tool-using skill in infancy. *Developmental Psychology*, *25*(6), 894-912.

Diamond, A. (1983). Comparison of performance on a Piagetian object permanence task in human infants and rhesus monkeys : evidence for involvement of the prefrontal cortex. *Neuroscience Abstracts*, *9*, 641.

Gesell, A. (1928). *Infancy and human growth*. New York: Macmillan.

Greif, M. L., & Needham, A. (2011). The development of human tool use in early life. In McCormack (Ed.), chapter *3*, 51-68.

Köhler, W. (1927). *The mentality of apes* New York: Harcourt, Brace.

Koslowski, B., & Bruner, J. S. (1972). Learning to Use a Lever. *Child Development*, *43*(3), 790-799.

Leslie, A. M., & Keeble, S. (1987). Do six-month-old infants perceive causality? *Cognition*, *25*(3), 265-288.

Lockman, J. J. (2000). A perception–action perspective on tool use development. *Child Dev*, *71*(1), 137-144.

McCarty, M. E., Clifton, R. K., & Collard, R. R. (1999). Problem solving in infancy: the emergence of an action plan. *Dev Psychol*, *35*(4), 1091-1101.

McCarty, M. E., Clifton, R. K., & Collard, R. R. (2001). The beginnings of tool use by infants and toddlers. *Infancy*, *2*(2), 233-256.

Meltzoff, A. N. (1988). Infant imitation and memory: nine-month-olds in immediate and deferred tests. *Child Dev*, *59*(1), 217-225.

O'Regan, J. K., Rat-Fischer, L., & Fagard, J. (2011). Mechanisms leading to tool use: a longitudinal study. *First Joint IEEE International Conference on Development and Learning and on Epigenetic Robotics–Frankfurt (Germany),* Conference Proceedings.

Piaget, J. (1936). *La naissance de l'intelligence chez l'enfant.* Delachaux & Niestlé, Neuchatel.

Richardson, H. M. (1932). The growth of adaptive behavior in infants: An experimental study at seven age levels. *Genetic Psychology Monographs*, *XII*, 195-357.

Sage, K. D., & Baldwin, D. A. (2011). Disentangling the social and the pedagogical in infants' learning about tool-use. *Social Development*, *20*(4), 825-844.

Schlesinger, M., & Langer, J. (1999). "Infant's developing expectations of possible and impossible tool-use between ages 8 and 12 months." *Developmental Science 2*(2): 195-205.

Seed, A., & Byrne, R. W. (2010). Animal tool use. *Current Biology*, *20*(23), R1032-1039.

Sommerville, J. A., Hildebrand, E. A., & Crane, C. C. (2008). Experience matters: the impact of doing versus watching on infants' subsequent perception of tool-use events. *Dev Psychol*, *44*(5), 1249-1256.

Thorndike. (1898).

Uzgiris, I. C., & Hunt, J. M. V. (1975). *Assessment in infancy: ordinal scales of psychological development.* Urbana: University of Illinois Press.

van Leeuwen, L., Smitsman, A., & van Leeuwen, C. (1994). Affordances, perceptual complexity, and the development of tool use. *J Exp Psychol Hum Percept Perform*, *20*(1), 174-191.

van Schaik, C. P., Deaner, R. O., & Merrill, M. Y. (1999). The conditions for tool use in primates: implications for the evolution of material culture. *Journal of Human Evolution*, *36*(6), 719-741.

Wang, L., Fu, X., Zimmer, H. D., & Aschersleben, G. (in press). Familiarity and complexity modulate the way children imitate tool-use actions: A cross-cultural study. *Journal of Cognitive Psychology.*

Willatts, P. (1999). Development of means-end behavior in young infants: Pulling a support to retrieve a distant object. *Developmental Psychology*, *35*(3), 651-667.

Wimmers, R. H., Savelsbergh, G. J., Beek, P. J., & Hopkins, B. (1998). Evidence for a phase transition in the early development of prehension. *Develomental Psychobiology*, *32*(3), 235-248.

Wynn, T. (1985). Piaget, stone tools and the evolution of human intelligence. *World Archaeology*, *17*(1), 32-43.

Appendix 3 – The emergence of tool use: a longitudinal study in human infants

(in prep.)

Abstract

We describe the results of a longitudinal study on five infants from age 12 to 20 months, presented with an out of reach toy and a rake-like tool within reach. Five conditions of spatial relationships between toy and rake were tested. Outcomes and types of behavior were analyzed. Apparent success around 12 months in the condition of spatial contiguity between rake and toy was followed by a stage when infants rejected the rake while reaching for the toy, thus casting doubt on their level of understanding at 12 months. In the condition of spatial separation infants' strategies fluctuated between paying attention to the toy only, exploring the rake, and connecting rake and toy with no apparent attempt to bring the toy closer. Around 18 months, infants suddenly started to make visible efforts to bring the toy closer with the tool: at this stage, the infants became able to learn from their failures and to correct their action, as well as to benefit from demonstration of an adult. Thus, it may be hypothesized that the reason for the rather sudden onset of success is that it can only occur once the conceptual notion of the tool's usefulness has been acquired.

Key words: tool use, infants, spatial contiguity, longitudinal

Tool use is the ability to use one object (the "tool") to manipulate other objects, and hence move beyond the limits set on the action space by the length of one's limbs or the type of one's end-effector (Nabeshima, Kuniyoshi, & Lungarella, 2006). Tool use has often been recognized as an important step during evolution (van Schaik, Deaner, & Merrill, 1999), and as a marker of the evolution of human intelligence (Wynn, 1985). Its importance as a milestone in human development has also long been recognised (Piaget, 1952) and is still emphasised ("a royal road to the study of problem solving," (Keen, 2011), p. 2). And more recently, understanding the basis of tool use has come to be seen as fundamental for robotics (Nabeshima et al., 2006).

Curiously, the development of tool use in human infants has received relatively little interest until recently (see Keen, 2011, for a recent review). In addition, most of the existing studies have been concerned more with describing stages of skill development or factors that induce success, than with suggesting precise learning mechanisms. Furthermore, very few of these studies have been longitudinal.

One possible exception is Piaget. Piaget first described "la conduite du bâton" (stick behavior) in 1953. He noticed that his children started to use a stick to move faraway objects by the end of the first year. Piaget had noted that his son Laurent discovered the use of the stick "almost without trial and error" (Piaget, 1952, p.290). The question asked by Piaget in 1952 was "how to explain the transition from trial and error to invention, from motor scheme to representative scheme." Another exception is Bruner, who observed how children progress from one level of organization to the next when using a primitive form of tool, a lever with fixed fulcrum (Koslowski & Bruner, 1972). From their study of 12-to-14, 14-to-16, and 16-to-23-month-old children learning to use the lever to obtain a toy attached to the end of the lever, Koslowski and Bruner extracted some principles to explain how the child progresses from one level of organization to the next. For them, the transition seems to consist of the child concentrating on the two individual components of the task (how the rotation of the lever affects the position of the goal, and how the child can effect a rotation of the lever) and once each of the components has been modularized and is less attentionally demanding, the child becomes able to attend simultaneously to the movement of both the lever's goal end and its hand end, which allows them to finally envision the solution to the problem.

A few cross-sectional studies have investigated what factors contributed to the difficulty to use a tool to get an out-of-reach object. They all stress that difficulty in tool use increases with an increasing spatial gap between the tool and the object to be acted upon (Bates, Carlsonluden, & Bretherton, 1980; van Leeuwen, Smitsman, & van Leeuwen, 1994), or more generally with an increasing number of steps needed to achieve the required result (Smitsman & Cox, 2008). In their 1980 study, Bates et al. compared 40 10-month-old infants retrieving an out-of-reach toy placed either on a cloth, at the end of a string, or at different positions near three kinds of tool likely to help the children retrieve it (hoop, crook or stick). The conditions where toy and tool are physically linked ("unbreakable contact") were most successful, followed by the conditions in which there was breakable contact (toy placed against/inside the hoop or the curved part of the crook). The conditions with no contact (toy beside the crook or the stick) were the least successful. The authors concluded that at 10 months problem solving is easier when the link between the tool and the toy is suggested by the spatial array. Van Leeuwen et al. suggested that the role of spatial contact between tool and toy in helping the infants solving the problem was partly linked to the number of mental transformations that the infants must perform to imagine the solution ("number of elements to be integrated," p.189).

In another study (McCarty, Clifton, & Collard, 1999) the focus was also not on learning mechanisms *per se* but rather on progress in planning action with a more or less familiar tool, a spoon. Nine-, 14-, and 19-month-old children were given a spoon presented in such a way that the bowl part was on the side of the preferred hand. Only the 19-month-olds anticipated the problem and directly grasped the handle with the ipsilateral non-preferred hand, whereas younger infants used their ipsilateral (preferred) hand to grasp the bowl part of the spoon or the handle part with an awkward movement.

Manual skill improvement in the use of a spoon was also the focus of another, longitudinal study (Connolly & Dalgleish, 1989). In it, Connolly and Dalgleish observed two groups of infants, ages 11 and 17 months, at monthly intervals over a 6-month period. However, Connolly and Dalgleish were more interested in changes in the shape of the movement leading to expertise (hand use, grip pattern, spoon trajectory) than in the underlying mechanisms leading to an understanding of the use of the spoon to retrieve the food.

In conclusion from this brief review of the literature, we know that spatial proximity and number of transformations are important factors, that planning of action improves with practice, but we still lack an understanding of the cognitive mechanisms that underlie the acquisition of tool use ability in the course of the second year. In particular, we cannot as yet answer Piaget's question as to whether tool use appears through sudden insight or emerges gradually through progressive familiarization with tool affordances. According to Lockman (2000), tool use emerges from a long period of object manipulation that familiarizes infants with the use of an object to interact with other objects. On this view, the progressive discovery of the various affordances of an object allows infants to later ascertain which affordance of an object will solve their problem. This ecological view contrasts with the more radical view that tool use results from a sudden insight (Köhler, 1927).

To explore the mechanisms underlying the acquisition of tool use more precisely, and in particular to ascertain whether this acquisition occurs gradually or through sudden insight, clearly a longitudinal study is called for. We decided to take a small number of infants and study their evolution from ages 12 to 20 months on a regular basis, carefully analyzing their behavior longitudinally as they learned to use a rake-like tool to obtain an out-of-reach toy. The questions we posed were: why is spatial proximity an important factor? What will allow infants to understand the affordance of the rake in conditions of no spatial contact: observation of their success in easier conditions of spatial contact? Exploration of the rake? Trial and error? Observation of a demonstration? Sudden insight?

Regularly following a small number of infants during the months preceding the acquisition of a skill has in the past proven to be a good way to gather useful information on mechanisms underlying skill acquisition (Thelen et al., 1993). It is also one way to look at individual trajectories as well as common patterns. At this stage in the understanding of tool use, it seems advantageous, rather than testing particular hypotheses, first to simply try to provide a description of the transition to tool use from a longitudinal perspective, and then to propose possible underlying mechanisms in the progressive comprehension of the tool's usefulness. This was therefore the purpose of the exploratory study presented here.

Methods

We constructed a T-shaped rake-like tool made out of white cardboard with a 20-cm-long handle. We used a selection of small toys that we had previously determined to be interesting to children in a day-care nursery. Infants were comfortably seated at a testing table during the whole session. They were either on the parent’s lap or, at older ages, in a high chair. By using a white rake, we ensured that the rake was not very attractive per se, as opposed to the visually highly salient toys so as to attract the attention and trigger the desire of the infants.

Five infants (two girls and three boys) were observed regularly in five conditions of tool use: toy on top of rake, attached to it (C1), toy inside/against the rake (C2), toy inside the rake but not against it (C3), toy to the side of the rake (C4), and rake handed to the infant (C5) (see Figure 1). The toy was always just out of arm's reach.

