Comparison of active and purely visual performance in a multiple-string means-end task in infants

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Abstract: The aim of the present study was to understand what factors influence infants' problem-solving behaviours on the multiple-string 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 to the desired object. We investigated whether this difficulty is related to infants' ability to inhibit their spontaneous immediate actions by comparing active and purely visual performance in this task. During the first part of the experiment, we assessed the ability of infants aged 16 to 20 months to solve the multiple-string task. The infants were then divided into three groups based on performance (a "failure" group, an "intermediate" group, and a "success" group). The results of this action task suggest that there were differences in infants' performance according to their level of inhibitory control of their preferred hand. In the second part of the experiment, the three groups' predictive looking strategies were compared 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 suggests that inhibitory control was not the only factor influencing infants' performance on the task. Furthermore, the data support the direct matching hypothesis (Rizzolatti & Fadiga, 2005), according to which infants need to be able to perform actions themselves before being able to anticipate similar actions performed by others.

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Keywords

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1. Introduction

Physical properties of objects and their relations to other objects are detected very early in infancy. Studies using visual habituation paradigms have shown that abilities such as identifying an object's 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 studies where infants' understanding is probed by investigating their ability to act, 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. Some 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 infants did not immediately succeed in choosing to pull the attached string among three strings aligned toward the object at 14 months. According to the author, infants at this age need to succeed with fewer strings before solving the situation with more strings. In an exploratory study on 14 infants aged 16 months (unpublished data), we also observed that infants rarely chose the correct string among a set of four including three non-connected strings. 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 possibly influencing infants' performance at the task is inhibitory motor control. Infants presented with multiple strings have to inhibit motor responses of pulling the strings, in order to choose the correct string. In the literature, inhibitory motor control is reported to develop between 8 and 12 months of age in situations involving object retrieval or detour reaching (Diamond, 1991). Inhibiting this natural response may be that much more difficult, given the complexity of the multiple-string task, involving (1) scanning the multiple-string 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. 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' actual physical performance on the multiple string-pulling task with their looking behaviour during passive observation of the experimenter accomplishing the task. 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, 2013, 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 behaviour 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 string 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 in solving the string problem, then we expected to find differences in looking strategies, at least between the failure group and the success group.

2. Methods

2.1 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 distributed over all three age groups), 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.

