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Can infants make transitive inferences?

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ABSTRACT

Researchers have long been interested in the emergence of transitive reasoning abilities (e.g., if A > B and B > C, then A > C). Preschool-aged children are found to make transitive inferences. Additionally, nonhuman animals demonstrate parallel abilities, pointing to evolutionary roots of transitive reasoning. The present research examines whether 16-month-old infants can make transitive inferences about other people's preferences. If an agent prefers object-A over B ($A > B$) and B over C ($B > C$), infants seem to reason that she also prefers A over C ($A > C$) (Experiment 1). Experiment 2 provides indirect evidence that a one-directional linear ordering of the three items ($A > B > C$) may have helped infants to succeed in the task. These and control results present the first piece of evidence that precursors of transitive reasoning cognitive abilities exist in infancy.

1. Introduction

The ability to make transitive inferences is an important element of logical thinking (e.g., Breslow, 1981; Piaget, Inhelder, & Szeminska, 1960; Thayer & Collyer, 1978). Making transitive inferences involves learning relationships among objects or entities and reasoning inductively about these relationships. For example, if told that "Jon is taller than Drew, and Drew is taller than Jory" and then asked "who is taller, Jon or Jory," adults can answer "Jon" by reasoning transitively; based on the relationship between Jon and Drew and that between Drew and Jory, they make inferences about the relationship between Jon and Jory.

Researchers have long been interested in the emergence of transitivity reasoning. Piaget was the first one to ask when children can make transitive inferences. In his theory, children's transitive reasoning abilities develop as they engage in flexible and logical thinking at around 7 or 8 years of age

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(Piaget, 1970; Piaget et al., 1960). Accordingly, younger children should have difficulty understanding transitivity since they still reason rigidly. In the previous example, they should be puzzled by the presence of two seemingly conflicting relationships, that is, Drew is both taller and shorter than others. As a result, children cannot integrate these two premises to draw the logical conclusion. Piaget used the inference task to gauge children's transitive reasoning abilities. In the task, children were asked to build a tower of blocks identical in height to one built by an experimenter. The two towers stood on surfaces of different heights, and various sticks were provided. To succeed, children had to spontaneously use the sticks as the intermediate measure of the heights of the towers. For example, the child needed to pick a stick (B), mark the height of the experimenter's tower (A) on the stick, and check if his own tower (C) had the same height as the mark on the stick. If his tower was taller or shorter ($A = B < C$ or $A = B > C$), then he needed to remove or add blocks to get the same height ($A = B = C$). Children younger than 7 or 8 typically failed to do so. Other researchers also reported negative results with young children in various transitivity tasks (e.g., DeBoysson-Bardies & O'Regan, 1973; Murray & Youniss, 1968; Smedslund, 1963).

However, theorists have challenged Piaget's view on cognitive development. Instead of characterizing the difference between younger and older children as a qualitative shift from rigid to more flexible and logical thinking, they propose that cognitive abilities develop more continuously than Piaget thought (e.g., Carey, 1995; Gelman & Baillargeon, 1983; Gelman & Spelke, 1981; Spelke, 1994; Trabasso, 1975; Wellman & Gelman, 1998). In the case of transitive reasoning, many investigations reported preschoolers' success in tasks more straightforward than Piaget's (e.g., Braine, 1964; Bryant & Trabasso, 1971; Harris & Bassett, 1975; Riley & Trabasso, 1974; Trabasso, Riley, & Wilson, 1975). For example, in Bryant and Trabasso (1971), five sticks of different lengths and colors (denoted here as A, B, C, D, and E) were used. During training, 4- to 7-year-old children learned the relative heights of the sticks in four comparison pairs ($A > B$, $B > C$, $C > D$, $D > E$). The sticks were partly occluded so that their lengths were hidden; the children had to remember which colored stick was longer or shorter in a pair. During testing, children were asked to make length comparisons for learned and unlearned (and hence transitive) pairs. Critically, children's transitive comparisons, i.e., AC, AD, AE, BD, BE, and CE, were well above chance level, demonstrating their abilities to make transitive inferences about the sticks' relative lengths.

The task described above differs from Piaget's inference task in several aspects (e.g., Riley, 1976; Riley & Trabasso, 1974). For one, children did not have to discover the premise relationships among the items themselves; instead, they learned the premises through training, which ensured their comprehension and memory of the premises. Task comparisons such as these suggest that preschoolers can demonstrate their transitive reasoning abilities in supportive and optimal conditions (e.g., Thayer & Collyer, 1978). This speaks to the possibility of finding even earlier evidence of transitivity reasoning with age-appropriate methods.

Nevertheless, it remains unclear what accounts for the origins of transitive reasoning abilities. Findings from nonhuman animal studies shed light on this issue. Many investigations report that a wide variety of animal species succeed in transitivity tasks, including chimpanzees (e.g., Boysen, Berntson, Shreyer, & Quigley, 1993), squirrel monkeys (e.g., McGonigle & Chalmers, 1977), lemurs (e.g., MacLean, Merritt, & Brannon, 2008), rats (e.g., Roberts & Phelps, 1994), pigeons (e.g., von Fersen, Wynne, Delius, & Staddon, 1991), pinyon jays (e.g., Paz-y-Miño, Bond, Kamil, & Balda, 2004), and fish (e.g., Grosenick, Clement, & Fernald, 2007). These tasks involve transitivity along physical dimensions, e.g., orders in which images are presented, as well as social dimensions, e.g., linear dominance hierarchies. To illustrate, consider the study by Grosenick et al. (2007). During training, a bystander fish watched paired fights among other fish. For example, fish-A won over fish-B in fighting, thus demonstrating "$A > B$." As such, the bystander was trained on premises "$B > C$," "$C > D$," as well as "$D > E$." During test, when allowed to choose between A and E and between B and D by swimming towards one, the bystander fish was more likely to choose the potential "loser" in the pair, i.e., E and D, respectively. These results suggest that the fish used its observations during training to make transitive inferences about the untrained pairs, AE and BD.

These findings across various nonhuman animal species are consistent with the hypothesis that transitive reasoning abilities may be beneficial for the species' survival and are thus selected by evolution. As shown by the fish study described above (Grosenick et al., 2007), even without being exposed to all possible dyadic interactions, the bystander fish used its transitive reasoning skills to avoid direct competition with strong competitors. It hence saved energy and protected itself from harm.

In sum, preschool-aged children are found to make transitive inferences. Additionally, nonhuman animals demonstrate parallel abilities, pointing to evolutionary roots of transitive reasoning. Together, these findings suggest that precursors of transitive reasoning abilities may be found even before preschool years in humans, for example, in infancy. The present research aimed to examine this possibility.