Insert Figure 1 about here

All infants were brought in for familiarization with the experimental room and the experimenters at 11 months. Testing started when the infants were 12 months old. They were tested about every month until they could use the rake with success (16 months for one infant, 18 months for three of the infants, 20 months for the fourth). Mean age was 12 months in session 1 (S1), 13 months 1 day at S2, 14 months 4 days at S3, 15 months 6 days at S4, 17 months 1 day at S5, and 18 months 8 days at S6. Four infants took part in 6 sessions. Infant 2 (I2) was seen at 11 months but missed sessions 1 and 2 for family reasons; we kept him in the study for two reasons: first because of the small number of infants; second, because we thought it interesting to compare his performance on his first session with that of the other infants of the same age but who had had two practice sessions). Infant 5 succeeded at session 4 (16 months) and was seen again at 20 months for checking the performance. Condition C1 was only tested once at the beginning of each session since it did not represent a challenge for infants at the ages tested here. Results from this condition are briefly mentioned at the beginning of the results section but not included in later analyses. The other conditions were tested several times per session. Since this study was exploratory, we decided to test the infants for as long as they were willing to participate, rather than to have exactly the same number of trials per infant. At the beginning of each session, the order of presentation was from C1 to C5, but when an infant was willing to continue, conditions C2, C4 and C5 were retested in random order. After the first failure on C4 and C5, a demonstration was provided by one of the adults present in the room, either a parent or an experimenter so that the infant could see the demonstration from a perspective similar to its own. A demonstration consisted in two or three repetitions of showing the infant, while he or she was looking, how to bring the object toward himself or herself. The rake was then either put back in front of the infant (C4) or handed directly to the infant (C5). There were 389 trials in all, and between 1 and 3 demonstrations per session. A trial was terminated if the infant did not try to obtain the toy within one minute, or after failure in retrieving the toy. After getting the toy, the infants were allowed to play with it for about one minute.

Coding of behaviors

We first coded elementary behaviors in each condition of each trial for each of the four infants. These elementary behaviors involved looking (infant looks at toy, at rake, at adult, or elsewhere); pointing toward toy (with bare hand or with rake); grasping the rake (after touching it by chance, spontaneously, encouraged by the experimenter, or put in the baby's hand by the experimenter), moving the rake (rakes it or lifts it from the table with inside or outside lateral movements, or with a straight movement toward himself; makes a detour around the object or not); refusing the rake (refuses it when handed by experimenter, places it on table, throws it away); manipulating the rake per se (puts rake into mouth, bimanually explores rake) or on the table (swipes table, rubs table, hits table); manipulating the rake in connection with the toy with no clear intention to bring it back (hits toy or pushes toy with rake); interacting with the adult, clearly asking for help (gives rake to adult, takes the adult's hand and places it on rake); and manipulating the rake with clear intention to bring the object back (brings object to hand with rake; with wrong movements, peculiar but effective movements, or direct movements; prepares the second hand while raking the toy with the first hand). These elements of behavior occurred together in several ways during trials, leading to a count of 26 whole-trial behaviors among all 362 trials of C2 to C5 (see Table 1). The whole-trial behaviors are grouped into categories as a function of the level of performance they reflect. The notation NT (No Try) means that the child did not try either to retrieve the toy or to explore the rake. The notation T/T1 indicates that the child was interested in the toy and T/T2 that s/he was interested in the rake but not in their interaction. The notation T+T indicates that the child was interested in the interaction between rake and toy without showing a clear intention to retrieve the toy. The notation R1 indicates that the child has shown clear understanding of the rake as a possible tool to retrieve the toy but doesn't yet know how to use the rake. The notation R2 means that the child knows how to retrieve the toy with the rake.

Insert Table 1 about here

Notice that in our classification, the last category of behaviors, which we call "A" for "Ambiguous" (behaviors 22 to 26), has a special status. Behaviors 22 to 25 occurred essentially in conditions C2 and C3 where it was possible for the child to succeed without any understanding of the functionality of the rake. This is because, due to the physical position of the toy inside the rake, simple pulling the rake would automatically bring the toy into reach. Success in this condition was thus due to the contingency between rake and toy, and not necessarily indicative of understanding of the rake: hence our coding of it as "Ambiguous."

Finally, there was also another behavior that we could not interpret and that we have included in the "ambiguous" category: sometimes the infant simply grasped the rake and gave it to the adult. She may have done so because she wanted the adult's help and had understood that the rake was the key element, or because she wanted to get rid of the rake. This behavior was observed only eight times in all, in three of the infants.

Thus each infant received a score for each trial: 0 (No Try), 1 (interested only in the toy, T/T1), 2 (exploring the rake for its own sake, T/T2), 3 (using the rake in connection with the toy, not for retrieval, T+T), 4 (using the rake for retrieval but with difficult or partial success, or success only after demonstration, R1), or 5 (intentional spontaneous mature success, R2). This last score concerned only C4 and C5 where success was never ambiguous.

Results

1/ Retrieval of the toy as a function of condition and session

Before considering the detailed behaviors as classified in our detailed coding scheme, we present in this first section an analysis simply of overall success at retrieving the toy.

The results bear on 389 trials: 27 for C1, 89 for C2, 60 for C3, 118 for C4, and 95 for C5, in all. Most of the time the infants were interested during the session. They sometimes expressed frustration at not being able to get the toy, but they rarely refused a trial. NT (No Try) was coded for 31 trials (7.9 %). NT never occurred in C1. For the four other conditions the percentage of NT did not change with condition (p=.52) but was more or less frequent depending on the session (F(3,12) = 3.1, p=.06). A post-hoc LSD test showed that the rate of refusal was significantly lower in sessions 4 (14.5 mo) than 3 (15.5 mo).

An ANOVA on the percentage of reaching/pointing as a function of condition (C5 excluded, since in this condition the rake was handed directly to the infant) indicated a significant effect of condition on reaching/pointing (F(3,12) = 12.8, p<.001). An LSD post-hoc test indicated that the percentage of reaching/pointing was significantly lower in condition 1 (5%) than in all other conditions (respectively , and lower in condition 3 than in condition 4 (see Figure 3).

Toy attached to the rake (C1)

When the toy was attached to the rake (C1), the infants grasped the rake without hesitation and then detached the toy from the rake (see Figure 2). They almost never first reached or pointed toward the toy in this condition, showing that visual information sufficed for them to understand that the toy was connected to the rake (100% success, starting on the first trial). Further analyses, including statistics, bear only on the four other conditions, thus on 333 trials, corresponding to the 362 trials of conditions C2 to C5 minus the 31 refusals.

Insert Figure 2 about here

Insert Figure 3 about here

Toy inside the rake (C2 and C3)

The rate of toy retrieval was high as of the first session, particularly for C2, as can be seen in Figure 4 which represents the mean percentage of trials in which the toy was retrieved successfully.

Rates of success for C2 and C3 differed significantly only in the first session (T(2,3)=16, p<.01). In C2, in the first session infants almost always immediately grasped the rake, most of the time to make a raking movement leading to successful retrieval. When the toy was not against the rake (C3), these successful retrievals represented only 30% of trials.

The rate of toy retrieval in C2 showed a u-shaped form (see Figure 4). After the first session and the rather stereotyped behavior seen in it (all observed strategies but one were A25), infants demonstrated various behaviors in C2, as we shall see below. An ANOVA on the frequency of object retrieval in C2 as a function of session showed a significant effect (F(5,20) = 9.3, p<.01). An LSD post-hoc test indicated that the percentage of retrieval was significantly different in sessions 3 and 4 as compared with the other sessions, which did not differ significantly from each other. Percentage of success in C3 showed a regular increase across sessions. No statistics were calculated on C3 alone because of missing data.

Toy to the side of the rake (C4 and C5)

All infants younger than about 17 months (5th session) failed to retrieve the toy when it was not inside the rake, with the single exception of one infant who succeeded once after a demonstration from an adult in the third session. Successes in C4 and C5 showed a rather sudden increase between sessions 5 and 6. In session 6, all four children succeeded in C4 and C5, although they still did not succeed on all trials, as can be seen in Figure 4. An ANOVA on the frequency of object retrieval in C4 and C5 combined (percentage of “S1” + “S2”) as a function of session showed a significant effect (F(5,15) = 4.4, p<.02). An LSD post-hoc test indicated that the percentage of retrieval was significantly different in session 6 as compared with all the other sessions, which did not differ significantly from each other.

Insert Figure 4 about here

In conclusion, retrieval of the toy was always successful when the toy was attached to the rake as of 12 months of age (C1), mostly successful when the toy was inside and against the rake when infants were 12 and 13 months old (C2) but less so on the next two sessions, and not successful at all when the toy was to the side of the rake until 17-20 months of age (C5-C6). Thus, early successes in C2 did not help much in allowing the infants to understand how to use the tool, since these early successes were followed by many failures in C2 and by almost total failure in C4 and C5. In order to get cues to understand the U-curve shape observed in C2 and the relatively sudden onset of success observed in C4 and C5, and to answer our other questions (why is spatial proximity an important factor? What helps infants understand the affordance of the rake in conditions of no spatial contact: Exploration of the rake? Trial and error? Observation of a demonstration? Sudden insight?), we shall undertake a finer analysis of behaviors as a function of condition and session. This is the purpose of the following section.

2/ Finer analysis of behaviors as a function of condition and session: what do these behaviors tell us about infants' understanding of the rake's functionality?

2.a/ *Toy inside the rake (C2)*

In the following paragraphs we shall analyse more finely the behaviors observed in condition C2 in order to try to understand the origin of the U-shaped curve in retrieval rate observed over the successive sessions.

As mentioned above, in session 1 the most frequent behavior was elementary behavior A25, in which the child almost immediately grasps the rake and pulls it. Because the toy is spatially inside the tool, the toy generally comes along with the rake, and the child is able to retrieve it. This stereotyped direct pulling of the rake observed in session 1 for C2 was soon replaced by more varied behaviors in the next three sessions.

In the second session, infants often pointed to the toy before pulling the rake (behaviors A23 and A24). In the third and fourth sessions, the rate of successful retrievals was at its lowest because infants frequently took an interest only in the toy (reaching/pointing to the toy while ignoring the rake or after discarding it, (Video1) or the rake (exploring the rake in itself, putting it into the mouth, rubbing, sweeping or hitting the table with it). Connecting rake and toy not for retrieval (touching or hitting it), was not often observed at this stage, except for one infant who used it as of the first session.

Thus we see that the drop in success rate in sessions 3 and 4 was due to an increase in non-effective alternate behaviors. These alternate behaviors were of a variety of different types, so that globally the total number of behaviors increased during sessions 3 and 4 (see Figure 5). In particular the mean number of different whole-trial behaviors per infant in C2 increased from 1 and 1.3 in sessions 1 and 2 respectively to 2.75 and 2.25 in sessions 3 and 4 respectively.

In order to understand the origin of this pattern of behaviors, we may suppose the following. When, in the 3rd and the 4th sessions, rather than pulling the rake directly, infants moved the rake around the toy and then pointed to the toy, begging for it with their bare hands after getting rid of the rake (behaviors 6 or 7), they may have been showing their interest in the toy but also that they at this stage knew that the rake and the toy were not connected. But in this case they also clearly showed that they did not know that the rake could be used to bring an unconnected object closer.

Another good example of this lack of understanding was that when they raked with the rake but the object was not brought near enough to be retrieved, the infants did not use a further raking movement to retrieve the toy: instead they either stopped trying to get the toy, or used the rake to touch or hit the toy (Video2). We interpret all these behaviors typical of the 3rd and 4th sessions as showing that the high rate of toy retrieval observed in the 1st session did not reflect a real understanding of the rake's functionality. Thus, infants may have grasped the rake as their first action either because it was the closest object or because they believed the toy to be attached to it as in C1 (and it may have taken them some time to realize that this was not the case). In any case, the simple pulling of the rake was enough to bring the toy closer most of the time. Ultimately however, by sessions 5 and 6, the rate of successful retrieval in C2 went up again, probably corresponding to a true understanding of the rake's affordance. The variability in behaviors (number of different behaviors) also dropped to 1.25 (session 5) and 1 (session 6).

Insert Figure 5

It is worth noting that there were interindividual differences in the way new behaviors replaced the systematic pulling of the rake in the first sessions (see Figure 6a,b,c,d). Infant 1 was more interested in the toy than in the rake and behavior “T” replaced “A” in C2. Infant 2 frequently explored the rake in itself on the third session (his first session) in C2. Infant 3 was very interested in exploring the rake from the beginning, either in connection with the object or alone. For him, behaviors “R” and “T+R” replaced the “A” successes in C2. Infant 4 was the infant whose ambiguous successes in C2 decreased the least after the first sessions. For her, behaviors “T” and then, to a lesser extent, “R” replaced “A” in C2.

Insert Figure 6 about here

In conclusion, observation of behavior in condition C2 across sessions indicates that after the early successes of the first sessions, infants’ behavior changed dramatically in sessions 3 and 4. Instead of immediately pulling the rake, they either pointed to the toy, sometimes after discarding the rake, or they grasped the rake and explored it. Thus, in those sessions, infants tended to pay attention either to the toy or to the rake but they seldom connected the two objects and when they did, it was not to retrieve the toy. These switches between different strategies across sessions are comparable to the overlapping wave patterns described by Chen & Siegler (2000) in their microgenetic study of tool use at 18-35 months of age.