2.2 Design and materials

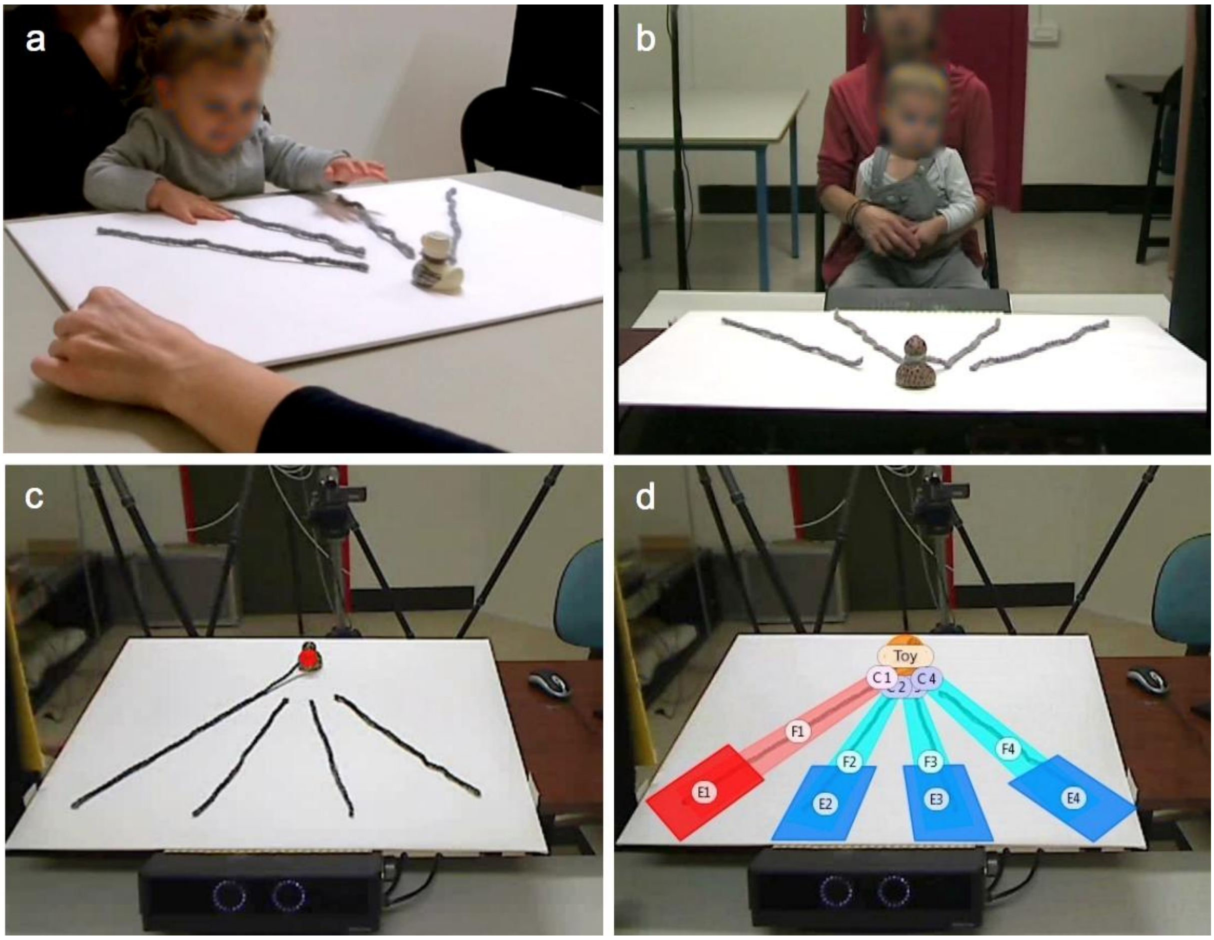

Figure 1. Illustration of the two experimental tasks. (1a) Infant performing the action task. (1b) infant looking at the scene in the vision task (front camera). (1c) View of the vision task from the scene camera, above the subject's head. (1d) View of the four areas of interest (AOIs): E = string-end, 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.

2.2.1 Action task (Figure 1a)

The task was presented on a solid white cardboard panel (50 cm x 70 cm) which the experimenters could slide from their side of the table toward the opposite side, to 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 reach of the infant, 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.

2.2.2 Vision task (figure 1b, c, d)

The scene for this task was laid out on the same cardboard board as in the action task. The board was again placed in front of the infant, but at a distance of approximately 70 cm 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 larger distance was calculated trigonometrically so that, taking into account the larger distance between the board and the infant, and the inclination of the board, to the child the gap appeared to be the same as in the action task. 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 cardboard 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.

The "scene" eye-tracking design was set up once at the beginning of the whole study in the Tobii Studio program. The position of the cardboard scene relative to the scene camera was verified within Tobii Studio before each testing session, to make sure that the scene camera had not been moved accidentally between two subjects. The calibration of the Tobii eye-tracker was performed immediately before the vision task and lasted between one to two minutes. A small toy was held by the experimenter successively at 5 different calibration positions, one at each corner and one in the centre of the scene (marked on the scene by a light cross, not visible from the distance of the infant). The toy was either a small bell that the experimenter could shake, or a small plastic cat, with a button on which the experimenter could press to make the cat miaow and light its eyes, so that the look of the infant was attracted toward each calibration point successively. If the first calibration failed because of the infant's inattentiveness, a second calibration was performed and the toy was replaced by the second object.

2.3 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. This is an important point, as infants needed to know that the desired toy was out of the experimenter's reach, and that it could be retrieved by pulling one of the strings.

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 infant from seeing the connection through a simultaneous movement of the toy and the connected string. The test began when the opaque screen was removed.