1.1. How does one succeed in transitivity tasks?

Trabasso and colleagues proposed a linear-ordering hypothesis to explain how one solves transitivity problems (e.g., Trabasso & Riley, 1975; Trabasso et al., 1975). Take the five-stick task (Bryant & Trabasso, 1971) described above as an example. Children may form a linear ordering of all five items (A > B > C > D > E) by seriating the premise pairs during training. They then use this internal spatial representation to respond to test comparison pairs. Two pieces of evidence from studies using six-item tasks (ABCDEF) support this hypothesis; the items differed in several dimensions such as length as well as people's weight, happiness, and niceness (Riley, 1976; Trabasso et al., 1975). First, during training when the adjacent pairs were presented in a random order, the end pairs (AB and EF) were learned first and the central pair (CD) last, suggesting the *construction* of a linear ordering of the items (e.g., Bower, 1971). Second, during test, the reaction time and error rate decreased as the steps between the two items in a pair increased (excluding pairs with end items A or F because they were the easiest; six items allow two-step pairs), indicating the *use* of the linear ordering to provide answers.

Results from nonhuman animal studies also support the linear-ordering hypothesis (e.g., Gillan, 1981; Roberts & Phelps, 1994; Terrace & McGonigle, 1994). In a six-item task with rats (Roberts & Phelps, 1994), the rats were trained to discriminate between two boxes with distinctive odors. They received a reward when they went to box-A as opposed to box-B (hence A > B). In the linear condition, the six boxes were lined up vertically or horizontally in the order from A through F; in the nonlinear condition, the boxes' positions changed randomly or they formed a circle. After learning premise pairs (A > B, B > C, C > D, D > E, E > F), rats were exposed to boxes B and D. The results showed that they went to box B, based on the transitive inference (B > D), but only in the linear condition. Presumably, the nonlinear arrangement during training had made it difficult for the rats to form a linear ordering of the boxes and they were hence unable to use it to make transitive inferences. The present research would also vary how the premise pairs were presented, linearly or not, as well as the spatial arrangements of the items, in an infant transitivity task.

1.2. The present research

In the present study, we used preference attribution to examine transitivity. A preference is defined as a dispositional state that helps explain why an agent chooses a particular goal-object in the presence of another option. The reason for choosing preferences as the target dimension was two-fold.

First, findings from various looking-time studies show that by 3 months of age, infants who watch an agent repeatedly act towards object-A but not object-B behave as though they attribute to the agent a preference for object-A over object-B (e.g., Luo, 2011b; Luo & Baillargeon, 2005; Woodward, 1998). Infants seem to expect the agent to continue acting towards object-A even with the two objects' positions reversed; they respond with prolonged looking when the agent acts toward object-B. In contrast, when the agent is faced with object-A only because object-B is absent or hidden from the agent (but not from infants), infants act as though they recognize that the agent's same actions towards object-A do not suggest a preference. They therefore do not respond with increased attention when the agent later acts towards object-B (e.g., Luo, 2011a, 2011b; Luo & Baillargeon, 2005, 2007; Luo & Johnson, 2009; Sodian, Thoermer, & Metz, 2007).

A recent study (Luo & Beck, 2010) extended these preference-attribution findings to situations involving an agent's preferences for a specific color. After watching an agent point to a red as opposed to a yellow or a black object, 16-month-old infants seemed to recognize that she had a color preference for red. Their responses were thus consistent with their generalizing this color preference to a different context and expecting the agent to choose another red object over a green one; they responded with heightened interest when the agent pointed to the green object.

Built on these results, we designed the following situation to examine whether infants can make transitive inferences about others' preferences. If shown that an agent prefers object-A over object-B and that she prefers object-B over object-C, will infants infer that she also prefers object-A over object-C? In fact, there is strong evidence that transitivity of preferences is an axiomatic assumption underlying adults' decision making process (e.g., Regenwetter, Dana, & Davis-Stober, 2011), contrary to earlier findings (Tversky, 1969). Therefore, finding a positive answer to the question in the present study would inform future research exploring whether infants, like adults, satisfy the transitivity axiom in their understanding about others' preferences. We will return to this issue in Section 4.

As the first attempt to examine early transitive reasoning abilities, the present task was kept simple in that only three objects were involved, and that the objects differed only in color. Given 16-month-olds' success in the color preference task (Luo & Beck, 2010), we tested the same age group in two experiments. Experiment 1 examined infants' looking-time responses in the aforementioned situation. Experiment 2 explored *how* infants might solve such a transitivity problem.

2. Experiment 1

In Experiment 1, the infants first received six *familiarization* trials (see Fig. 1, *linear condition*). In the first three trials, they watched the familiarization event 1. To start, a human agent sat behind and

Fig. 1. Schematic drawing of the familiarization and test events shown in Experiment 1.

between a red football (A) on the right (from the infant's perspective) and a yellow football (B) on the left; the two footballs were otherwise identical. The agent reached for and grasped the red football; she then paused until the trial ended. In the last three trials, infants watched the familiarization event 2 in which the yellow football (B) was on the right and a green football (C) was now on the left. The agent reached in the same direction and grasped the yellow football. Following familiarization, the green football (C) was on the right and the red one (A) on the left. The infants received four *test* trials in which the agent reached for and grasped the green (unexpected event) or the red football (expected event).

If during the familiarization trials, infants encoded the agent's actions as showing that she preferred the red over the yellow football ($A > B$) and that she also preferred the yellow over the green football ($B > C$), they should predict, based on transitivity, that when faced with the red and the green footballs, the agent should choose the red one ($A > C$). Therefore, infants should expect the agent to grasp the red (A) as opposed to the green football (C) during the test trials and hence look reliably longer at the unexpected than at the expected event.

A potential difficulty was that the infants might look long at the unexpected event simply because it was the first time when the agent acted towards the green football (C). To rule out this possibility, we tested infants in a *reversed condition* identical to the linear condition except that the order in which the agent demonstrated her preferences during familiarization was reversed (see Fig. 1, $B > C$ and then $A > B$). If infants in the linear condition responded with heightened interest to the unexpected event because the agent grasped the green football for the first time, those in the reversed condition should respond similarly. However, if the infants' responses in the linear condition were consistent with their having expected the agent to prefer the red over the green football during test based on the premise preferences she demonstrated during familiarization, a different pattern of results should be found. According to the linear-ordering hypothesis described earlier, we reasoned that in the reversed condition, it might be difficult for infants to form a linear ordering of the agent's preferences (red > yellow > green, or $A > B > C$), if they had done so to succeed in the linear condition. They should then be unclear about whether the agent should prefer the red over the green football and hence have no prediction of what the agent should do during test. Therefore, we expected the infants in the reversed condition to look about equally at the expected and unexpected events.