This may indicate that the early successes in toy retrieval in this condition were due, not to a true understanding of the rake’s functionality, but to the physical contingency between rake and toy. Thus, the fact that using a tool to get an out-of-reach toy is easier without a spatial gap between tool and object than it is with such a gap, observed at 12 months in our study and at 10 months by Bates et al. (1980), may be due more to the mechanical constraints of the task than to an understanding of tool affordances triggered by perceptual proximity.

If indeed infants did not anticipate that using the rake would bring the toy to hand at first in condition C2, or if they did not immediately grasp that rake and toy were unattached, this may explain why there was no rapid transfer from “successes” in C2 to C4 and C5. We will next analyze behaviors in conditions C4-C5 in order to elucidate how children understood how to use the rake when the toy was not next to it.

b/ ***Toy not near the rake (C4 and C5)***

We have seen that despite all their experience of success (expected or not) when the toy was inside the rake, it took the infants several sessions and many trials to understand how to use the rake to retrieve the toy when it was not presented inside the rake (in C4 and C5). In particular, it took the infants 30 to 48 trials in all in C4 and C5 (mean: 35.2 trials) across 5 to 6 sessions (mean: 5.25) to succeed, and they were aged 17 to 20 months (mean 18.2 months) when they reached this stage. If the infants did not learn much from their own "unexpected" success in C2, then how did they learn to use the rake in conditions C4 and C5? By exploring the rake? By trial and error? By watching a demonstration by an adult? In the following section we explore these alternatives by checking which behaviors preceded real success in C4 and C5.

Exploring the rake alone and in connection with the toy

In this section we ask whether exploring the affordances of the rake over successive sessions allowed the child to accumulate enough knowledge to finally make the link between rake and tool, and thereby accomplish the task.

First of all, exploring the rake in itself ("R") was very frequent over the successive sessions. It was the second most frequent behavior (23.7%, all sessions considered) after behavior "T" (38.1%). Connecting the rake with the toy (T+R) was less frequent (18.2%). Note that the first 'T+R" behaviors of the first sessions seemed not to be directed toward retrieving the toy, and were very different from the "T+R" observed in later sessions. Hitting the toy with the rake seemed to be a game *per se* in the first sessions (Video3), and infants who used this strategy did not even grasp the toy systematically when it happened to come within reach after they hit it.

A second point is the following: a look at individual patterns showed that all four infants fluctuated between the different strategies across sessions (see Figure 7). Sometimes they mostly pointed toward the toy, sometimes they mostly explored the rake, and at other times they mostly connected rake with toy. Doing statistics on the evolution of the different strategies across sessions would be misleading as it is clear that the four infants switched in different ways between pointing to the toy, exploring the rake, and connecting the rake with the toy during sessions preceding success. What is common across infants is the large amount of fluctuation and the lack of a clear, single tendency: we might have expected, for instance, to observe an increase in the connection between rake and toy in the session preceding success, but this was not the case.

Insert Figure 7 about here

Thus, we found little evidence that gradual accumulation of knowledge about rake affordances leads to the ability to make the connection between rake and toy. There was frequent rake behavior but it did not gradually increase; nor was rake + toy behavior systematically preceded by frequent rake behavior.

Learning from trial and error

While the infants appeared not to have learned from their unexpected successes in C2 during the first session, we wondered if they learned from their errors. In other words, did they correct their movements after trying unsuccessfully to grasp the toy with the rake? There is some indication of this, since behavior S1, which reflects awkward or partly successful attempts to use the rake to obtain the toy (trial and errors), was much more frequent in the last session than S2. This was particularly true if we consider the first half of this session, with 35% of behaviors classified as S1 versus 4.17% as S2. In the second half of this session, S1 decreased to 27.6% whereas S2 increased to 16.7% (see Video3).

Learning from demonstration by an adult

Another mechanism to learn how to use a rake might be to observe others doing it. This would be a more economical method than trial and error. As mentioned above, in all sessions, after the first failure in C4 and C5, infants received a demonstration from either the parent or one of the experimenters (usually two demonstrations in a row). Infants clearly did not learn much from the adult's demonstration until late in the study. With only one exception (infant 1, session 3), none of the infants succeeded in retrieving the toy with the rake in C4 or C5 after demonstration before the sixth session. In addition, infant 1 did not repeat her success before the sixth session, either before or after demonstration. To check whether the behavior had been influenced by the demonstration despite not sufficing to lead to retrieval of the toy, we compared the level of performance, indexed by the obtained score, on the trials preceding and following demonstration for C4 and C5 considered together (see Figure 8). It can be seen that the score on trials just following demonstration did not differ greatly from the score of the trials preceding a demonstration until the last session. An ANOVA on the mean score as a function of condition with repeated measures on session showed a significant effect of session (F(5,15) = 12.3, p<.0001) but no effect of condition. Although the session x condition interaction did not reach significance (F(5,15)=2.47, p=.08), a post-hoc LSD test indicated that on the last session the score after demonstration differed significantly from the score after demonstration (p<.0001).

Thus, infants started to benefit from demonstration relatively late, and not before 18 months.

Insert Figure 8 about here

In sum, when the toy was not inside the rake, infants started to use the rake to retrieve the toy between 17 and 20 months of age. In the preceding sessions, they either explored the rake per se or focused on the toy, or to a lesser extent made some connection between rake and toy. When success first appeared, it often occurred after corrections of awkward attempts to use the tool or after demonstration by an adult. But neither of these behaviors were observed during the first sessions. It could be that the capacity to correct inadequate motor planning (trial and error strategy), and the capacity to benefit from a demonstration (observational learning) require that the infant already have some intuition of the solution.

Discussion

In this study, we analyzed the behavior of four infants presented with a rake within reach and with an out-of-reach toy in different positions relative to the rake. We set up the experiment so that the rake was not very attractive per se, as opposed to the toy that we chose to be very salient visually so as to attract the attention and trigger the desire of the infants. Our goal was to finely describe behaviors so as to disclose some of the mechanisms leading to the discovery of the affordance of a rake to bring an object to hand. In particular we wanted to answer the following questions: why is spatial proximity an important factor in determining success in retrieving the toy? What will help infants understand the affordance of the rake in conditions of no spatial contact: observation of their success in easier conditions of spatial contact? Exploration of the rake? Trial and error? Observation of a demonstration? Sudden insight? Before trying to answer these questions, let us summarize our main results and present a few conclusions that can be retained from them.

Globally, we observed the expected hierarchy of success, with systematic success when the toy was attached to the rake (C1), and earlier success (12-13 months) when the toy was inside the rake (C2-C3) than when it was outside (C4-C5). This pattern fits with previous findings showing that spatial proximity helps young infants succeed in tool-use (Bates et al., 1980; van Leeuwen et al., 1994).

However, finer analysis of the behaviors led us to interpret with caution 12-13 month old's successes with the toy close to the rake. In the sessions immediately following their first successful sessions, that is, at ages 14-16 months, the same infants often failed in condition C2, with success returning only in the very last sessions. We observed this U-shaped pattern in all three infants who started the experiment at 12 months of age. In the unsuccessful sessions at the bottom of the "U", many of the infants' behaviors indicated that they wanted the toy but did not know that the rake was the solution: for example they might actively discard the rake or ignore it before or while reaching/pointing to the toy. Furthermore, at the bottom of the U-shape, the number of different behaviors displayed by the infants was much larger than in the first and last sessions. We interpret these facts as showing that success at 12-13 months in C2 may be due, not to infants understanding that a rake can bring an out-of-reach object to hand, but instead simply to the physical rake-toy contingency, in other words to the task setup itself. U-shape has often been observed during development (Mounoud, 1993; Rakinson & Yermolayeva, 2011; Voulomanos, 2011) and is generally interpreted as being caused by new knowledge temporarily disorganizing behavior before being integrated into a new organization. In our case the new knowledge could be that the two objects are separated in C2, which keeps the child from using the rake as a tool until s/he understands or at least suspects that it might be useful.

A first conclusion we can thus draw from behavior in C2 is that even in this condition of spatial contiguity, children probably do not understand the notion of a rake at the beginning of their second year. Sampling a variety of different behaviors when they do not succeed may be one mechanism infants use to try to solve the problem at hand.

A second conclusion concerns learning from early successes. It seems that infants did not learn from their early successes in condition C2, since they failed in the following sessions and in the other conditions. It may be hypothesized that so long as infants pull the tool without the intention of retrieving what they see as an independent toy, they do not make the connection between their action and its result on the toy. In other words, understanding the causal relationship between the raking movement and the effect on the toy may require a minimum of intention while raking; only the intention to obtain the toy with the rake may direct the attention to its effect sufficiently to anticipate a result and to see what actually happens. This could also be interpreted in the light of Brown’s assertion that transfer depends on the deep structural principles that the child possesses (Brown, 1990).

Let us now recall the results for the conditions with spatial gap (C4-C5). Learning to use the rake in these conditions was a protracted process. In the first four or five sessions, infants often reached/pointed to the toy, with the next most frequent behavior consisting in exploring the tool. There was a lot of alternation between the different strategies during the first sessions. First successes did not occur before the last two sessions and they were often obtained with awkward or ineffectual movements, soon corrected during the trial or on the next one. Some of these first successes occurred after demonstration, whereas demonstration almost never led to success in the first sessions. Considering C4 and C5 together, the rate of success increased rather abruptly between the 5th and 6th sessions.

Several conclusions may be drawn from this: (1) Alternating attention between toy and rake may reflect attentional limits, infants being able to attend either to the rake or the tool but less often connecting both; (2) Exploring the rake and connecting it to the toy, even when this is not for retrieval, may help the infant acquire knowledge of various affordances of the rake; it may also help increase manual dexterity in using the rake, which may thus increasingly become felt as an extension of the hand; (3) The understanding of the specific affordance of the rake to bring the toy within reach comes after a large number of these explorations; (4) When the infant finally understands that the rake can be useful, s/he uses both trial and error and observational learning, and becomes able to retrieve the toy with the rake after only a few unsuccessful or partly successful trials.

We now come to the five questions raised in the introduction.

Why is spatial proximity an important factor? One main reason why spatial proximity/perceptual continuity facilitate tool use is that success may occur early through simple contingency. By saying this however, we do not imply that perceptual continuity does not contribute to providing some intuition of the solution. We mean that early successes may be misleading and that even in the condition of perceptual continuity infants do not understand the tool's usefulness before the middle of the second year.

What can help infants understand the affordance of the rake in conditions of no spatial contact: (a) Observation of their success under the easier conditions of spatial contact? There was clearly no transfer from the early success in C2 to C4 and C5. As mentioned above, this could be interpreted as reflecting the fact that before infants have the intention to retrieve the toy with the rake, they do not "see" the consequence of their own behavior or relate the effect to the cause and thus cannot repeat it; (b) Exploration of the rake? Exploration of the rake does indeed start in the first session. This progressive familiarization with the rake may have had a role in building the basis for tool use. This would fit with the ecological view that object exploration on surfaces or on other objects forms the basis of tool use (Lockman, 2000). However, we did not observe an increase in the exploration of the rake alone preceding first successes, as one might have expected. Rather, there was a switch between different strategies across sessions. This fits with the notion of the overlapping wave patterns described by Chen & Siegler (2000) in their microgenetic study of tool use at 18-35 months of age. It is also congruent with the notion that variability plays an important role in motor development (Fagard & Lockman, 2005; Piek, 2002; Thelen, 1995); (c) Trial and error? There seems to be a change in the capacity to correct inefficient movements that results in the toy being brought closer around 17-18 months: before that age, a trial resulting in partial success is not followed by corrections. In contrast, by the last two sessions, trial and error seems to be an efficient strategy leading to full success; (d) Observation of a demonstration? As for trial and error, observational learning of tool use occurred rather late. One may wonder why it takes so long for the infants to benefit from the adult's demonstration. Many studies have shown that infants below 15 months can imitate simple actions, that they can reproduce three-step actions (Elsner, 2007), and learn means-end tasks from observation as of the beginning of the second year (Provasi, Dubon, & Bloch, 2001; see Elsner, 2007 for a review). Why then was it the case that in our study, the trial after adult's demonstration did not differ from the trial before until the sixth session (mean age: 18.5 months)? Our results bear on too few children to draw conclusions on this point. However, in the case of a new complex manual skill, the absence of observational learning before late in the second year is congruent with a previous result (Esseily, Nadel, & Fagard, 2010). An additional point is that we might have obtained more success after demonstration had we included more of what Sage and Baldwin (2011) calls "pedagogical cues" in our demonstration. Sage has shown that with pedagogical cues during demonstration 11-month-old infants benefit from the demonstration of tool use (toy to the side of a hook), whereas they do not so benefit from demonstration without such cues. (e) Sudden insight? The fact that infants needed very few trials before full success once they started to try to use the tool to bring the toy to hand fits with Piaget's observation that his son discovered the use of the stick "almost without trial and error" (Piaget, 1952, p.290).