In the action task, the board was first presented out of the infant's reach, to prevent the infant 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, the infant was allowed to play with it for about one minute. If the infant 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 restrain their infant by gently holding their chest and arms during the task (see Fig. 1b). Again, each trial was prepared behind 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 from behind the opaque screen toward the calibrated position, the object and its connection to one of the four strings were covered by an opaque box to prevent infants from seeing the connection before the cardboard panel was in the calibrated position. Then, the experimenter went to the child's left side and removed the box. The experimenter's position (left or right) relative to the side of the infant could not be randomised because of the lack of space on the right side, due to the presence of the USB camera stand. For this reason, we controlled for the presence of an effect of the left position of the experimenter 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 attracted 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 on the lap of one of their parents, in front of the test table. The attractive toy was always presented at the same position on the board, out of reach of the infant, 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 randomised between the four trials across all infants, 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.

2.4 Data Analysis

2.4.1 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 done independently of the infants' age (16, 18 or 20 months). Even though more of the 20-month-olds succeeded at the task than the younger infants, there was a great deal of age variability in each performance group, as we will see in the Results section. Moreover, because the purpose of this work was not to evaluate age differences, we chose 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%.

2.4.2 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 panel). 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.

3. Results

3.1 Action task

3.1.1 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 between ages. In the following section we give the mean age for each performance group.

3.1.2 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

3.1.3 Distribution of handedness

For the handedness test, the laterality index was calculated as follows: [Nb of right hand grasps (HG) - nb of left HG]/[Nb of right HG + nb of left HG + nb of bimanual HG]. Based on the laterality index (LI), infants were categorised as right-handed ($LI \geq .5$), left-handed ($LI \leq -.5$) and non- lateralised ($-.5 < LI < .5$). The overall distribution of handedness was 54% right-handed infants (n=22), 7% left-handed infants (n=3), and 39% non-lateralised infants.

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-lateralised	Right-handed
1	15	1 (6.7%)	7 (46.7%)	7 (46.7%)
2	13	2 (15.4%)	5 (38.5%)	6 (46.1%)
3	13	0 (0%)	4 (30.8%)	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, and, for example, right-handed infants might express a bias toward the string at Positions 3 or 4 (see Fig. 1). Given the same distribution of handedness among the three performance groups, a difference in such bias between groups (as we will see below), should not be caused by differences in handedness between the groups.

3.1.4 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 in 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 the majority of infants were right-handed (54% of infants against 7% of left-handers). At least right-handed 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, right-handed 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-lateralised 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, we observed significant differences between performance groups. Figure 2 illustrates the performance of infants from each group by string position.

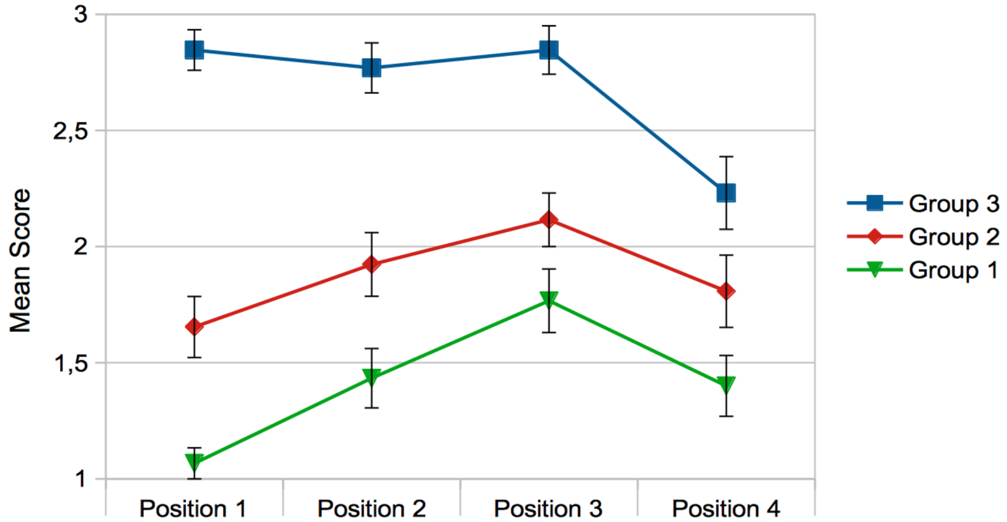

Figure 2. Mean score for each position of the connected string by group. Error bars give standard error.