2.1. Method

2.1.1. Participants

Participants were 28 healthy, full-term infants, 15 male and 13 female (M = 16 months, 4 days, range: 15 months, 3 days to 17 months, 29 days). Fourteen infants, 7 male and 7 female, were randomly assigned to the linear condition, and the rest to the reversed condition. Three infants were tested but their data were excluded because one walked away before test, one infant's test looking time difference was 2 *SD*s from the mean of the condition, and one because of observer error. Of the 31 infants, 97% of them were white based on parental report.

2.1.2. Apparatus

The apparatus consisted of a white wooden display box, 182 cm high, 104 cm wide, and 64 cm deep, that was mounted 75 cm above the room floor. The infant sat on the parent's lap and faced an opening (54 cm high × 102 cm wide) in front of the apparatus. A wooden frame covered with white muslin was 60 cm high and 101 cm wide, and it could be pulled up or lowered in front of the opening between trials. The white back wall had a rectangular window (35.5 cm high × 45 cm wide) located 28.5 cm from each side of the apparatus. The agent, wearing a white shirt, sat behind the window. The apparatus floor was covered with khaki-colored contact paper.

The three footballs were covered with red, yellow, and green tape, respectively. Each football was mounted on a small circular base (2.6 cm high and 7.5 cm in diameter) so that it stood upright. The combined height of the football and the base was 24 cm, and the diameter of the football at the widest point was 14 cm.

2.1.3. Procedure

The infant sat on a parent's lap in front of the apparatus. Parents were instructed to close their eyes during the test trials and not interact with the infants. Two naïve observers monitored the infant's looking behavior by viewing the infant through peepholes in large cloth-covered frames on either side of the apparatus. Looking time recorded by the primary observer was used. To assess interobserver agreement during the experiment, each trial was divided into 100-ms intervals, and the computer determined within each interval whether the two observers agreed on whether the infant was or was not looking at the event. Percent agreement was calculated for each trial by dividing the number of intervals in which the observers agreed by the total number of intervals in the trial. For 23 of the 112 infants in the two experiments, only the primary observer was present. Interobserver agreement for the remaining 89 infants in the two experiments averaged 93% per trial per infant.

All infants first received six *familiarization* trials appropriate for their condition. Each trial involved a 2-s pre-trial (in which the agent reached for and grasped a football) and a main-trial (in which the agent paused until the trial ended). Infants in the linear condition saw the red (A) and the yellow (B) football pair in the first three familiarization trials, and the yellow (B) and the green (C) football pair in the last three trials; infants in the reversed condition saw these two pairs in reversed order. Each familiarization main-trial ended when the infant looked away for 2 consecutive seconds after having looked for at least 2 cumulative seconds, or looked for 30 cumulative seconds.

Infants were given two pairs of *test* trials alternating between the expected and unexpected events. The agent grasped the red (A) (expected event) or the green (C) (unexpected event) football during the 2-s pre-trial and paused until the trial ended during the main-trial. The infants in both experiments were highly attentive during the 2-s pre-trials of the familiarization and the test trials ($M = 1.9$). Half of infants saw the expected event first; and half saw the unexpected event first. Two of the 28 infants only contributed one pair of test trials because of fussiness (no second test pair) and observer error (the second test pair could not be used). Each test main-trial ended when the infant looked away for 2 consecutive seconds after having looked at it for at least 5 cumulative seconds, or looked for 60 cumulative seconds.

2.2. Results and discussion

2.2.1. Preliminary analyses

Infants' mean looking times during the familiarization phase did not differ reliably on condition (linear or reversed) or familiarization event (red > yellow or yellow > green), both $Fs(1,26) < .44$.

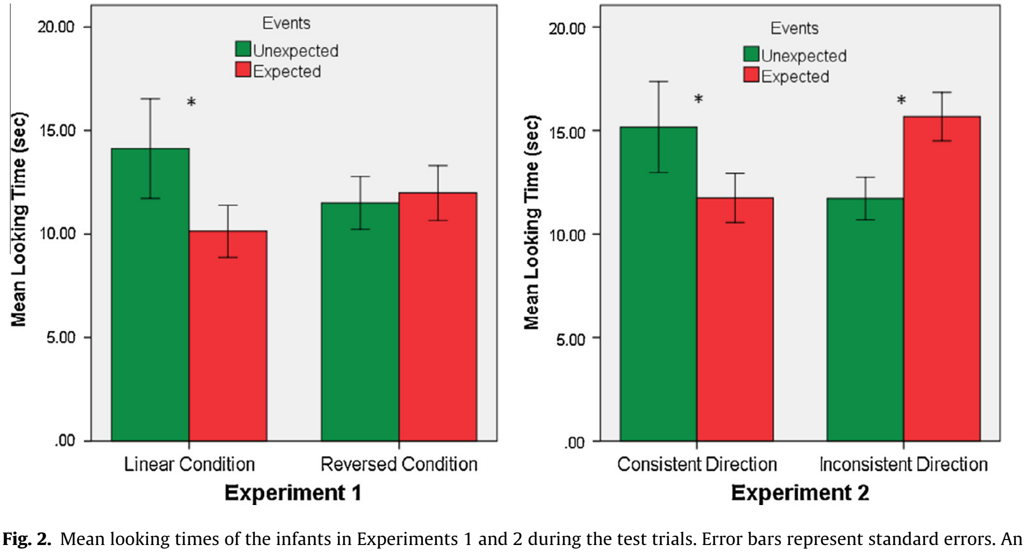

Fig. 2. Mean looking times of the infants in Experiments 1 and 2 during the test trials. Error bars represent standard errors. An asterisk (*) indicates a statistically significant difference ($p < .05$) between infants' mean looking times at the two test events.

However, the condition × familiarization event interaction was significant, $F(1,26) = 4.32$, $p < .05$. This was because infants in both conditions looked longer at the familiarization event presented in the first three trials than that in the last three trials (linear condition: red > yellow event, $M = 15.0$, $SD = 5.0$; yellow > green event, $M = 13.0$, $SD = 6.4$, $F(1,26) = 1.01$, $p > .32$; reversed condition: yellow > green event, $M = 16.9$, $SD = 5.2$; red > yellow event, $M = 13.0$, $SD = 6.2$, $F(1,26) = 3.74$, $p > .06$). Preliminary analysis of the test data revealed no significant interactions involving condition and event (expected or unexpected) with sex and/or order, all $Fs(1,20) < 2.63$, $ps > .12$; the data were therefore collapsed across sex and order in subsequent analyses.