Our study was an exploratory study aimed at examining the processes by which a few infants seen repeatedly during their second year come to understand the functionality of a tool. As opposed to the few existing studies on tool use in infants, this study did not investigate change in manual skill at using a tool per se (Connelly & Dalgleish, 1989), anticipatory prehension of the tool's handle (McCarty et al., 1999), or the capacity to transfer tool learning and to choose the best-fitted tool among several (Brown, 1990). Our goal was to advance the understanding of the role of spatial separation in tool use and examine when and how the infants really start to understand the functionality of a tool to bring an out-of-reach object closer.

It is often said that there are two approaches to the study of tool use: one conceptual and one sensorimotor (Greif & Needham, 2011). In the conceptual approach, the accent is put on children's acquisition of the notion that the tool's affordances include the possibility of causing the effect that they want (toy being brought closer). In this approach, the authors argue that since the notion of causality seems to be acquired by a few months of age (Baillargeon, Kotovsky, & Needham, 1995; Leslie & Keeble, 1987), what the infant lacks is the motor skill itself. In the sensorimotor approach, the accent is put on the spontaneous exploration of the tool, from which the understanding of its affordance may gradually emerge (Lockman, 2000). On this view, the conceptual understanding follows the manual capacity (Schlesinger & Langer, 1999).

These two components—manual and conceptual—may be distinguished in our task: the infants must understand the usefulness of the tool to bring the toy closer, and they must learn how to move the tool skillfully. It appears from our results that learning the conceptual aspect of the problem (knowing that the tool may serve to retrieve the toy) and learning the motor skill part (knowing how to use the rake to retrieve the toy) are two different processes with different time courses, since as soon as a trial and error strategy is observed, success arises fairly quickly. Thus, the specific sensorimotor process consisting in trying to use the tool intentionally to retrieve the toy is not protracted. However, in the long process that precedes and during which the affordance of the tool in bringing the toy closer is slowly built, unspecific sensorimotor processes take place, during which several affordances of the tool may be discovered (hitting, displacing, etc.). This continuous exploration of the tool alone or in relation to the toy does not lead to success until the specific affordance of the tool in bringing the object closer is understood, but it allows rapid success once the conceptual aspect is acquired; on the other hand, the conceptual aspect may need many types of exploration to emerge. One possibility is that such exploration of the tool, by increasing the child's dexterity in manipulating the tool (which may thus become more of an extension of the hand) and thereby releaving some of the attentional load associated with manual control, makes the infant readier to imagine a new affordance such as bringing the toy closer. In sum then, we would like to argue that development should not be viewed as a single process (be it concept or skill) that develops linearly one stage after another, but as a process involving reciprocal facilitation between conceptual understanding and skill learning (see Greif & Needham, 2011, for a similar view).

Further investigation is needed to determine whether the accumulation of skills derived from successive episodes of exploration alone explains the relative suddenness of success. This would be compatible with some older studies (Richardson, 1932; Piaget, 1952) indicating that only when conceptual understanding and manual dexterity with the rake has reached a certain level, that infants are suddenly able to intuit the solution and make use of feedback (trial and error) and/or observation of a model to guide their own action. An alternative (or an additional consideration) might be that other mechanisms (e.g. increase in short-term memory, attentional capacity, inhibition) might come into play suddenly due to maturation of the central nervous system or to progress in other domains of behavior. A cross-sectional study bearing on a greater number of infants and further longitudinal investigations done with more frequent testing of infants near the critical transition period are on their way to elucidate this question.

References

Baillargeon, R., Kotovsky, L., & Needham, A. (1995). The acquisition of physical knowledge in infancy. In D. Sperber (Ed.), *Causal cognition: A multidisciplinary debate* (pp. 79-116). New York, NY, US: Clarendon Press/Oxford University Press.

Bates, E., Carlsonluden, V., & Bretherton, I. (1980). Perceptual Aspects of Tool Using in Infancy. *Infant Behavior & Development, 3*(2), 127-140.

Brown, A. L. (1990). Domain-Specific Principles Affect Learning and Transfer in Children. *Cognitive Science, 14*(1), 107-133.

Chen, Z., & Siegler, R. S. (2000). Across the great divide: bridging the gap between understanding of toddlers' and older children's thinking. *Monogr Soc Res Child Dev, 65*(2), i-vii, 1-96.

Connolly, K., & Dalgleish, M. (1989). The emergence of a tool-using skill in infancy. *Developmental Psychology, 25*(6), 894-912.

Elsner, B. (2007). Infants' imitation of goal-directed actions: the role of movements and action effects. *Acta Psychol (Amst), 124*(1), 44-59.

Esseily, R., Nadel, J., & Fagard, J. (2010). Object retrieval through observational learning in 8- to 18-month-old infants. *Infant Behav Dev, 33*(4), 695-699.

Fagard, J., & Lockman, J. J. (2005). The effect of task constraints on infants' (bi)manual strategy for grasping and exploring objects. *Infant Behavior & Development, 28*(3), 305-315.

Greif, M. L., & Needham, A. (2011). The development of human tool use in early life. In McCormack (Ed.), (pp. 51-68).

Keen, R. (2011). The development of problem solving in young children: a critical cognitive skill. *Annu Rev Psychol, 62*, 1-21.

Köhler, W. (1927). *The mentality of apes* New York: Harcourt, Brace.

Koslowski, B., & Bruner, J. S. (1972). Learning to Use a Lever. *Child Development, 43*(3), 790-799.

Leslie, A. M., & Keeble, S. (1987). Do six-month-old infants perceive causality? *Cognition, 25*(3), 265-288.

Lockman, J. J. (2000). A perception--action perspective on tool use development. *Child Dev, 71*(1), 137-144.

McCarty, M. E., Clifton, R. K., & Collard, R. R. (1999). Problem solving in infancy: the emergence of an action plan. *Dev Psychol, 35*(4), 1091-1101.

Mounoud, P. (1993). The emergence of new skills : dialectic relations between knowledge systems. In G. J. P. Salvesberg (Ed.), *The development of coordination in infancy* (pp. 13-46): Elsevier.

Nabeshima, C., Kuniyoshi, Y., & Lungarella, M. (2006). Adaptive body schema for robotic tool-use. *Advanced Robotics, 20*(10), 1105-1126.

Piaget, J. (1952). *The origins of intelligence in the child.* New York: Routledge.

Piek, J. P. (2002). The role of variability in early motor development. *Infant Behavior and Development, 25*, 452-465.

Provasi, J., Dubon, C. D., & Bloch, H. (2001). Do 9- and 12-month-olds learn means-ends relation by observing? *Infant behavior and development, 24*, 195-213.

Rakinson, D. H., & Yermolayeva, Y. (2011). How to identify a domain-general learning mechanism when you see one. *Journal of Cognition and Development, 12*(2), 134-153.

Richardson, H. M. (1932). The growth of adaptive behavior in infants: An experimental study at seven age levels. *Genetic Psychology Monographs, XII*, 195-357.

Sage, K. D., & Baldwin, D. A. (2011). Disentangling the social and the pedagogical in infants' learning about tool-use. *Social Development, 20*(4), 825-844.

Schlesinger, M., & Langer, J. (1999). Infant's developing expectations of possible and impossible tool-use between ages 8 and 12 months. *Developmental Science, 2*(2), 195-205.

Smitsman, A. W., & Cox, R. F. A. (2008). Perseveration in tool use: A window for understanding the dynamics of the action-selection process. *Infancy, 13*(3), 249-269.

Thelen, E. (1995). Motor development. A new synthesis. *Am Psychol, 50*(2), 79-95.

Thelen, E., Corbetta, D., Kamm, K., Spencer, J. P., Schneider, K., & Zernicke, R. F. (1993). The transition to reaching : mapping intention and intrinsic dynamics. *Child Development, 64*(4), 1058-1098.

van Leeuwen, L., Smitsman, A., & van Leeuwen, C. (1994). Affordances, perceptual complexity, and the development of tool use. *J Exp Psychol Hum Percept Perform, 20*(1), 174-191.

van Schaik, C. P., Deaner, R. O., & Merrill, M. Y. (1999). The conditions for tool use in primates: implications for the evolution of material culture. *Journal of Human Evolution, 36*(6), 719-741.

Voulomanos, A. (2011). Are U-shaped developmental trajectories illusory? *Journal of Cognition and Development, 12*(2), 154-158.

Wynn, T. (1985). Piaget, stone tools and the evolution of human intelligence. *World Archaeology, 17*(1), 32-43.

Figures and Tables

Table 1: Different strategies observed during a whole trial (in a few trials two strategies, or more rarely three, occurred in succession)

Typical whole-trial behaviors:

No try (NT)

Grasps tool, gets rid of it, stops being interested (*tool is grasped here without being the focus of attention)*
Looks at toy, looks at tool, looks at adult, doesn't do anything
Refusal

T/T1: Interested mainly to toy and not using tool in connection with toy (level 1)

Points to toy and refuses or ignores the tool
Points to toy, then grasps tool (either spontaneously or encouraged by the experimenter), points again toward toy with other hand
Grasps tool, the toy does not come, does not try again with the tool, may then point to toy with bare hand
Grasps tool, gets rid of it (throws it away, places it on the table), and points to the toy
Looks at toy, pulls tool while looking at toy, stops action with tool when sees that toy does not come, points to toy

T/T 2: Explores the tool but not using it in connection with the toy (level 2)

Points to toy, then grasps tool and plays with it (puts into mouth or rubs, swipes, hits, ,etc. on table)
Grasps tool, interested in tool only (puts into mouth or rubs, swipes, hits, ,etc. on table)
Grasps tool, swipes table with it and sweeps toy away by accident
Grasps tool, plays with it and then rejects it, may be interested in toy again

T+T: Interested in tool in connection with toy (not for Retrieval) (level 3)

Points to toy, then grasps tool (spontaneously or encouraged by the experimenter) and touches or pushes toy with it
Grasps tool, touches or pushes object with tool
Grasps tool (after pointing first to toy or not), points to toy with tool

R1: Interested in tool for Retrieval: trials and error, difficult or half success, or only after demonstration (level 4)

Grasps tool, moves tool, tries to bring back toy, half-success
Grasps tool (after pointing first to toy or not), retrieves or tries to retrieve toy after demonstration
Grasps tool after being encouraged (after pointing first to toy or not), moves tool and retrieves toy with it
Grasps tool (after pointing first to toy or not), awkward movements to bring toy to hand, success
Grasps tool (after pointing first to toy or not), retrieves toy after several attempts

R2: Using tool for Retrieval: Intentional mature success

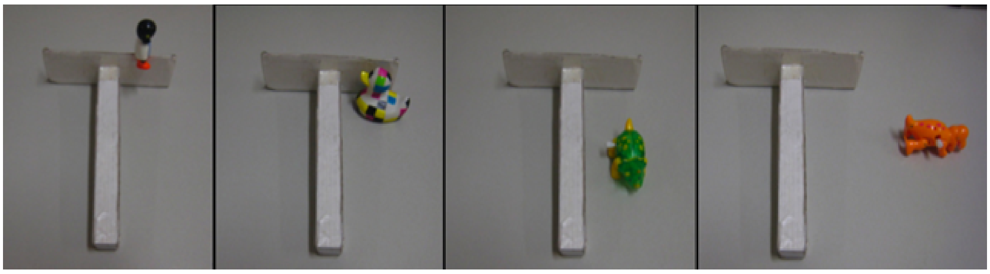
Grasps tool, moves tool to retrieve toy, success

Ambiguous cases (not interpretable, thus no score)

Points to toy, hand on tool more or less by chance, grasps tool, tools with it, toy comes by contingency (at C2 or C3)
Points to toy then grasps tool encouraged by experimenter and brings the toy to hand possibly by contingency (at C2 or C3)
Points to toy, grasps tool spontaneously, retrieves toy possibly by contingency (at C2 or C3)
Grasps tool spontaneously, retrieves toy possibly by contingency (at C2 or C3)

Grasps tool (spontaneously or encouraged by the experimenter) and gives tool to adult or grabs adult's hand

(R1 and R2 were coded for C4 and C5 only, when the tool had first to be displaced laterally to be used.)



