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Five-month-old infants attribute inferences based on general knowledge to agents

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ABSTRACT

To make sense of others' actions, we generally consider what information is available to them. This information may come from different sources, including perception and inference. Like adults, young infants track what information agents can obtain through *perception*: If an agent directly observes an event, for example, young infants expect the agent to have information about it. However, no investigation has yet examined whether young infants also track what information agents can obtain through *inference*, by bringing to bear relevant general knowledge. Building on the finding that by 4 months of age most infants have acquired the physical rule that wide objects can fit into wide containers but not narrow containers, we asked whether 5-month-olds would expect an agent who was searching for a wide toy hidden in her absence to reach for a wide box as opposed to a narrow box. Infants looked significantly longer when the agent selected the narrow box, suggesting that they expected her (a) to share the physical knowledge that wide objects can fit only into wide containers and (b) to infer that the wide toy must be hidden in the wide box. Three additional conditions supported this interpretation. Together, these results cast doubt on two-system accounts of early psychological reasoning, which claim that infants' early-developing system is too inflexible and encapsulated to integrate inputs from other cognitive processes, such as physical reasoning. Instead, the results support one-system accounts and provide new

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evidence that young infants' burgeoning psychological-reasoning system is qualitatively similar to that of older children and adults.

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Introduction

To predict and interpret agents' actions, we generally need to consider what information is available to them. Agents may gather information from a number of different sources, including perception and inference. To illustrate, imagine the following scene: We are in a park enjoying the antics of a young girl and her large dog. At some point, the dog becomes hidden behind one of two bushes. If the girl saw the dog disappear behind the bush or heard it bark once there, we would expect her to know its location through *perception*. If she did not watch the dog disappear or hear it bark but could see that one of the bushes was small, we would again expect her to know the dog's location, this time through *inference*: By bringing to bear the physical knowledge that a large object cannot become fully hidden behind a smaller object, the girl could infer that her dog must be hidden behind the other, larger bush. Thus, in both cases, we would expect the girl to search the correct location for her dog, based on the information available to her directly through perception or indirectly through inference.

When reasoning about an agent's actions in a scene, can infants also take into account what information might be available to her through perception or inference? Over the past 10 years, evidence has steadily accumulated that infants in the first year of life are able to track what information agents can gather through perception (for a review, see Baillargeon, Scott, & Bian, 2016). For example, infants aged 6 months and older realize that an agent will be able to see an event and will gain information about it if she is present when it occurs, if she is looking toward it, and if no obstacle blocks her view of it; conversely, the agent will be unable to see the event, and hence will lack information about it, if any of these conditions are not met (Kim & Song, 2015; Liszkowski, Carpenter, & Tomasello, 2008; Luo & Baillargeon, 2007; Luo & Johnson, 2009; Meristo & Surian, 2013; Repacholi, Meltzoff, & Olsen, 2008; Scott & Baillargeon, 2009; Ting, He, & Baillargeon, 2019).

Are young infants also able to track what information agents can garner through inference, by bringing to bear general knowledge about objects? To the best of our knowledge, no investigation has yet addressed this issue. At first glance, it might appear that a key impediment to doing so would be that young infants possess little general knowledge about objects. However, evidence from the physical-reasoning literature indicates that infants begin acquiring physical rules about occlusion, containment, support, collision, and other events in the first months of life (Aguiar & Baillargeon, 2002; Hespos & Baillargeon, 2008; Káldy & Leslie, 2005; Kotovsky & Baillargeon, 1998; Luo, Kaufman, & Baillargeon, 2009; Wang, Baillargeon, & Brueckner, 2004; Wang & Onishi, 2017; Wilcox, 1999). The current research built on these findings to ask the following question: Would 5-month-old infants expect an agent to correctly infer the location of an object hidden in her absence, via the application of relevant physical knowledge?

Not surprisingly, different accounts of infants' ability to reason about others' actions offered different answers to this question. Whereas *two-system* accounts suggested that infants would be unable to track information the agent could attain only through an inference from relevant physical knowledge, *one-system* accounts suggested that infants would be able to do so, at least under optimal conditions. In the following sections, we first describe these accounts and then introduce the present research.