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 occurred 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.

3.1.5 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 ($F_{6,114} < 1$).

3.2 Vision task

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 explored 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.

3.3 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 groups. In the first paragraph we analyse 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 3.3, the dependent variable is the difference between the percentage of fixation duration (%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 a between-subjects variable. To control for an 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. Positive values indicate that the mean looking time was higher toward the connected string's AOI than toward the AOIs of the non-connected strings. Negative values indicate that infants looked less at the connected string areas than at the non connected areas. 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) *****

3.3.1 Looking time at the scene and the AOIs as a function of performance group

Before analysing the differences between connected and non-connected areas between each performance group, we need to assess that infants from all groups had similar opportunities to look at the whole scene, as well as the toy and string areas. 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.

3.3.2 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.

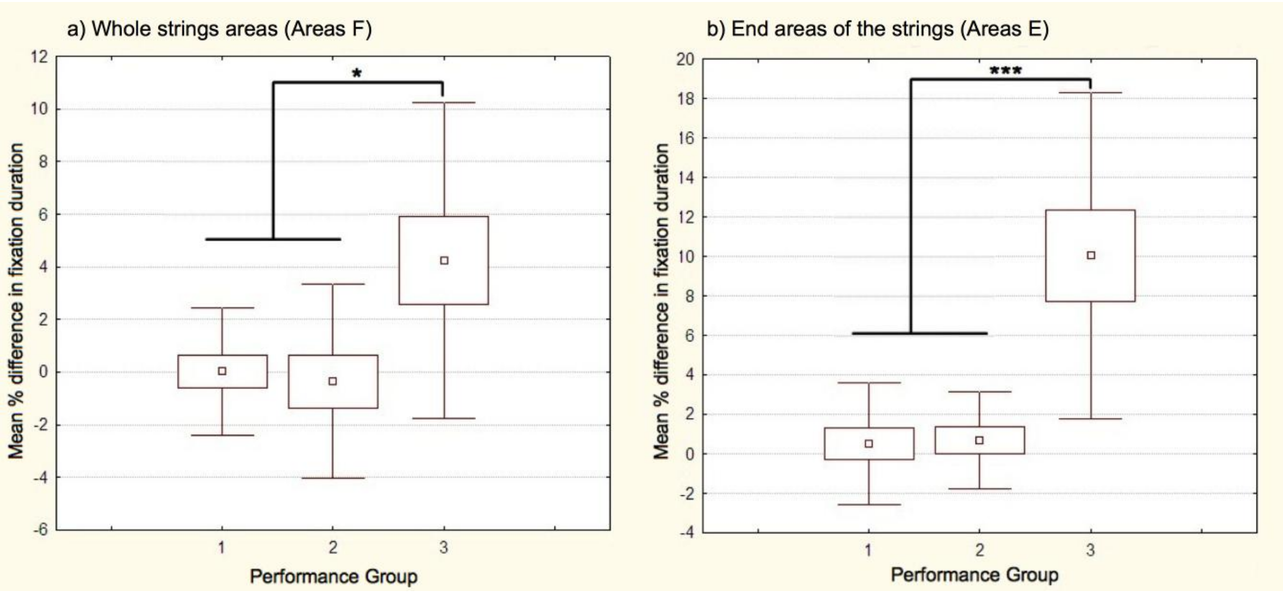

Figure 3. a) Mean percentage fixation duration difference between connected and non-connected whole strings, by group. b) Mean %FD difference between the end areas of the the connected versus non-connected strings, by group. Dots correspond to mean, boxes to standard error, and whiskers to standard deviation. Significance level: * <.05, ** <.01, ***<.001.