2.2.2. Test outcomes

Infants' looking times in the four *test* main-trials (see Fig. 2) were averaged and analyzed separately in the two conditions. A single-factor repeated measure analysis of variance (ANOVA) with event (expected or unexpected) as the within-subject factor was performed in each condition. Infants in the linear condition looked reliably longer at the unexpected ($M = 14.1$, $SD = 9.0$) than at the expected event ($M = 10.1$, $SD = 4.7$), $F(1,13) = 4.78$, $p < .05$, Cohen's $d = 0.6$. Infants in the reversed condition looked about equally at the two test events (unexpected event: $M = 11.5$, $SD = 4.8$; expected event: $M = 12.0$, $SD = 5.0$; $F(1,13) = .07$, $d = -0.1$). Examinations of individual infants' looking times confirmed these results. Eleven of the fourteen infants in the linear condition looked longer at the unexpected than at the expected event, Wilcoxon signed-ranks $T = 87$, $p < .05$, whereas only six infants in the reversed condition did so, $T = 45$, $p > .63$.

Infants in the linear condition looked reliably longer at the unexpected than at the expected event. These results suggested that they interpreted the agent's actions during familiarization as evidence for her preferences for the red over the yellow football ($A > B$) and for the yellow over the green football ($B > C$). Infants therefore seemed to have reasoned transitively that the agent should prefer the red over the green football ($A > C$). As a result, they responded with heightened interest during test when the agent changed her preference and grasped the green football (C).

In the reversed condition, infants' looking times at the two test events did not differ significantly. These results were consistent with their being unable to infer that the agent should prefer the red over the green football during test ($A > C$). These results ruled out low-level explanations for the linear condition data, because the only difference between the two conditions was the order in which the agent demonstrated her preferences during familiarization.

More importantly, the Experiment 1 results were compatible with previous data supporting the linear-ordering hypothesis described earlier (Riley, 1976; Trabasso et al., 1975). When the agent's two premise preferences were presented linearly, infants succeeded in inferring that the agent should prefer the red over the green football ($A > C$) during test. Otherwise, they failed to make predictions on the agent's actions when she was faced with the red and the green footballs (A and C) in the reversed condition. Unlike the previous research (Riley, 1976; Trabasso et al., 1975), however, the present experiment did not use a six-item task, nor were the premise pairs presented in a random order. The current data therefore could not demonstrate directly that infants might have constructed a linearly-ordered mental representation of the agent's preferences (red > yellow > green; $A > B > C$). Nevertheless, in Experiment 2, we examined how a linearly-ordered lineup of the three items could help infants succeed in a situation similar to that of the reversed condition.

2.2.3. Control results: Experiment 1A

However, a remaining issue was whether infants in the linear condition could have succeeded by using only one of the two premise preferences. That is, when knowing that the agent preferred the red over the yellow football ($A > B$), they might have inferred that she should also prefer the red over a different football (hence, $A > C$) since the red football was the "liked" one. Or, when knowing that the agent preferred the yellow over the green football ($B > C$), they might have inferred that she should also prefer a different football over the green one (hence, $A > C$) because the green football was the "disliked" one. The results of the reversed condition argued against these alternatives: if the infants had attended to only one of the two premise preferences during familiarization, the results would have been positive in both conditions. Nevertheless, we conducted control conditions similar to Experiment 1 in which the infants watched only the familiarization event 1 or 2. In all six trials, the agent chose the red over the yellow football (*AB* condition) or she chose the yellow over the green football (*BC* condition). The test trials were identical to those of Experiment 1. Obtaining negative results would render the alternatives outlined above unlikely.

Participants were 28 infants, 12 male and 16 female (M = 16 months, 3 days; range: 15 months, 2 days to 18 months, 2 days). Fourteen infants, 5 male and 9 female, were randomly assigned to the AB condition and the remainder to the BC condition. Five infants were tested but their data were excluded because of differences in test looking time more than 2 *SD*s from the mean (2), observer errors (2), or being distracted (1). Of these 33 infant, 88% of them were white based on parental report.

The apparatus and procedure were identical to those of Experiment 1 except for the familiarization phase. Four of the 28 infants only contributed data from the first test pair because of observer errors or being distracted, or because the infant refused to look, said ''no,'' and got off from the parent's lap during the second test pair. In the AB condition, eight infants saw the unexpected event first during test.

Infants' mean familiarization looking times did not differ reliably between the two conditions, $F(1,26) = 2.17$, $p > .15$. Infants' looking times in the four test trials were averaged and analyzed by a 2×2 ANOVA with condition (AB or BC) as a between-subjects factor and event (expected or unexpected) as a within-subject factor. No effect was significant (condition: $F(1,26) = 2.46$, $p > .12$; event: $F(1,26) = .63$; condition $\times$ event: $F(1,26) = 3.58$, $p = .07$).

Therefore, separate single-factor ANOVAs with event as the within-subject factor were performed in the two conditions. Infants in the AB condition tended to look *less* at the unexpected ($M = 16.3$, $SD = 10.7$) than at the expected event ($M = 19.9$, $SD = 11.8$), $F(1,13) = 3.88$, $p > .07$, $d = -0.6$. Infants in the BC condition looked about equally at the two test events (unexpected event: $M = 14.0$, $SD = 5.7$; expected event: $M = 12.6$, $SD = 5.1$), $F(1,13) = .56$, $d = 0.2$. Examinations of individual infants' looking times confirmed these results. Five of the fourteen infants in the AB condition looked longer at the unexpected than at the expected event, Wilcoxon signed-ranks $T = 27$, $p > .10$, whereas eight infants in the BC condition did so, $T = 57.5$, $p > .40$.

These control results thus strengthened the Experiment 1 data, in that the infants had considered both premise preferences ($A > B$ and $B > C$) presented during familiarization to determine whether or not the agent should prefer A over C during test. More critically, this extended the previous results on infants' preference attributions. As mentioned in the Introduction, when given evidence that an agent prefers A over B and also A over C (Luo & Beck, 2010), 16-month-olds respond as though they have induced that the agent should also prefer A over D. The positive results of the linear condition of Experiment 1 make clear that when given evidence that an agent prefers A over B and also B over C, infants respond as if they have reasoned that the agent should prefer A over C. The negative results of Experiment 1A suggest that infants cannot make inductive references about agents' preferences based on only one particular piece of information. That is, if an agent prefers A over B, infants have no information to predict whether the agent should also prefer A over a new item or this new item over B. Instead, in the AB condition, infants had the tendency to respond to the direction of the agent's reach, rather than the target of her reach. Infants looked long at the expected event in which the agent reached to the left. In the unexpected event and familiarization event, the agent always reached to the right.

3. Experiment 2

Together, the results of Experiments 1 and 1A suggest that 16-month-old infants make transitive inferences on an agent's preferences (if A > B, B > C, then A > C). If the premises are presented in a reversed order (BC then AB), infants no longer respond as if they reason transitively. These results were consistent with but could not provide direct evidence for the linear-ordering hypothesis. That is, infants might have succeeded in the linear condition by forming a linearly ordered representation (A > B > C) but failed in the reversed condition because this process was disrupted. In Experiment 2, we addressed how we could help infants to succeed in a situation similar to that of the reversed condition.