C1 C2 C3 C4

Figure 1: Rake and toys in the different conditions of testing from C1 to C4 (C5 is not shown: the toy is placed too far to be reached and the rake is handed directly to the infant)

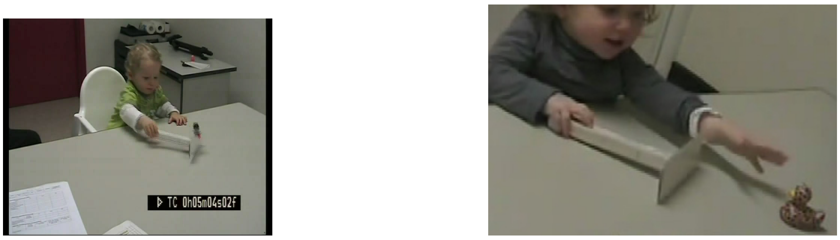


Figure 2: (a) Grasping the rake directly (C1), (b) Reaching/pointing toward the toy (C4)

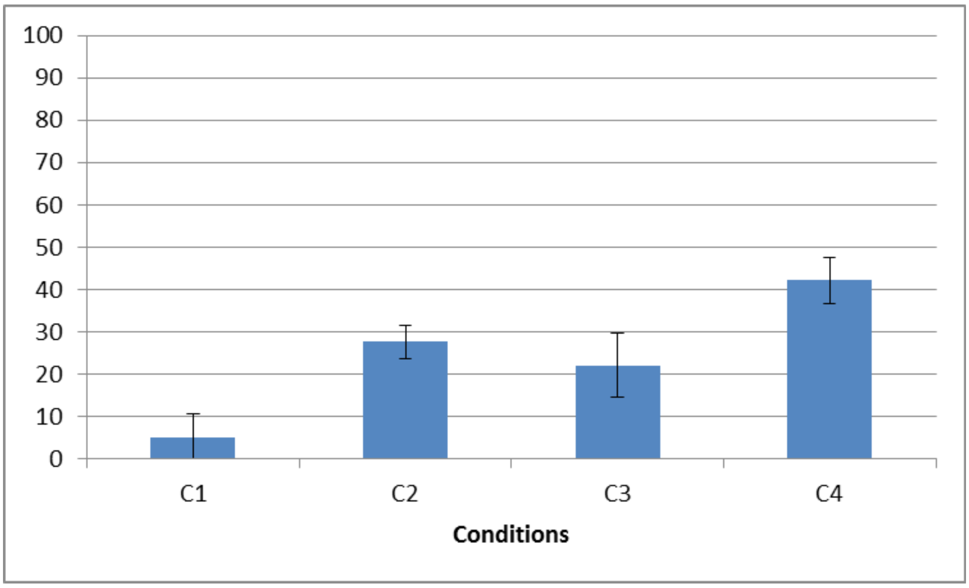


Figure 3: Reaching/pointing toward the object as a first movement as a function of condition

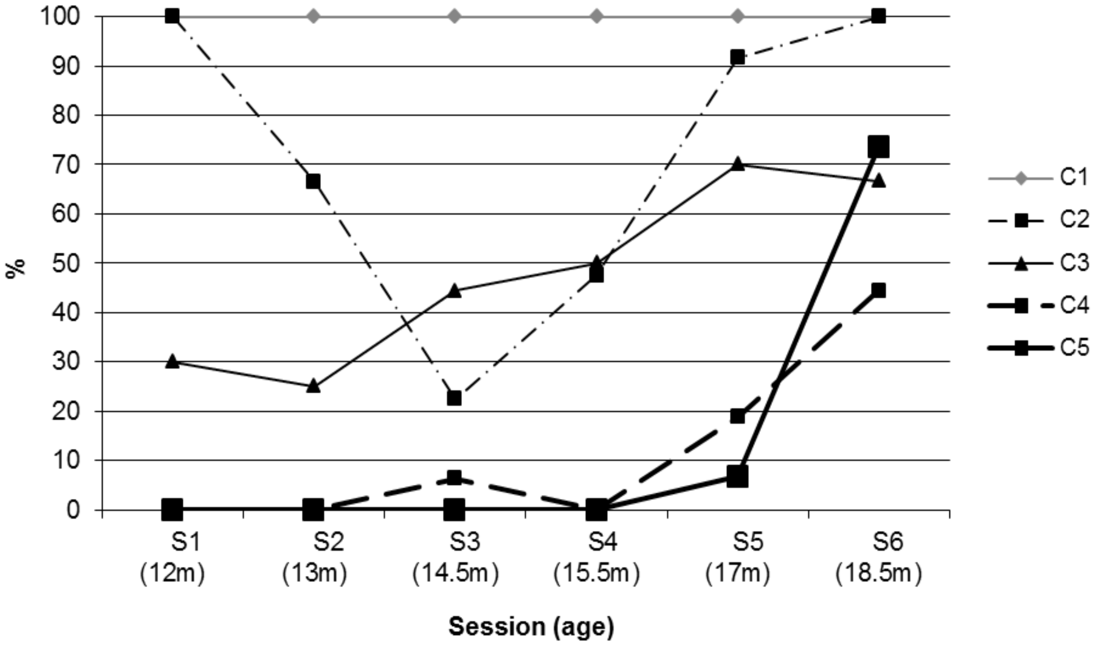


Figure 4: Retrieval of the toy as a function of session and condition

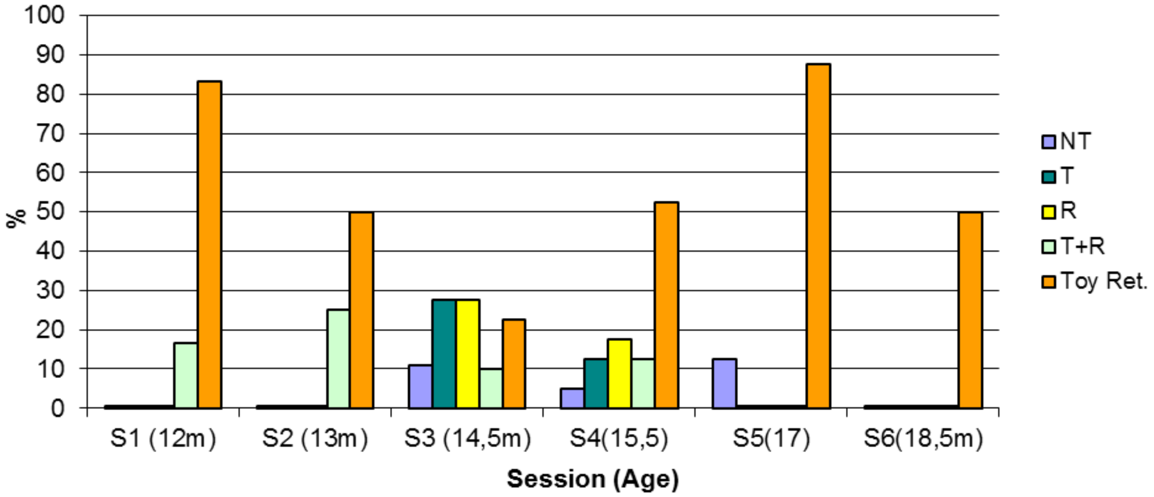
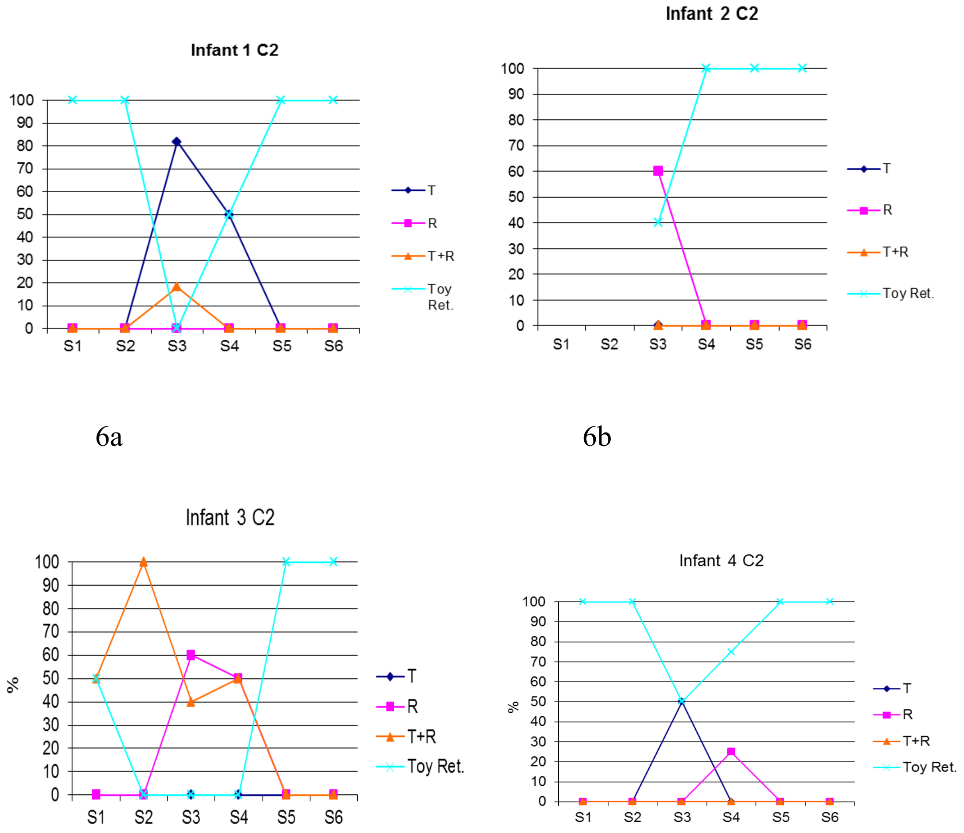


Figure 5: Percentage of the different categories of behavior in C2 as a function of session (Toy retrieval corresponds to A in the first sessions and more often to S toward the last sessions)



6a

6b

6c

6d

Figure 6 a, b, c, d: Individual profiles in C2 (“Toy Ret” corresponds to “A” during the first sessions)

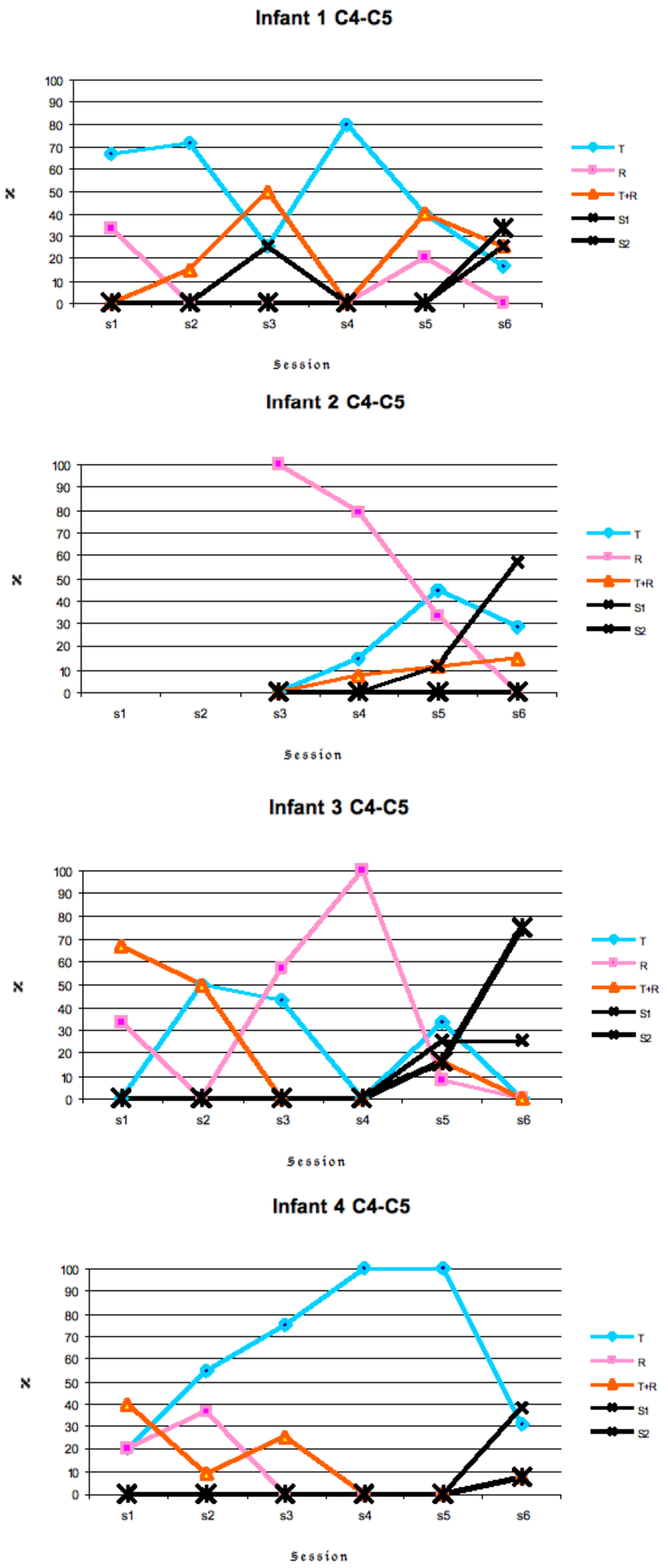


Figure 7a, b, c, d: Individual profiles in C4-C5 (Ambiguous behavior no. 26, “Grasps rake spontaneously and gives it to adult,” is not represented on the figures because of its rarity; thus the total percentage of behaviors may sometimes differ from 100%)