3.3.3 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 ($F_{6,114} = 1.27$, $p = .28$, $\eta^2 = .06$).

3.3.4 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 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 ($F_{6,114} < 1$).

3.3.5 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 (AOIs F) with trials (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 (AOIs C) ($F_{3,114} = 1.25$, $p = .29$, $\eta^2 = .03$), 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 (AOIs E) ($F_{3,114} < 1$), 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.

4. 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 action task are discussed first, followed by the differences in visual behaviours between performance groups.

4.1 Infants' performance on the multiple-string task

The results of the “action” part of the study showed that efficient performance at the multiple-strings task does indeed develop late in the 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, although 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. Taking only the results from the action part however does not necessarily indicate that infants are not able to identify which string has to be pulled. As specified by Diamond (1991), "cognitive development can be conceived of, not only a progressive acquisition of knowledge, but also as the enhanced inhibition of reactions that get in the way of demonstrating knowledge that is already present" (p. 67). In a study investigating the concept of gravity in a multiple-tube task in children aged 2- to 4-years, Hood (1995) drew similar conclusions. The task consisted in finding a ball that was dropped into one out of three opaque tubes, interwoven with each other to produce a visuospatial maze, in which the ball fell diagonally rather than vertically. Hood found that the youngest children were not able to inhibit the prepotent response of searching directly under the tube (named the “gravity error”), instead of going for the correct location following the diagonal path of the tube. However, Hood noted that after children had made the incorrect prepotent response, they were immediately able to make the correct response on their second choice. Another choice situation with blocks and holes was studied by Örnkloo & von Hofsten (2009) who found that choice substantially increases the difficulty of the task. Besides the ability to inhibit an incorrect choice, the authors cite author factors that may be responsible for incorrect choices before a certain age, such as the systematic examination of the objects involved in the problem, and a working memory that cannot handle several items at a time.

In our task, it is possible that besides the differences in inhibitory control between groups, other factors influence infants' response to the multiple strings problem. A way to verify this was 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.

4.2 Comparison between vision and action

4.2.1 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 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 of the 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 one's own actions develops very early in infancy. Infants as young as four months 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 3D design was probably not precise enough to precisely distinguish looking at these two areas, which were very close together. It is quite probable that the infants identified the connection using peripheral vision during the visual exploration of the toy area, a fact that could not be recorded by the eye-tracker. However, the fact that we were not able to accurately measure the infants' looking behaviour toward the connection area per se does not diminish 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.

4.2.2 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, 2013, Gredebäck & Kochukhova, 2010, Falck-Ytter, Gredebäck & von Hofsten, 2006). Gredebäck and Kochukhova (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 that 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 live observational task using a real, 3D scene. In contrast, previous studies, such as the one of Gredebäck and Kochukhova (2010) who 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 were not due to differences in the infants' visual abilities. First of all, infants of all three 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.

4.2.3 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. This result is similar to the findings of Hood (1995) on the multiple-tubes task involving the concept of gravity, described above in section 4.1. Despite a minimum of 5 trials, a majority of children who failed on their first attempt were unable to correct their response from one trial to another, sometimes even never finding the correct location of the ball on the 5 trials, showing that no learning took place. However, in our task as well as in Hood's study, infants were given as many attempts as necessary during each trial, until they retrieved the toy correctly. Thus, not retrieving the toy on the first attempt might not have been costly enough to motivate infants to improve the efficiency of their choice across trials. To control for possible learning between trials, one solution would have been to give infants only one pulling chance before removing the cardboard panel with the strings. As it was not the main purpose of this study to assess infant's ability to learn over trials, we chose to give them the opportunity to retrieve the toy on every trial. In this way, we tried to prevent demotivation after unsuccessful trials, which may have possibly resulted in lower attentiveness during the vision task.