Two situations have been shown to be useful for forming the linear ordering of items in transitivity tasks. In Bryant and Trabasso (1971), the premise pairs were presented in a linear order during training. This is similar to the linear condition of Experiment 1. In Riley (1976) and Roberts and Phelps (1994), all items were also displayed in a linear order simultaneously. The subjects in these studies made transitive inferences about the relative weight of a person or about which box contained a "positive" (leading to a reward) odor; neither was perceptible from the all-item display. Presumably, the subjects still needed to forge a link between the display they are presented with and their representation of the complete set.

In Experiment 2, we used a linear all-items display. Specifically, the premise pairs were presented in a nonlinear order during familiarization, as in the reversed condition of Experiment 1, infants were then given the opportunity to watch a static display in which the three footballs were lined up based on the agent's preferences, but with the agent absent. Experiment 2 was thus identical to the reversed condition of Experiment 1 except that the display was inserted between the familiarization and the test trials.

In the familiarization trials of Experiment 1, the preferred football in a pair was always on the right. There were two ways to arrange the linear display horizontally. The three footballs, red, yellow, and green, could line up with the red football (*A*) on the right or the left. The ordering of the three footballs

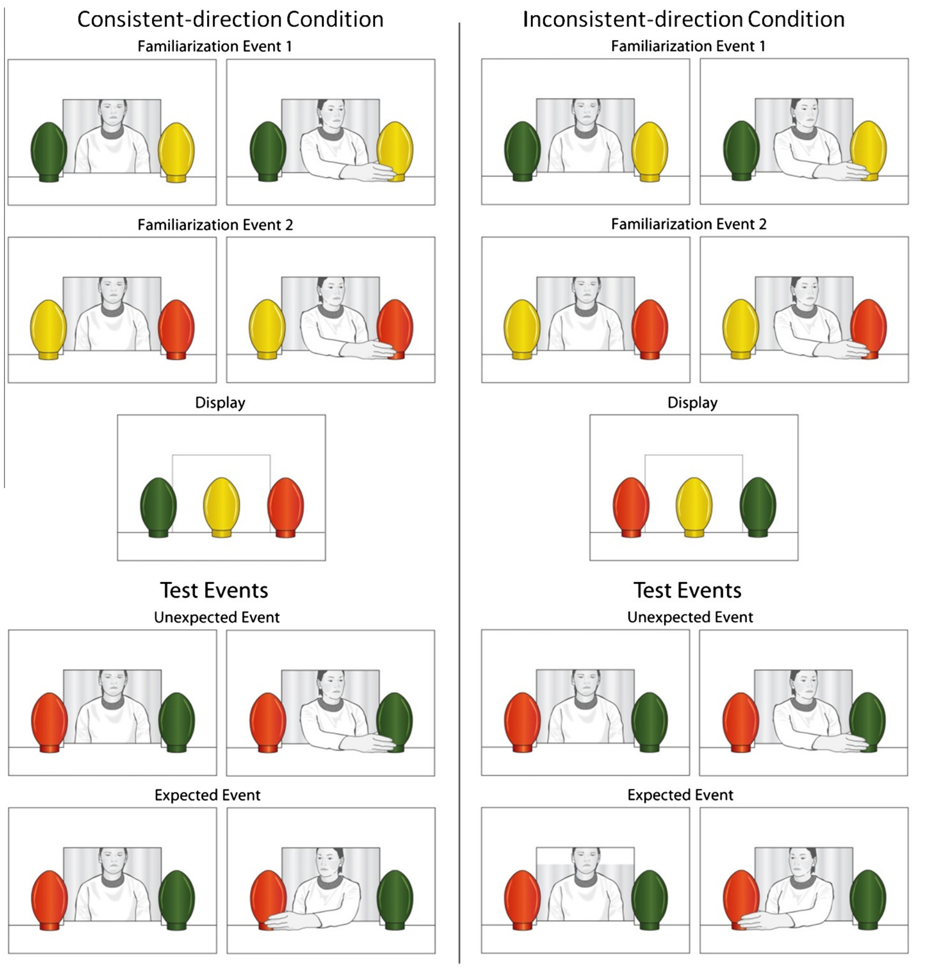

Fig. 3. Schematic drawing of the familiarization, display, and test events shown in Experiment 2 with the preferred football on the right during the familiarization trials.

based on preferences was thus consistent with the spatial arrangement in the former (*consistent-direction* condition; *CBA*) but inconsistent in the latter (*inconsistent-direction* condition; *ABC*) case (see Fig. 3). Conversely, if the preferred football was always on the left during familiarization, the red football (*A*) should be on the left in the consistent display (*ABC*) and right in the inconsistent display (*CBA*). Therefore, four conditions were formed by crossing side (preferred football on the left or right during familiarization) and display (consistent-direction or inconsistent-direction).

If infants could use the linearly-ordered display to infer that the agent liked the red football (*A*) the most and the green football (*C*) the least, positive results should be obtained in all conditions. However, it might be possible that infants were also sensitive to whether or not the spatial arrangement in the linear ordering was consistent with the side the preferred football was on during familiarization. If so, the display in the inconsistent-direction conditions would be unhelpful because the red football (*A*) was not on the preferred side. Therefore, negative results might be obtained in the inconsistent-direction conditions.

3.1. Method

3.1.1. Participants

Participants were 56 infants, 28 male and 28 female ($M = 15$ months, 29 days; range: 15 months, 2 days to 17 months, 28 days). Fourteen infants, with roughly equal numbers of male and female (6, 7, or 8), were randomly assigned to one of the four conditions. Fourteen infants were tested but their data were excluded because of fussiness (4), differences in test looking time more than 2 *SD*s from the mean of the condition (4), observer errors (3), being distracted (2) or inattentive (1). Of the 70 infants, 91% of them were white based on parental report.

3.1.2. Apparatus and procedure

The apparatus and procedure of Experiment 2 were identical to those of the reversed condition of Experiment 1 except that the display trial was added between the six familiarization and four test trials. This display trial ended when the infant looked away for 2 consecutive seconds after having looked for at least 5 cumulative seconds, or looked for 60 cumulative seconds.

Two of the 56 infants completed only one pair of test trials because of fussiness. Eight other infants only contributed data from the first test pair because of observer error, experimenter error, being fussy or distracted, or because one infant essentially refused to look by getting off from the parent's lap during the second test pair.