Different accounts

There is currently a heated debate in psychology over how best to characterize the development of children's ability to reason about agents' actions (this ability is variously referred to as psychological reasoning, theory of mind, mindreading, and mentalizing). According to *two-system* accounts (Apperly & Butterfill, 2009; Butterfill & Apperly, 2013; Low, Apperly, Butterfill, & Rakoczy, 2016; Low,

Drummond, Walmsley, & Wang, 2014; Low & Watts, 2013), two distinct cognitive systems underlie this development. The *early-developing* system, which emerges during infancy, is automatic, fast, and inflexible, whereas the *late-developing* system, which emerges around 4 years of age, is nonautomatic, slow, and flexible. A key strength of the early-developing system is its ability to track what objects agents “register” and to use these registrations to predict their actions. For example, if an agent sees a toy being hidden in one of two locations, the early-developing system can predict, by considering where she last registered the toy, that she will search for it in the correct location. Beyond this ability, however, the early-developing system suffers from a number of “signature limits” that distinguish its minimal capacity for psychological reasoning from the more advanced capacity of the late-developing system. Of particular relevance to the present research is the signature limit of *cognitive encapsulation*. Because the early-developing system is “largely automatic and independent of central cognitive resources” (Low et al., 2016, p. 185), it is encapsulated from the rest of cognition. This makes it fast and efficient but also inflexible and sharply limited in its ability to integrate inputs from other cognitive processes (e.g., physical reasoning, language) when reasoning about agents’ actions (Butterfill & Apperly, 2013).

In contrast to two-system accounts, *one-system* accounts assume that a single system underlies psychological reasoning from infancy to adulthood (Baillargeon et al., 2016; Carruthers, 2016; Hyde, Simon, Ting, & Nikolaeva, 2018; Leslie, Friedman, & German, 2004; Scott, Roby, & Baillargeon, in press). Although significant developments take place in this system with age and experience, they are largely quantitative in nature: Infants’ psychological reasoning is qualitatively similar to that of older children and adults, albeit less well developed. Thus, one-system accounts dispute the various signature limits proposed by two-system accounts, including the claim that early psychological reasoning is inflexible and cognitively encapsulated. From a young age, infants’ burgeoning psychological-reasoning system is thought to be capable of integrating inputs from other cognitive processes, provided that task demands do not overwhelm infants’ limited information-processing resources (Scott et al., in press).

The present research

Would 5-month-old infants expect an agent who was absent while a toy was hidden to still be able to determine its location, if this location could be inferred by bringing to bear relevant physical knowledge? To find out, we took advantage of the prior finding that by 4 months of age, most infants have acquired the physical rule that wide objects can fit into wide containers but not narrow containers (Wang et al., 2004). In a preference task adapted from Woodward (1998), infants first received familiarization trials in which an agent consistently preferred a wide toy, which jingled when shaken, over a narrow toy, which did not. In the test trial, while the agent was absent, an experimenter hid the wide toy in a wide box and the narrow toy in a narrow box. Of interest was whether infants would expect the agent, when she returned, to correctly infer that her preferred toy was in the wide box even though she had not witnessed the hiding of the toys.

As should be clear from the previous section, two-system and one-system accounts offered different predictions for infants’ responses. According to two-system accounts, the early-developing system should be able to track information the agent registered through perception—but it should be unable, due to its cognitive encapsulation, to track information the agent could attain only through inference, by bringing to bear relevant physical knowledge. In other words, the encapsulated early-developing system should be unable to integrate physical knowledge into its reasoning about what information was available to the agent about the wide toy’s location. Thus, infants should hold no particular expectation about which box the agent would choose, and they should look equally whether she reached for the wide or the narrow box.

In contrast, one-system accounts predicted that infants would be able to integrate physical knowledge into their reasoning about what information was available to the agent about the wide toy’s location, provided that task demands did not overwhelm infants’ limited information-processing resources. Specifically, infants should assume that the agent (a) would share the physical knowledge that wide objects can fit only into wide containers and hence (b) would infer that the wide toy must be

hidden in the wide box. Thus, infants should expect the agent to reach for the wide box, and they should find it unexpected when she reached for the narrow box instead.