In the vision task, even on seeing several demonstrations of the successful performance of the 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 rake task in which the rake is spatially separated from the toy (Rat-Fischer, O'Regan & Fagard, 2012a; O'Regan, Rat-Fischer & Fagard, 2011). Even if they happen to fortuitously succeed in retrieving the toy, 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 of the string pulling task might be explained in relation to infants' very poor ability to learn tool use from observation at that age (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-month-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 similar information, such as showing the experimenter's intention to retrieve the toy before pulling the connected string, could enhance infants' ability to predict which string has to be pulled.

4.3 General conclusion

This work aimed to understand what factors influenced infants' problem-solving behaviour 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), proposing that infants' predictive behaviour on an observed action is only present if infants are able to perform that action themselves.

A potential criticism of the current study is that the action part was always run before the vision part. One might think that a more balanced design would have been to run another group that was presented with the visual task first. Indeed numerous studies with this kind of counterbalanced design have investigated the effect of early experience on object or action visual exploration, by comparing a group of infants with previous experience and a control group without experience. Needham and colleagues for example, have in this way conducted a series of studies investigating the effect of early pre-reaching experience with “sticky mittens” on infants' perception of objects and others' actions (e.g. Needham, Barrett & Peterman, 2002; but see Woodward et al., 2009, for a review). Another example is the study of Hauf, Aschersleben & Prinz (2007), who investigated how action production with objects influenced action perception with similar versus novel objects. The authors show that agentive experience with objects enhances interest in the actions of other people with the same object. These types of studies however answer a completely different question than the one investigated here. In our study, we did not assume that before coming to the lab, infants had no previous experience with strings. On the contrary, we expected most infants to have encountered situations in which objects were connected to strings in their everyday life. Also, if infants in our study had not being given the opportunity to familiarise with the task first, they might not have understood the reason why the experimenter was pulling on the string to retrieve the out-of-reach object instead of taking the object directly with the hand. As already mentioned in the methods section of the paper, the action task was thus always presented first, to ensure that the infants had understood the task when measuring their looking behaviour during the vision task.

The present results show converging evidence across looking and reaching tasks, contributing to the debate about the emergence of understanding and reasoning about simple physical events in infancy. The debate refers to the question of whether the understanding of physical causality is present in infancy well before infants act consistently in goal-directed actions (e.g. Leslie, 1988; Baillargeon, 1994) or whether such understanding is progressively built up from infants' sensorimotor experience with the physical world (e.g. Piaget, 1936/1952). Most studies trying to disentangle the two hypotheses have compared infants' ability to solve a task involving a particular concept (e.g. solidity, height, continuity of objects) with their expectation when observing a scene involving the same concept, using a violation-of-expectation (VOE) paradigm (Spelke, 1985) or a habituation-paradigm to assess novelty preference. One concept that has been investigated is the notion of supporting object: when do infants understand that an out-of-reach toy standing on a piece of cloth can be retrieved by pulling the cloth in reach? According to researchers using the VOE paradigm, infants understand the notion of object support very early in their first year of life, even if they do not act on this knowledge (e.g. Baillargeon, 1994). This is one example of many studies using VOE have often shown a discrepancy between the age at which infants appear to formulate expectations of objects close to mature physical reasoning, and the age at which older infants and children are able to use the same expectations (see Mash, Novak, Berthier, Neil & Keen, 2006 for a review). In contrast, when using a habituation-paradigm, Sommerville and Woodward (2005) showed that knowledge about the ultimate goal of the experimenter ('retrieving the out-of-reach toy', and not only 'retrieving the cloth') developed in parallel with the ability to planfully solve a similar sequence of actions. Although our own study does not measure looking preference for one situation over another as in Sommerville & Woodward's study, the results of these two means-end tasks are quite similar, suggesting that action representations and action production are closely linked and develop in parallel.

A striking aspect 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. Knowledge of 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, Rat-Fischer & O'Regan, 2013; 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 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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***Highlights (for review)**

Title of the paper

Comparison of active and purely visual performance in a multiple-string means-end task in infants

Highlights

Most 16- to 20-month-old infants have difficulties solving the multiple-string task

One difficulty in solving this means-end task resides in a lack of inhibitory control

Our results comparing action and purely visual performance support the direct matching hypothesis