3.2. Results and discussion

3.2.1. Preliminary analyses

Infants' mean looking times during the six familiarization trials did not differ by side (left or right), $F(1,52) = .09$, or condition (consistent-direction or inconsistent-direction), $F(1,52) = .42$. As in Experiment 1, infants in all four conditions looked reliably longer at the familiarization event 2 (yellow > green) presented in the first three trials than at the familiarization event 1 (red > yellow) presented in the last three trials, $F(1,52) = 37.83$, $p = .00$. During the display trial, infants' looking times did not differ reliably by side ($F(1,52) = 1.98$, $p > .16$) or condition ($F(1,52) = 2.91$, $p > .09$). Preliminary analysis of the test data revealed no significant interactions involving condition and event with sex and/or order, all $Fs(1,40) < 1.60$, $p > .21$; the data were therefore collapsed across sex and order in subsequent analyses.

3.2.2. Test outcomes

Infants' looking times during the *test* main-trials (see Fig. 2) were averaged and analyzed by means of a $2 \times 2 \times 2$ ANOVA with side (left or right) and condition (consistent-direction or inconsistent-direction) as between-subjects factors and event (expected or unexpected) as a within-subject factor. The analysis only yielded a significant interaction of condition and event, $F(1,52) = 12.16$, $p = .001$. Planned comparisons revealed that infants in the consistent-direction conditions looked reliably longer at the unexpected ($M = 15.2$, $SD = 11.6$) than at the expected event ($M = 11.7$, $SD = 6.3$),

$F(1,52) = 5.24$, $p < .05$, $d = 0.4$, while those in the inconsistent-direction conditions looked reliably less at the unexpected event ($M = 11.7$, $SD = 5.4$) than at the expected event ($M = 15.7$, $SD = 6.2$), $F(1,52) = 6.98$, $p < .025$, $d = -0.6$. Examinations of individual infants' looking times confirmed these results. Nineteen of the 28 infants in the consistent-direction conditions looked longer at the unexpected than at the expected event, Wilcoxon signed-ranks $z = 1.94$, $p = .05$, whereas only seven of those in the inconsistent-direction conditions did so, $z = -2.71$, $p < .01$.

The results of the consistent-direction conditions suggest that the linear ordering shown in the display trial helped infants infer that the agent liked the red football (*A*) the most and the green football (*C*) the least among the three. They therefore responded with prolonged looking during test when the agent grasped the green football (*C*). Note that how much the agent liked each of the three footballs was imperceptible from the display. There were at least two possible explanations for how the consistent display worked. First, the consistent display might have reflected how the footballs were arranged in one's representation, if infants in the linear condition of Experiment 1 had built a spatial mental representation of the three footballs, red, yellow, and green, with red on the preferred side, to succeed. The consistent display might have helped infant in the current conditions to construct such a representation. Second, since there was no direct evidence that infants did build the linearly ordered spatial mental representation, the consistent display simply triggered infants to engage in transitive inferences about the agent's preferences, even when the premise preferences were presented in a nonlinear order.

Surprisingly, unlike the infants in the reversed condition of Experiment 1, those in the inconsistent-direction conditions looked significantly less at the unexpected than at the expected event. The only difference between the two conditions was the display inserted between the familiarization and test trials. Again, there were at least two possible explanations for the result pattern. First, the addition of the inconsistent display somewhat disrupted infants' processing of the familiarization trials. They hence responded to the expected event since they just saw the agent reach for the red football in the familiarization event 2. Second, the inconsistent display enabled infants to make predictions about the agent's actions based on which side, left or right, the agent reached to. They therefore responded with prolonged looking when the agent reached to the different side from the familiarization trials in the expected event. Without this display, as in the reversed condition, infants were unable to make any prediction and hence respond similarly to the expected and unexpected events. Further testing involving different kinds of partial display with only one or two footballs present may help decide between the two possibilities. If infants had responded to the familiarity of the expected event, then any display, e.g., with only the yellow football present, or with the yellow and the green footballs present, might yield results similar to those of the inconsistent-direction conditions. If, however, infants had responded to the side to which the agent reached during the test trials, then we might find different results. For example, in the inconsistent display, the red and the green footballs were already in the same locations as in test. This might have triggered infants' reasoning based on the direction of the agent's action. If so, only the partial display with the red and the green footballs in place might have yielded similar results as the inconsistent-direction conditions.

Note that unpredictable negative results have been reported when infants' cognitive abilities under examination are fragile. In Woodward (1998), infants were first shown a human agent's arm and hand or an inanimate object (e.g., a flat occlude shaped like one's arm and hand, or a mechanical claw) reach for and grasp toy-A but not toy-B during habituation. During test, the positions of the two toys were reversed and the hand or the object reached for A (old-goal/new-path) or B (new-goal/old-path). Both 6- and 9-month olds seemed to encode the hand's actions, but not those of the objects', in terms of preferences. They looked reliably longer at the new-goal event than at the old-goal event in the hand condition but looked about equally at the two events in the object conditions. With younger, 5-month-olds, however, the positive results in the hand condition were weaker ($p = .08$). In the object condition, they actually looked reliably longer at the old-goal/new-path than at the new-goal/old-path event, differently from older infants. Likewise, the present experiments yielded surprisingly negative results in situations proved challenging to infants' transitivity abilities in which the agent's premise preferences were presented in the reversed order.

4. General discussion

The present results provide the first piece of evidence that infants at 16 months of age appear to reason transitively about an agent's preferences. After seeing that the agent repeatedly grasped a red but not a yellow football ($A > B$), and that she also repeatedly grasped the yellow but not a green football ($B > C$), infants seemed to infer that the agent should choose the red over the green football ($A > C$). When the agent's premise preferences were presented nonlinearly, that is, infants saw her grasp the yellow as opposed to the green football ($B > C$) and then the red as opposed to the yellow football ($A > B$), infants did not expect her to later choose the red over the green football ($A > C$). A display with the three footballs lined up in a way consistent with the spatial ordering (red, yellow, green; *A*, *B*, *C*) seemed to have helped infants to form this expectation again. Positive results were found if the red football (*A*) in the display was on the same side it was on, left or right, as when the premise preferences were introduced, but not otherwise.

In the present research, three footballs only differing in color were used as the items in the transitivity task. It remains an open question whether or not the task would be easier to infants if the items were three very different objects. Furthermore, a caveat of the present research is that the transitivity task only involved three items. Historically, Piaget's task involved three items as well. However, it is suggested that in such a task, one can simply "label" the items to come up with the answer. For example, A is "the longer" than B and C is "the shorter" than B. Therefore, these labels make the inference comparison between A and C unnecessary (e.g., Bryant & Trabasso, 1971; DeBoysson-Bardies & O'Regan, 1973). Researchers (e.g., Bryant & Trabasso, 1971; Grosenick et al., 2007) thus adopted five-item tasks in which the critical, BD pair comparison renders the labeling strategy unhelpful because both B and D should be labeled "larger" and "smaller" during training; subjects in their tasks nonetheless succeeded. In addition, tasks with even more items, e.g., six items, yield results supporting the linear-ordering hypothesis by showing the inverse relationship between subjects' reaction time and the steps between two items in a pair during test. Six items (ABCDEF) also allows two-step comparisons, e.g., BE (Trabasso, 1975). In the present three-item task, infants might have assigned positive and/or negative valence to the three footballs during familiarization, similar to using the labeling strategy, which could lead to positive results in the linear condition. However, it would be difficult to explain the negative results of the reversed condition as well as the Experiment 2 results without additional assumptions. Therefore, the transitivity explanations are appropriate and parsimonious for the present results. Nevertheless, future research will examine infants' performances in transitivity tasks involving more than three items, to corroborate the current findings.