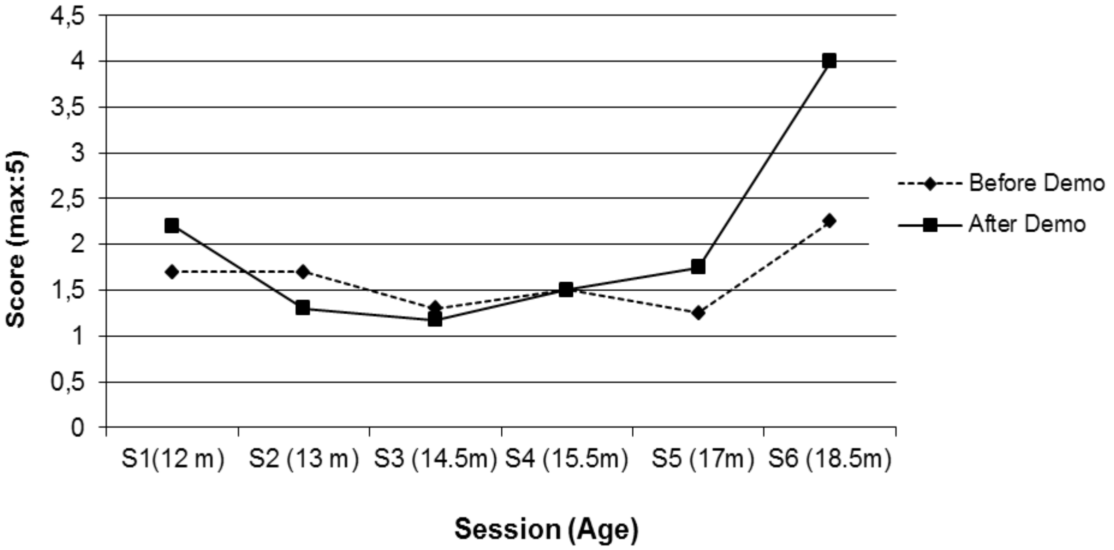


Figure 8: Mean score (all infants, all trials) as a function of session and demonstration in C4 and C5

Videos

Video 1: Infant 1, 15 months, C2: Discarding the tool
Video 2:Infant 3, 12 months, C4: Hitting the toy with the rake
Video 3:Infant 1, 18 months, C5: Trial and error and observational learning before first full success

Appendix 4 – Résume extensif

Bases cognitives, perceptuelles et motrices de l'utilisation d'outils chez le très jeune enfant

Introduction (Chapitres 1 et 2)

L'utilisation d'outils est définie comme la capacité d'agir sur un objet par l'intermédiaire d'un autre objet. On sait que cette capacité se met en place chez l'enfant vers la fin de la deuxième année de vie. Malgré un intérêt grandissant pour l'étude de l'apprentissage de l'utilisation d'outils, les étapes ainsi que les mécanismes sous-jacents de cet apprentissage restent très peu connus. Dans ce travail de thèse, nous avons cherché à savoir à partir de quel âge, dans quelles conditions et grâce à quels mécanismes le jeune enfant apprend à utiliser un outil pour rapprocher un objet hors de portée.

Le premier chapitre de la thèse porte sur les diverses définitions de l'utilisation d'outils qui ont été proposées dans la littérature. La définition la plus courante, tant pour les études sur l'animal non-humain que sur les bébés humains, est celle de Beck (1980, p.10) décrivant l'outil comme « l'emploi externe d'un objet détaché de l'environnement de façon à modifier avec efficacité la forme, la position ou l'état d'un autre objet, d'un autre organisme, ou de l'utilisateur lui même, lorsque l'utilisateur tient ou transporte l'outil pendant ou juste avant de l'utiliser, et qu'il est responsable de l'orientation correcte et efficace de l'outil ». Afin de pouvoir comparer nos données avec celle de la majorité des études de la littérature, c'est donc d'après cette définition que nous avons considéré l'utilisation d'outils chez le très jeune bébé.

Dans un deuxième temps, nous décrivons au sein du premier chapitre les principales utilisations d'outils que l'on retrouve dans la littérature sur l'homme et l'animal non humain. Ces utilisations peuvent être classées selon six catégories : 1) l'extension de la portée (par exemple pour atteindre un objet hors d'atteinte), 2) l'amplification de la force mécanique (par exemple l'utilisation d'un marteau pour casser quelque chose), 3) l'amplification des comportements d'agression ou antagonistes (par exemple l'utilisation d'armes), 4) la collection et le transport de liquides ou de petits objets (par exemple un récipient pour contenir de l'eau, cuillère pour contenir des aliments liquides), 5) l'entretien du corps (par exemple utiliser un objet pour se laver), et enfin 6) la protection d'une partie du corps (par exemple utiliser un bâton pour explorer à travers des flammes). Parmis ces différentes fonctions, celle que nous avons choisi d'étudier tout au long de se travail de thèse est la fonction d’extension de la portée, plus particulièrement celle qui consiste à rapprocher avec un râteau un objet attrayant hors de portée.

Le second chapitre porte sur le développement de l'utilisation d'outils pendant les deux premières années de la vie. Dans une première partie nous commençons par une brève description des étapes du développement des bébés, et plus particulièrement de leurs habiletés manuelles depuis la naissance jusqu'à l'apparition de l'utilisation d'outils. Dès la naissance, les bébés commencent à explorer leur nouvel environnement à partir d'un répertoire moteur comprenant principalement trois catégories de comportements. Ces catégories correspondent aux comportements innés, qui sont des comportements déclenchés par des stimuli externes, aux mouvements spontanés qui ont lieu en l'absence de stimulus particulier, ainsi qu'aux boucles sensorimotrices, permettant au bébé d'ajuster ses mouvements en fonction des feedbacks qu'ils reçoivent de l'environnement. Dès l'âge de deux mois, les bébés commencent à élaborer des mouvements volontaires en direction des objets. Ces mouvements s'affinent au cours du développement, aussi bien en terme de contrôle moteur de la trajectoire, que de vitesse de la main ou d'adaptation à la gravité par exemple. Ces gestes de préhension volontaire permettent à l'enfant une première exploration des objets, qui s'affinera au cours de la première année de vie au fur et à mesure que les gestes de préhension progressent et que le rôle de chacune des deux mains se différencie. Les enfants peuvent alors découvrir les propriétés des objets en eux-mêmes et dans l'environnement, ainsi que les possibilités d'actions avec ces objets (également appelé « affordance » des objets, Gibson, 1966). C'est sur la base de ces nouvelles connaissances sur le monde physique extérieur que les enfants pourront acquérir des notions plus complexes telles que celle du concept d'outil.

La seconde partie de ce second chapitre porte sur la description des études qui ont été réalisées sur l'utilisation d'outils chez le très jeune enfant, principalement entre 12 et 36 mois. Dans un premier temps, nous décrivons le développement de l'utilisation de la cuillère entre 12 et 19 mois. Cependant, nous mettons l'accent sur le fait que la cuillère est un outil un peu particulier, dans le sens où l'enfant a eu de multiples occasions de se familiariser avec son utilisation en observant d'autres personnes s'en servir dans la vie de tous les jours, ainsi qu'en ayant lui même l'occasion de l'utiliser. Malgré ces différences, il est intéressant de rappeler brièvement le développement de l'utilisation de la cuillère dans le sens où c'est généralement le premier outil que les enfants apprennent à utiliser. En particulier, nous décrivons les études de McCarty et al. (1999, 2001) sur le développement de la planification du geste de préhension de la cuillère, en fonction de l'orientation de la cuillère vers la main préférée ou la main non-préférée. Ces études ont permis de mettre en évidence que l'enfant ne planifie pleinement le geste d'utilisation de la cuillère qu'à partir de l'âge de 19 mois. Concernant les recherches sur l'utilisation de l'outil pour rapprocher un objet hors de portée, à notre connaissance, très peu d'études ont été réalisées sur la planification du geste. Cox & Smitsman (2006a) par exemple, mettent en évidence que les enfants ne planifie la préhension de l'outil, et de l'action avec l'outil, qu'à partir de l'âge de trois ans. D'après cette étude, avant cet âge là les enfants sont plus influencés par leur latéralité manuelle lorsqu'il s'agit de prendre l'outil, même si l'utilisation de la main préférée rend l'action plus difficile que si l'enfant avait utilisé l'autre main.

Dans une troisième partie, nous décrivons cinq principaux aspects qui ont été particulièrement étudiés pour l'utilisation de l'outil chez le jeune enfant : 1) les facteurs perceptuels (tels que la couleur, la forme de l'outil, etc) et la relation spatiale entre l'objet et l'outil, 2) la capacité de transférer sa connaissance d'un outil à une autre situation d'utilisation d'outil (par exemple, choisir un outil fonctionnel parmi un choix d'outils dont un seul est fonctionnel), 3) la capacité de planifier une action d'utilisation d'outils, comme déjà évoqué dans le paragraphe précédent, 4) l'effet de la familiarité avec un outil, qui peut rendre moins flexible l'utilisation du même outil dans un contexte inhabituel, et enfin 5) l'apprentissage de l'utilisation d'outils par observation.

Deux des aspects précédemment cités ont particulièrement retenu notre attention dans ce travail de thèse : les relations spatiales entre objet et outils et l'apprentissage par observation. Les études portant sur le premier aspect ont mis en évidence que les enfants ont plus de difficultés à utiliser un outil lorsque celui-ci est séparé spatialement de l'objet à rapprocher, que lorsque l'objet est placé contre l'outil, directement dans la trajectoire entre l'outil et l'enfant (Bates et al., 1980 ; van Leeuwen et al., 1994). D'après Brown (1990), cette difficulté vient du fait que les enfants doivent « anticiper mentalement » la position de l'outil par rapport à l'objet pour pouvoir l'utiliser, ce qui est difficile avant la fin de la deuxième année de la vie. Cependant, ces études ne permettent pas de mettre en évidence les mécanismes impliqués dans la difficulté d'utiliser un outil lorsque l'objet n'est pas proche de l'outil. Le second aspect sur lequel nous nous sommes penchés est l'apprentissage par observation. On sait que tout au long de son développement, le bébé interagit avec le monde extérieur dans un contexte social très riche, et qu'il commence à imiter de nombreuses actions très tôt au cours du développement. Dès 12 mois par exemple, l'enfant est capable d'imiter des actions pour atteindre un but précis, par exemple ouvrir une boîte afin de récupérer un objet qui est à l'intérieur. En ce qui concerne l'apprentissage par observation de l'utilisation d'outils, une seul étude à notre connaissance s'est focalisée sur l'effet de la démonstration sur la performance des enfants dans une tâche d'utilisation d'outils (Fattori et al., 2008). Cette étude a montré que dès 15 mois, certains enfants pouvaient apprendre à utiliser un râteau pour rapprocher un jouet hors de portée après observation de cette action par un expérimentateur. Cependant, le taux de réussite après observation ne dépassait pas les 30%, ce qui reste relativement faible. De plus, cette étude portait sur des actions différentes à chaque groupe d'âge testé (entre 8 et 18 mois), ce qui ne permet pas de savoir à partir de quel âge et dans quelles conditions de démonstration l'enfant est capable d'apprendre à utiliser un outil par observation.

Dans cette revue de littérature de ce chapitre introductif, nous avons mis en évidence le peu d'études sur le développement de l'utilisation d'outils chez le très jeune enfant, et l'absence de connaissances sur les mécanismes impliqués dans cet apprentissage. En particulier, aucune étude n'a été réalisée de façon systématique tout au long du développement, afin de bien situer les étapes et les mécanismes du développement de cette habileté. Dans ce travail de thèse, les études que nous avons menées avaient pour but de compléter ce manque dans la littérature en apportant une description plus systématique de cet apprentissage sur les deux premières années de la vie. Trois aspects ont été plus particulièrement ciblés au sein de ces études : l'utilisation d'outils spontanée au cours du développement, les pré-requis de l'utilisation d'outils, et le rôle de l'apprentissage par observation dans l'acquisition de cette capacité. Le but principal de ce travail de thèse est ainsi de mieux comprendre comment l'utilisation d'outils émerge chez le jeune enfant, et de proposer des mécanismes potentiellement impliqués dans cet apprentissage.