Which of the two preceding predictions was more likely to be correct? Findings from two prior reports, in particular, seemed to us to provide tentative support for the prediction from one-system accounts. In the first report, 18-month-olds attributed to an agent a false inference based on a statistical regularity about objects (similar objects are more likely than dissimilar objects to share nonobvious properties; [Welder & Graham, 2001](#)) that happened to not hold true in the experimental situation ([Scott, Baillargeon, Song, & Leslie, 2010](#); for a replication in traditional non-Western societies, see [Barrett et al., 2013](#)). In a familiarization trial, Agent 1 sat at a side window in a puppet-stage apparatus and faced a red toy with silver stars. Two additional toys stood at the rear of the apparatus: One was visually identical to Agent 1's toy (red test toy), and the other was green with yellow stripes (green test toy). Agent 1 shook each toy in turn, thereby revealing that her toy and the green test toy rattled when shaken but the red test toy did not. In the test trial, Agent 2 now sat behind the two test toys. Agent 1 shook her toy and said, "Can you do it?" Agent 2 then grasped either the red or the green test toy and paused. Infants looked significantly longer if Agent 2 selected the green as opposed to the red test toy, suggesting that they expected her (a) to share the intuition that similar objects are more likely than dissimilar objects to have the same nonobvious properties and hence (b) to falsely infer that the red test toy rattled. If 18-month-olds could attribute to an agent a false inference based on a statistical regularity about objects' nonobvious properties, it seemed possible that 5-month-olds could attribute to an agent a true inference based on a physical rule about containment events.¹

The second report hinted at some degree of cognitive integration in the first half-year of life between infants' psychological reasoning and another cognitive process, namely language ([Vouloumanos, Martin, & Onishi, 2014](#)). In the report, 6-month-olds were tested with a preference task that made use of the linguistic knowledge that words are linguistic conventions that are shared by members of the same speech community ([Henderson & Woodward, 2012](#)). In the familiarization trials, Agent 1 consistently selected Object A over Object B, indicating that she preferred it. In the test trial, Agent 1 could no longer reach the objects (she peered at them through a small window) and was joined by Agent 2, who could reach both objects. Agent 1 looked at Agent 2 and said, "Koba, koba!" Infants expected Agent 2 to pick up Object A, suggesting that they (a) guessed that this novel word referred to Agent 1's preferred object, (b) assumed that Agent 2, like Agent 1, knew the meaning of this word, and hence (c) expected Agent 2 to give Object A to Agent 1. If 6-month-olds could integrate language into their psychological reasoning, it seemed possible that 5-month-olds could integrate physical knowledge as well.

Design

Infants were assigned to one of four conditions ($N = 96$, with 24 per condition): inference, ignorance, no-preference, and perception. Each infant sat on a parent's lap facing a puppet-stage apparatus and received four familiarization trials and one test trial. Each trial had a computer-controlled initial phase followed by an infant-controlled final phase. During the initial phase, infants saw the scripted

¹ Other experiments have shown that infants in the second year of life can attribute to agents inferences based on local patterns established through simple repetition ([Buttelmann, Over, Carpenter, & Tomasello, 2014](#); [Scott & Baillargeon, 2009](#); [Song & Baillargeon, 2008](#); [Surian, Caldi, & Sperber, 2007](#)). For example, after an agent was shown that three identical boxes, introduced separately, each contained a block, 18-month-olds expected the agent to falsely assume that a fourth identical box also contained a block (infants knew that this box in fact contained a spoon; [Buttelmann et al., 2014](#)). Similarly, after an agent saw a desired object being hidden behind one screen four times, 13-month-olds expected the agent, when returning to the scene after the object was already hidden, to falsely infer that it had been hidden in the same location as before (infants knew the object had in fact been hidden behind a different screen; [Surian et al., 2007](#)). In each case, thus, infants attributed to the agent the inference that the latest event in the scene had followed the same pattern as the preceding events. In contrast to inferences based on general knowledge about objects, which depend on the integration of infants' psychological reasoning with other cognitive processes, these inferences based on local patterns require little or no cognitive integration and, as such, are compatible with both two-system and one-system accounts of early psychological reasoning.