In Experiment 1, the reversed condition served as a control for the linear condition. When the agent's premise preferences were presented in the reversed order (BC then AB), infants failed to engage in transitive inferences. What made the reversed conditions difficult? In early studies with adults (e.g., De Soto, London, & Handel, 1965), subjects received two premise statements (A is better than B, and B is better than C; people's names were used for A, B, and C) in all eight possible combinations. They then judged between A and C; they only had 10 s to write down the answer. Of relevance to the present research is that subjects performed better in the "linear" combination, as described above, than in the "reversed" combination (B is better than C, and A is better than B). De Soto et al. (1965) proposed that people most readily learned the ordering of items when the relationship was from better to worse both within and between premises. Such was the case in the "linear" combination, whereas the "reversed" combination was "better-to-worse" within premises but "worse-to-better" between premises. Given that the linear (red is chosen over yellow, and yellow is chosen over green) and reversed (yellow is chosen over green, and red is chosen over yellow) conditions in the present research were highly similar to those described above, analogous processes might have underlain the 16-month-olds' performances as well. The mix-up of within and between premises relationships in the reversed condition might have made it difficult to construct the linear ordering ($A > B > C$) that could be used later for the test comparison, if infants had done so in the reversed condition, or infants' memory of the agent's preferences might have been disrupted.

A recent study on infants' understanding of social dominance further underscores the difficulty of a reversed condition in transitivity tasks. In Mascaro and Csibra (2012), 15-month-olds seem to understand that if A dominates B in one context, the same dominance relationship remains stable in a different context. They do not, however, seem to recognize that the dominance relationship can be transitive. Interestingly, in their transitive task, the infants were presented with reversed ordered premise relationships. During familiarization, infants saw that B dominated A and then C dominated B. During test, infants did not differentiate between events depicting A dominating C or vice versa.

In Experiment 2, the consistent but not the inconsistent displays turned the results of the reversed conditions positive. The most preferred red football had to be on the preferred side for the display to work. This uni-directional linearly ordered cue might have triggered infants to engage in transitive reasoning about the agent's preferences. Or, if infants had formed a *uni-directional* linear ordering of the three footballs during familiarization; the mental process might have been equivalent to first putting the red football (A) on the side that the preferred football in a pair was always on, possibly for reasons of convenience. When adults organize linguistic information, they also tend to build a uni-directional spatial representation (e.g., Clark, 1969; Huttenlocher, 1968; Johnson-Laird, 1972). For example, in De Soto et al. (1965), when subjects were left to arrange the names based on the given premise sentences, most of them did so from top to bottom for "better than" relations and the reverse for "worse than" relations. The present results are not from overt responses such as these. To bridge the gap between the present results and the adult data, one can extend the current task to preschoolers and examine whether they also arrange the red, yellow, and green footballs in one direction only, adopting Riley's (1976) approach. She asked third-graders to organize the items during training. The children mostly arranged the items in a linear order, although no direction data were reported.

In the present experiments, the side the preferred football was on remained the same during familiarization. This might have contributed to infants' success in the current transitivity tasks. Nevertheless, it remains an open question whether infants in the linear condition would still succeed if the side the preferred football was on changed within and/or between premises during familiarization. Additionally, this manipulation might have induced infants to use spatial location in their reasoning about the agent's preferences. The fact that the consistent-direction but not the inconsistent-direction conditions yielded positive results in Experiment 2 suggested that infants might have used an egocentric reference frame, i.e., "the preferred or most preferred football was on my right." The spatial reasoning literature has shown the malleability of species' abilities, including rats, great apes, and humans, to use egocentric or allocentric reference frames given different landmark cues (e.g., Acredolo & Evans, 1980; Haun, Rapold, Call, Janzen, & Levinson, 2006; Li & Gleitman, 2002). For example, one is more likely to use an egocentric reference frame in an unfamiliar landmark-free environment, e.g., a laboratory room (as in the present experiments), but an allocentric one in a landmark-rich environment, e.g., outdoor space or one's home. These results give rise to the intriguing questions of whether adding landmarks in the present experiments would induce infants to "reconsider" the egocentric framing and hence affect the results, e.g., to turn the inconsistent-directions conditions data positive.

The present findings are in agreement with previous results from children, adults, and nonhuman animals demonstrating their abilities to make transitive inferences. The 16-month-old infants succeed in a three-item transitivity task along the dimension of an agent's preferences for different objects ($A > B$, $B > C$, and therefore $A > C$). As mentioned in the Introduction, transitivity of preferences is assumed to be an axiom in decision making processes. A major challenge to evaluate the transitivity axiom is to take into account the fact that people's choices between two options when demonstrating preferences are probabilistic. Regenwetter et al. (2011) have used statistical models to meet the challenge. In behavioral studies, the present experiment provides the point of departure to test transitive preference when an agent's choice is stochastic. Ongoing research in our laboratory shows that when an agent chooses A four times but B once, infants still attribute to her a preference for A over B. Such inconsistencies could be introduced to the agent's premise preferences in a transitivity task similar to the present one. Infants' successes in these tasks could help build the developmental link between infant and adult cognition.

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References

Acredolo, L. P., & Evans, D. (1980). Developmental changes in the effects of landmarks on infant spatial behavior. *Developmental Psychology, 16*, 312–318.

Bower, G. H. (1971). Adaptation-level coding of stimuli and serial-position effects. In M. H. Appley (Ed.), *Adaptation-level theory* (pp. 175–201). New York: Academic Press.

Boysen, S. T., Berntson, G. G., Shreyer, T. A., & Quigley, K. S. (1993). Processing of ordinality and transitivity by chimpanzees (*Pan troglodytes*). *Journal of Comparative Psychology, 107*, 208–215.

Braine, M. D. S. (1964). Development of a grasp of transitivity of length: A reply to Smedslund. *Child Development, 35*, 799–810.

Breslow, L. (1981). Reevaluation of the literature on the development of transitive inferences. *Psychological Bulletin, 89*, 325–351.

Bryant, P. E., & Trabasso, T. (1971). Transitive inferences and memory in young children. *Nature, 232*, 456–458.

Carey, S. (1995). On the origins of causal understanding. In D. Sperber, D. Premack, & A. J. Premack (Eds.), *Causal cognition: A multidisciplinary debate* (pp. 268–302). Oxford: Clarendon Press.