Etapes principales de l'utilisation d'outils (Chapitre 3)

Dans ce chapitre, nous présentons une étude longitudinale sur cinq enfants observés régulièrement durant la deuxième année, ainsi qu'une étude transversale sur 60 enfants vus par groupes d'âges sur la même période du développement. La tâche d'utilisation d'outils consistait à ramener vers soi un objet attrayant à l'aide d'un râteau en carton. Ces deux études ont un protocole commun basé d'une part sur différentes conditions de relation spatiales entre l'outil et l'objet dans un ordre de difficultés croissantes (voir Fig. 1), et d'autre part sur la démonstration d'une condition par un adulte lorsque celle-ci n'est pas réussie spontanément par l'enfant.

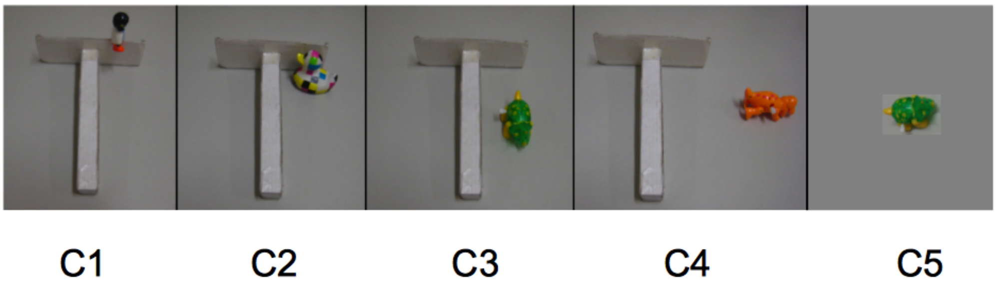


Fig 1. Conditions de relation spatiales entre l'outil et l'objet (de C1 à C5) présentées dans les études longitudinale et transversale.

L'étude préliminaire longitudinale a été initiée par J. Fagard et J.K. O'Regan avant le début de ce travail de thèse (voir Annexes 2 et 3 pour les articles issus de cette recherche). Le protocole de cette étude étant très semblable à l'étude principale de ce chapitre, et le codage ayant été élaboré en collaboration pour les deux exprériences, nous la décrivons brièvement dans une première partie de ce chapitre. Le codage est basé sur 26 comportements observés chez les enfants lorsqu'un objet attrayant est placé devant eux, sur une table, en présence d'un outil placé dans différentes conditions spatiales, comme présenté en figure 1. Ces comportements sont répartis en cinq principales classes de comportements, nous permettant d'attribuer aux enfants un score pour chaque essai, moyenné ensuite par condition et par enfant. Ainsi, un score de 0 est attribué en l'absence d'intérêt pour la tâche, un score de 1 lorsque l'enfant est uniquement attiré par l'objet, un score de 2 lorsque l'enfant s'intéresse principalement au râteau sans le mettre en lien avec l'objet, un score de 3 lorsque l'enfant met en lien l'outil et l'objet sans intention particulière de rapprocher l'objet, un score de 4 lorsque l'enfant tente d'utiliser l'outil pour rapprocher l'objet suivi, éventuellement, d'une réussite maladroite, et enfin un score de 5 est attribué pour une réussite immédiate. Cette échelle de réussite permet d'évaluer de façon plus précise la performance de l'enfant que sur une simple dichotomie entre succès et échec. Elle sera réutilisée par la suite pour toute les études sur l'utilisation d'outils chez l'enfant menées au sein de notre équipe.

Les résultats de cette étude longitudinale sur cinq enfants ont montré principalement que les premiers succès spontanés apparaissent dès 12 mois lorsque le jouet est initialement placé contre le râteau ou dans sa trajectoire. Lorsque le jouet est placé à distance du râteau sur la table, les premières réussites spontanées n'apparaissent qu'à partir de 18 mois. De même lorsqu'un adulte fait la démonstration de cette condition, l'enfant n'est sensible à la démonstration qu'à partir de 18 mois.

La seconde étude, qui a donné lieu aux deux publications présentées dans ce chapitre, a été réalisée sur 60 enfants de 14, 16, 18, 20 et 22 mois (12 enfants par âge). Cette étude a permis notamment de tester de façon plus systématique et contrôlée, ainsi que sur un plus grand nombre d'enfants, les conditions d'utilisation d'outils observées lors de l'étude longitudinale. Nous avons ainsi pu confirmer que les premiers succès pour les conditions où l'objet est contre le râteau, dans la trajectoire entre l'enfant et le râteau, apparaissent dès le plus jeune âge testé. Au contraire, dans les conditions où l'objet et l'outil était séparés spatialement, aucun succès spontané n'était observé avant 18 à 22 mois. De même, dans ces conditions de relations spatiales, les enfants n'ont été sensibles à la demonstration de l'utilisation d'outils par un adulte qu'à partir de l'âge de 18 mois. Ces résultats sont présentés dans le premier article de la thèse, et discutés en termes de changement au cours du développement dans les capacités attentionelles des enfants. Ainsi, avant 18 mois, les enfants pourraient avoir du mal à centrer leur attention sur plusieurs éléments d'une même tâche au même moment. Dans la continuité de cette étude, une analyse plus fine des données nous a permis de mettre en évidence l'âge à partir duquel les enfants planifient leur action pour utiliser un outil. Ces résultats sont présentés dans le deuxième article de la thèse. Nous avons ainsi montré qu'avant 18 mois, les enfants sont principalement influencés par leur préférence pour la main droite lorsqu'ils prennent le râteau. Au contraire, les enfants plus âgés ont plutôt tendance à varier la main utilisée en fonction de la position du jouet par rapport au râteau. Ces résultats mettent en évidence une meilleure anticipation de l'action et de son résultat chez les enfants en phase d'acquisition de la capacité à utiliser un outil.

Étapes développementales prélables à l'utilisation d'outils (Chapitre 4)

Une observation faite lors de ces premières études transversale et longitudinale a retenu notre attention. En effet, lorsque le jouet était fixé directement sur le râteau, tous les enfants étaient capables de le récupérer dès 12-14 mois. Cela suggère que l'enfant a acquis dès 12 mois la notion d'objet composite, c'est-à-dire qu'il sait que deux parties d'un objet qui sont connectées dans l'espace forment un seul et même objet. Lors d'une étude complémentaire, nous avons cherché à savoir à partir de quel âge et dans quelles conditions l'enfant acquiert et utilise cette connaissance. Dans cette étude sur 38 enfants de 6 à 10 mois, en collaboration avec C. Florean (stagiaire pré-doctorale, Bologna, Italie), nous avons pu déterminer que l'enfant acquiert la notion d'objet composite entre 8 et 10 mois. En effet, nous avons observé un changement significatif de la connaissance de la notion de connexion entre objets entre 6 et 8 mois. À partir de 8 mois, on observe une anticipation visuelle vers la partie distale d'un objet composite lors de la prise de sa partie proche, montrant que l'enfant comprend qu'il peut agir sur la partie proche d'un objet composite pour atteindre la partie hors de portée de cet objet. Les résultats de cette étude sont brièvement présentés au début de ce chapitre, et font actuellement l'objet d'un article en cours de préparation, non inclus dans cette thèse.

D'après l'étude sur les objets composites, dès 8 mois l'enfant utilise donc la notion de connexion lorsqu'il interagit avec des objets composites. De même, on sait que dès 10-12 mois, lorsqu'un objet hors de portée est attaché à l'extrémité d'une ficelle à portée de sa main, un enfant tire sur la ficelle avant de chercher à prendre l'objet. Pourtant, lorsque dans une étude pilote nous avons présenté à des enfants de 16 mois un choix de plusieurs ficelles dont une seule était connectée à l'objet, les enfants ne choisissaient pas systématiquement la ficelle connectée. Nous avons cherché à savoir pourquoi même à 16 mois, l'enfant n'utilise pas cette notion de connexion entre objets pour résoudre cette tâche. Pour cela, nous avons réalisé une étude comparant les performances des enfants à cette tâche (condition action) avec leurs comportements visuels vis-à-vis de la scène lorsqu'un adulte résolvait la tâche devant eux (condition vision, voir l'illustration des deux conditions Fig. 2). Cette étude est présentée dans l'article 3 de cette thèse.

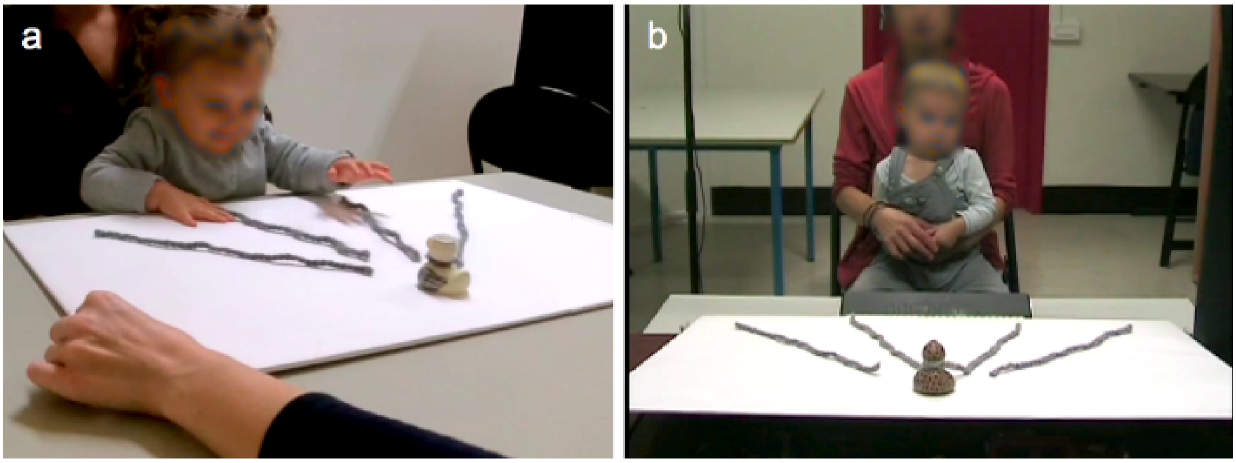


Fig 2. Conditions action (a) et vision (b) de la tâche expérimentale des multiples ficelles. Une seule ficelle est connectée à un objet attrayant hors de portée.

En fonction des performances des enfants pour les quatres essais de la condition action (un essai par position possible pour la ficelle connectée), les enfants étaient répartis en groupes de performance. Ces groupes étaient comparés sur leurs stratégies visuelles en condition vision, à l'aide d'un appareil de mesure de suivi du regard ('eyetracker'). Plus particulièrement, il s'agissait de voir si les enfants qui réussissaient systématiquement la tâche en condition action, étaient capables de visuellement anticiper la ficelle qui devait être tirée pour que l'objet puisse être rapproché, c'est à dire la ficelle connectée. Deux hypothèses sont possibles pour les enfants qui ne réussissaient pas à identifier la ficelle connectée en condition action. La première hypothèse serait que les enfants perçoivent quelle ficelle est connectée, ce qui se traduirait par une stratégie visuelle comparable à celles des enfants qui réussissent en action, mais ne peuvent pas utiliser cette information lorsqu'ils doivent agir eux-mêmes sur cette tâche complexe nécessitant d'inhibier le comportement de tirer n'importe quelle ficelle au hasard. Selon la deuxième hypothèse, si d'autres facteurs que l'inhibition interviennent dans la difficulté des enfants à résoudre cette tâche, nous devrions observer des comportements visuels différents entre les enfants qui réussissent systématiquement, comparés aux enfants qui échouent.

Une première comparaison des différents groupes de performance en action nous permettent de suggérer que les enfants qui échouent à choisir la bonne ficelle pour attraper l'objet pourraient avoir du mal à inhiber le geste spontané de prendre la ficelle la plus proche de leur main préférée. En effet, ce biais n'est observé que dans le groupe d'enfants qui échouent, tandis que le groupe le plus fort des enfants qui réussissent à chaque essai ne présente pas un tel biais. Cela suggère donc, en lien avec la première hypothèse, que les difficultés de certains enfants à résoudre cette tâche sont duse à une capacité plus faible d'inhiber une action chez ces enfants que chez les enfants qui réussissent la tâche. Si seule cette différence dans le niveau d'inhibition entre les enfants des différents groupes de performance est en jeu, dans ce cas nous devrions observer des stratégies visuelles comparables dans tous les groupes, lorsque les enfants n'ont pas à agir eux-mêmes sur le dispositif, et où donc ce facteur d'inhibition n'interviendrait que dans une moindre mesure.

Cependant la comparaison des groupes de performance en condition vision montrent que seuls les enfants qui réussissent à choisir la bonne ficelle, sont également capables d'anticiper visuellement quelle ficelle doit être tirée. Ce résultat rejoint celui d'autres études récentes montrant que la capacité d'un individu d'anticiper visuellement une action réalisée par un autre agent n'est en place que lorsque l'individu est capable de réaliser cette tâche lui-même (correspondant à la « direct matching hypothesis » formulée par Rizzolatti & Fadiga, 2005). Ce résultat suggère que si la performance des enfants à résoudre cette tâche eux-mêmes peut être influencée par leur capacité à inhiber une action spontanée telle que la saisie de la ficelle la plus proche de la main préférée, il semble que ce facteur ne soit pas le seul à l'origine de la difficulté des enfants à résoudre cette tâche.

Pour en revenir à nos résultats sur la difficulté des enfants à utiliser un outil avant la fin de la deuxième année de la vie, il est possible que la capacité d'inhibition de certains gestes soit également un facteur entrant en jeu dans cette tâche. Par exemple, pour résoudre la tâche de l'outil, les enfants doivent inhiber le geste spontané de pointer vers l'objet, afin de prendre l'outil pour rapprocher l'objet. Une analyse approfondie des gestes de pointage dans l'étude transversale de l'article présenté au chapitre 3 semble montrer que le pourcentage d'essais pour lesquels le premier geste est un geste de pointage vers l'objet est semblable à tous les âges, même à 22 mois lorsque l'enfant arrive spontanément à utiliser l'outil pour rapprocher l'objet. Notamment, en condition où l'objet et l'outil sont séparés spatialement, en moyenne un essai sur deux est débuté par un geste de pointage vers l'objet, et ce même lorsque l'enfant a résolu la tâche d'utilisation d'outil à l'essai précédent. Ceci pourrait donc aller dans le sens de l'hypothèse selon laquelle le niveau d'inhibition de l'enfant ne serait pas encore complètement développé à cet âge là, pouvant rendre difficile l'acquisition de l'utilisation d'outils.

Apprentissage par observation (Chapitre 5)

Enfin, nous avons cherché à savoir pourquoi les enfants n'ont pas appris à utiliser l'outil par observation avant l'âge de 18 mois dans nos études. Ce résultat est surprenant puisqu'un enfant est capable d'imiter des actions complexes bien avant cet âge. Une hypothèse possible est que les enfants, ne comprenant pas l’intention de l’expérimentateur, n’ont pas perçu le rôle de l’outil par manque d’anticipation de l’action de l’adulte. Nous avons donc mené une étude sur des enfants de 16 mois, présentée dans l'article 4, afin de vérifier si l'ajout d'éléments montrant l'intention du démonstrateur avant la démonstration aidait les enfants à apprendre plus tôt au cours du développement à utiliser un outil par observation. En effet, on sait que très tôt, le bébé est capable d'identifier l'intention d'un agent en train de réaliser une action (voir Woodward, Sommerville, Gerson, Henderson and Buresh, 2009, pour une revue détaillée de la littérature). On sait également que dès 14 mois, les enfants ont tendance à imiter plus un geste qui a été réalisé intentionnellement, que si ce même geste a été réalisé accidentellement (Carpenter, Akhtar & Tomasello, 1998). Nous avons donc testé 70 enfants de 16 mois dans différentes conditions de démonstrations de l'utilisation d'outils (14 enfants par groupe). Le premier groupe était testé sur sa capacité à résoudre cette tâche spontanément, sans démonstration particulière. Le deuxième groupe était testé après avoir observé une démonstration classique, impliquant la prise de l'outil pour ensuite rapprocher l'objet, comme cela avait été fait dans les études du chapitre 3. Le troisième groupe observait une démonstration précédée d'un pointage vers l'objet pour le démonstrateur, pour signifier son intention d'attraper l'objet, tout en indiquant que l'objet est hors de portée. Ensuite seulement le démonstrateur montrait comment utiliser l'outil. Enfin, les deux derniers groupes testés étaient des groupes contrôles afin de vérifier que si un effet était observé pour la démonstration avec intention, cela était bien lié à la compréhension de l'intention, et non à un simple rehaussement de l'attention de l'enfant vers l'objet ou vers la scène en général. Les résultats montrent en effet que seuls les enfants à qui le démonstrateur a signifié son intention d'obtenir l'objet avant la démonstration améliorent leur performance après la démonstration.

Discussion (Chapitre 6)

Dans les différentes études présentées dans le cadre de ce travail de thèse, nous avons pu dans un premier temps mettre en évidence les différentes étapes de l'utilisation d'un outil pour rapprocher un objet hors de portée chez le très jeune enfant. Nous avons d'abord mis en évidence que dès 12-14 mois, les enfants peuvent résoudre la tâche lorsque l'objet est situé dans la trajectoire directe entre l'outil (un râteau) et l'enfant. Par ailleurs, lorsque l'objet est situé en dehors de la trajectoire de l'outil, les enfants ne réussissent pas à utiliser l'outil pour rapprocher l'objet avant l'âge de 18 mois au plus tôt, que ce soit spontanément ou après observation. Ces résultats sont cohérents avec ce qui a été trouvé dans la littérature concernant la difficulté des enfants à résoudre des tâches comparables dès que l'outil et l'objet sont séparés (e.g. Bates et al, 1980 ; van Leeuwen et al., 1994). Bates et al. (1980) avaient conclu que les enfants étaient capables d'utiliser un outil (tels qu'un rateau, un bâton ou un crochet) dès le début de la deuxième année, et que la difficulté liée à la présence d'un espace entre l'outil et l'objet était liée à une difficulté d'imaginer mentalement le lien entre l'outil et l'objet. Cependant, certaines de nos observations dans les études longitudinale et transversale nous amènent à penser que même lorsque les enfants réussissent dans les conditions les plus simples de relation spatiales entre outil et objet, ils ne comprennent pas la notion d'outil pour rapprocher un objet hors de leur portée. Par exemple, nous avons pu observer que lorsque l'objet était posé dans la trajectoire du râteau, et que l'enfant soulevait le râteau au lieu de ratisser, ne permettant donc pas de rapprocher l'objet, l'enfant se débarrassait généralement rapidement du râteau, devenu 'inutile', et pointait vers l'objet sans chercher à le réutiliser. Selon notre interprétation, les conditions où l'objet et l'outil sont dans la même trajectoire ne permettent pas de montrer que l'enfant a compris la fonction de l'outil, puisque l'enfant peut rapprocher l'objet par hasard simplement en tirant sur le manche du râteau, permettant ainsi d'entraîner l'objet vers soi par 'contingence spatiale'. Ainsi, nous déduisons que seules les conditions dans lesquelles l'objet et l'outil sont séparés dans l'espace permettent d'évaluer si l'enfant a compris la notion d'outil.

Dans un deuxième temps, nous discutons des mécanismes susceptibles d'être impliqués dans l'émergence de la capacité à utiliser un outil tel qu'un râteau ou un bâton pour rapprocher un objet hors de portée chez le jeune enfant. A partir des différentes études que nous avons menées dans ce travail de thèse, plusieurs facteurs semblent être impliqués dans la difficulté à utiliser un outil.

Le premier facteur concerne ce que l'on appelle les fonctions exécutives, permettant à l'enfant d'agir de façon flexible et adaptée au contexte qui lui est présenté. Notamment, la planification de l'action et l'inhibition de gestes spontanés sont deux composantes majeures des fonctions exécutives. L'utilisation d'outil est une action complexe qui nécessite d'être décomposée en plusieurs phases : 1) identifier le but, c'est à dire d'attraper l'objet, 2) pouvoir mettre ce but de côté momentanément afin de 3) prendre l'outil, 4) de diriger l'outil vers l'objet et de le placer dans des conditions permettant ensuite de rapprocher efficacement l'objet. Dans le second article présenté dans le chapitre 3, nous nous sommes plus particulièrement intéressé aux phases 3 et 4, puisque nous avons pu mettre en évidence que selon le côté de l'objet par rapport au râteau, le mouvement pour rapprocher l'objet était très souvent influencé par la main qui prenait le râteau. De même, nous avons déjà évoqué, dans un paragraphe précédent, la possibilité que le niveau d'inhibition des comportements spontanés tels que le pointage vers l'objet était également susceptible d'influencer la performance des bébés dans la tâche d'utilisation d'outils.

Un autre facteur qui pourrait être à l'origine de la difficulté des enfants à utiliser l'outil est d'origine motrice. En effet, l'utilisation du râteau n'étant pas une action familière, il est possible que les enfants aient du mal à placer le râteau au bon endroit et faire le bon geste de ratissage. Cependant, il est important de noter que de façon générale avant 18 mois, les enfants connectaient très peu l'objet et le râteau. De plus, s'ils les connectaient, les enfants les plus jeunes faisaient rarement de nouvelles tentatives après avoir essayé une première fois d'utiliser le râteau. Ainsi, de notre point de vue, les limitations motrices ne sont pas un facteur suffisant pour expliquer les difficultés des enfants à utiliser un outil. Il est possible cependant que la difficulté motrice de la tâche induise un traitement partagé entre les processus cognitifs et moteurs, ce qui pourrait impliquer une baisse du traitement cognitif de la tâche chez l'enfant.

Le dernier facteur que nous évoquons dans cette discussion est l'apprentissage par observation de l'utilisation d'outils. Nous avons pu montrer que l'enfant n'apprend à utiliser un outil par observation qu'à partir de l'âge de 18 mois. Nous avons également mis en évidence que cet apprentissage est possible avant 18 mois si on ajoute lors de la démonstration des informations permettant de mieux identifier l'intention du démonstrateur. On sait que l'enfant évolue dans un milieu social qui joue un rôle très important dans l'apprentissage, comme celui de l'utilisation de la cuillère par exemple. Ainsi, il est possible que si l'enfant était plus souvent exposé, dans la vie de tous les jours, à d'autres personnes réalisant ce type d'utilisation d'outil pour rapprocher des objets hors de portée, ce comportement se développerait peut-être plus tôt chez le jeune enfant. Et en effet, c'est ce que suggèrent les résultats d'une étude réalisée en dehors du cadre de cette thèse (Somogyi, Ara, Rat-Fischer, O'Regan & Fagard, soumis), pendant laquelle des enfants de 14 mois ont été régulièrement familiarisés avec un adulte utilisant un râteau dans des contextes de la vie courante, pendant 6 semaines. Dès l'âge de 16 mois, ces enfants avaient de meilleures performances dans la tâche d'utilisation d'outil que les enfants qui n'avaient pas eu de familiarisation, ou des enfants qui n'avaient eu qu'une familiarisation manuelle avec le râteau, mais sans démonstration particulière de son utilisation.

En conclusion de ce travail de thèse, nous avons tenté de comprendre quand et comment la capacité d'utiliser un outil pour rapprocher un objet émerge chez le bébé. Nous avons décrit les étapes développementales de cet apprentissage durant la seconde année de vie. Nous avons proposé des mécanismes de bases susceptibles d'influencer la performance des enfants, tels que des mécanismes d'inhibition, de planification de l'action et d'apprentissage par observation. Ce travail de thèse est innovateur dans le sens où, avant cela, la trajectoire développementale de l'apprentissage de cette capacité n'était pas claire. Dans la continuité de cette thèse, de nombreuses recherches restent à mener pour mieux comprendre les mécanismes responsables de l'émergence de l'utilisation d'outil. En particulier, il nous semble important de mener des études longitudinales, permettant de suivre les mêmes enfants sur une période de temps donnée, afin d'avoir une meilleure vision de la façon dont des comportements complexes tels que l'utilisation d'outils se développe au cours de l'enfance. Par ailleurs, l'un des challenges actuels pour les psychologues développementalistes est de réaliser ces recherches en collaboration avec des roboticiens du développement. Depuis récemment, la robotique développementale a tenté de mettre en place des systèmes artificiels qui développent de façon autonomes des habiletés telles que l'utilisation d'outils (voir par exemple la thèse de Stoytchev, 2007). Une étroite collaboration entre ces deux domaines de recherche permettrait d'une part d'essayer de comprendre comment de telles habiletés peuvent être apprises par des robots qui n'ont pas été entièrement programmés à l'avance. En contrepartie, la robotique développementale pourrait tester, sur des systèmes artificiels, les mécanismes identifiés par les études expérimentales sur le développement de l'enfant, afin de vérifier la validité de ces mécanismes.