Clark, H. H. (1969). Linguistic processes in deductive reasoning. *Psychological Review, 76*, 387–404.

De Soto, C. B., London, M., & Handel, S. (1965). Social reasoning and spatial paralogic. *Journal of Personality and Social Psychology, 2*, 513–521.

DeBoysson-Bardies, B., & O'Regan, K. (1973). What children do in spite of adults' hypotheses. *Nature, 246*, 531–534.

Gelman, R., & Baillargeon, R. (1983). A review of Piagetian concepts. In J. H. Flavell & E. M. Markman (Eds.), *Handbook of child psychology* (4th ed., Vol. 3, pp. 167–230). New York: Wiley.

Gelman, R., & Spelke, E. S. (1981). The development of thoughts about animate and inanimate objects: Implications for research on social cognition. In J. H. Flavell & L. Ross (Eds.), *Social cognitive development: Frontiers and possible futures* (pp. 43–66). Cambridge, UK: Cambridge University Press.

Gillan, D. J. (1981). Reasoning in the chimpanzee: II. Transitive inference. *Journal of Experimental Psychology: Animal Behavior Processes, 7*, 150–164.

Grosenick, L., Clement, T. S., & Fernald, R. D. (2007). Fish can infer social rank by observation alone. *Nature, 445*, 429–432.

Harris, P. L., & Bassett, E. (1975). Transitive inferences by four-year-old children? *Developmental Psychology, 11*, 875–876.

Haun, D. B. M., Rapold, C. J., Call, J., Janzen, G., & Levinson, S. C. (2006). Cognitive cladistics and cultural override in hominid spatial cognition. *Proceedings of the National Academy of Sciences of the United States of America, 103*, 17568–17573.

Huttenlocher, J. (1968). Constructing spatial images: A strategy in reasoning. *Psychological Review, 75*, 550–560.

Johnson-Laird, P. N. (1972). The three-item series problem. *Cognition, 1*, 57–82.

Li, P., & Gleitman, L. (2002). Turning the tables: Language and spatial reasoning. *Cognition, 83*, 265–294.

Luo, Y. (2011a). Do 10-month-old infants understand others' false beliefs? *Cognition, 121*, 289–298.

Luo, Y. (2011b). Three-month-old infants attribute goals to a non-human agent. *Developmental Science, 14*, 453–460.

Luo, Y., & Baillargeon, R. (2005). Can a self-propelled box have a goal? Psychological reasoning in 5-month-old infants. *Psychological Science, 16*, 601–608.

Luo, Y., & Baillargeon, R. (2007). Do 12.5-month-old infants consider what objects others can see when interpreting their actions? *Cognition, 105*, 489–512.

Luo, Y., & Beck, W. (2010). Do you see what I see? Infants' reasoning about others' incomplete perceptions. *Developmental Science, 13*, 134–142.

Luo, Y., & Johnson, S. C. (2009). Recognizing the role of perception in action at 6 months. *Developmental Science, 12*, 142–149.

MaClean, E. L., Merritt, D. J., & Brannon, E. M. (2008). Social complexity predicts transitive reasoning in prosimian primates. *Animal Behavior, 76*, 479–486.

Mascaro, O., & Csibra, G. (2012). Representation of stable social dominance relations by human infants. *Proceedings of the National Academy of Sciences of the United States of America, 109*, 6862–6867.

McGonigle, B., & Chalmers, M. (1977). Are monkeys logical? *Nature, 267*, 694–696.

Murray, J. P., & Youniss, J. (1968). Achievement of inferential transitivity and its relation to serial ordering. *Child Development, 39*, 1259–1268.

Paz-y-Miño, C. G., Bond, A. B., Kamil, A. C., & Balda, R. P. (2004). Pinyon jays use transitive inference to predict social dominance. *Nature, 430*, 778–781.

Piaget, J. (1970). *Genetic epistemology*. New York: Columbia University Press.

Piaget, J., Inhelder, B., & Szeminska, A. (1960). *The child's conception of geometry*. New York: Basic Books.

Regenwetter, M., Dana, J., & Davis-Stober, C. P. (2011). Transitivity of preferences. *Psychological Review, 118*, 42–56.

Riley, C. A. (1976). The representation of comparative relations and the transitive inference task. *Journal of Experimental Child Psychology, 22*, 1–22.

Riley, C. A., & Trabasso, T. (1974). Comparative, logical structures, and encoding in a transitive inference task. *Journal of Experimental Child Psychology, 17*, 187–203.

Roberts, W. A., & Phelps, M. T. (1994). Transitive inference in rats: A test of the spatial coding hypothesis. *Psychological Science, 5*, 368–374.

Smedslund, J. (1963). Development of concrete transitivity of length in children. *Child Development, 34*, 389–405.

Sodian, B., Thoermer, C., & Metz, U. (2007). Now I see it but you don't: 14-month-olds can represent another person's visual perspective. *Developmental Science, 10*, 199–204.

Spelke, E. S. (1994). Initial knowledge: Six suggestions. *Cognition, 50*, 431–445.

Terrace, H. S., & McGonigle, B. (1994). Memory and representation of serial order by children, monkeys, and pigeons. *Current Directions in Psychological Science, 3*, 180–185.

Thayer, E. S., & Collyer, C. E. (1978). The development of transitive inference: A review of recent approaches. *Psychological Bulletin, 85*, 1327–1343.

Trabasso, T. (1975). Representation, memory, and reasoning: How do we make transitive inferences? In A. D. Pick (Ed.). *Minnesota symposia on child psychology* (Vol. 9, pp. 135–172). Minneapolis: University of Minnesota Press.

Trabasso, T., & Riley, C. A. (1975). On the construction and use of representations involving linear order. In R. L. Solso (Ed.), *Information processing and cognition: The Loyola symposium*. Hillsdale, NJ: Erlbaum.

Trabasso, T., Riley, C. A., & Wilson, E. G. (1975). The representation of linear order and spatial strategies in reasoning: A developmental study. In R. J. Falmagne (Ed.), *Reasoning: Representation and process in children and adults*. Hillsdale, NJ: Erlbaum.

Tversky, A. (1969). Intransitivity of preferences. *Psychological Review, 76*, 31–48.

von Fersen, L., Wynne, C. D. L., Delius, J. D., & Staddon, J. E. R. (1991). Transitive inference formation in pigeons. *Journal of Experimental Psychology: Animal Behavior Processes, 17*, 334–341.

Wellman, H. M., & Gelman, S. A. (1998). Knowledge acquisition in foundational domains. In W. Damon, D. Kuhn, & R. Siegler (Eds.), *Handbook of child psychology: Cognition, perception, and language* (5th ed., Vol. 2, pp. 523–573). New York: Wiley.

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