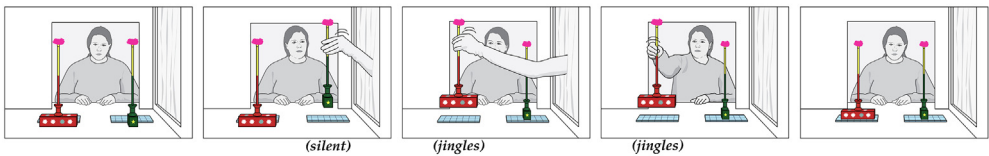
events appropriate for the trial, ending with a paused scene; during the final phase, infants watched this paused scene until the trial ended.

At the start of the initial phase in the first two familiarization trials of the *inference* condition (Fig. 1), a female agent sat at a window in the back wall of the apparatus, behind two rectangular mats. In front of each mat was a toy that consisted of a tall handle attached to a wide (left toy) or narrow (right toy) rectangular base; the toys' bases and the lower halves of their handles differed in color and pattern, but the upper halves of their handles were identical and each consisted of a thin yellow rod with a bright pink ornament at the top. As the agent watched, an experimenter's gloved hand entered the apparatus through a curtained window in the right wall. The hand grasped the handle of the nearer toy (~5 cm below the pink ornament), shook it four times, and placed it on its mat; next, the hand performed the same actions on the farther toy. The wide toy jingled when shaken, but the narrow toy did not. After the hand completed its actions and left, the agent grasped the handle of the wide toy and shook it four times, causing it to jingle. Next, she returned the wide toy to its mat and then paused with her hands on the apparatus floor. During the final phase, infants watched this paused scene until the trial ended. The last two familiarization trials were identical except that round mats were used and the toys' locations were switched; as before, the gloved hand acted on the nearer toy first. The familiarization trials thus served to establish that the agent preferred the wide toy, presumably because it jingled when shaken (Bahrick, Gogate, & Ruiz, 2002; Perone, Madole, Ross-Sheehy, Carey, & Oakes, 2008), and that she consistently reached for it irrespective of where it was placed in the apparatus.

During the initial phase of the test trial (Fig. 2), the agent was at first absent: Her window was closed. On the apparatus floor, instead of two mats, there were now two tall boxes, open at the top, that differed in color and pattern as well as width: The box on the left was sufficiently wide to hold either the wide or the narrow toy, whereas the box on the right was narrow and could hold only the narrow toy. The wide toy stood in front of the wide box, and the narrow toy stood in front of the narrow box. As in the familiarization trials, the gloved hand entered the apparatus, shook the nearer toy, placed it in its box, and then repeated these actions with the farther toy. Because both boxes were equally tall, only the identical upper portions of their handles protruded from them. After the hand completed its actions and left, the agent opened her window, grasped the handle of either the wide toy (*wide-toy event*) or the narrow toy (*narrow-toy event*), and paused. During the final phase of the trial, infants watched this paused scene until the trial ended.

We reasoned that finding that infants looked significantly longer if shown the narrow-toy as opposed to the wide-toy event would suggest that they (a) attributed to the agent a preference for the wide, jingling toy over the narrow, silent toy during the familiarization trials, (b) expected her to continue acting on this preference in the test trial, (c) realized that although she was absent when her preferred toy was hidden, she could infer its location by bringing to bear the physical knowledge

Familiarization Trials 1 and 2



Familiarization Trials 3 and 4

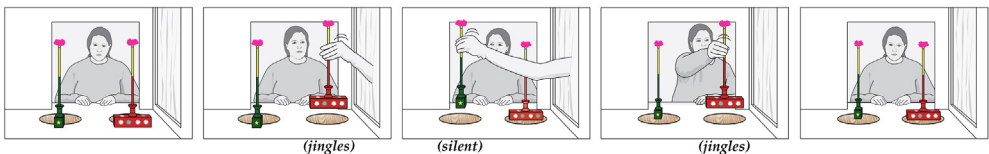
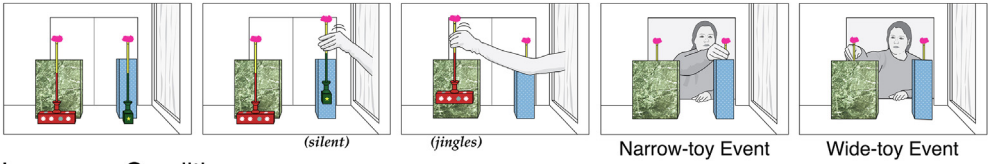


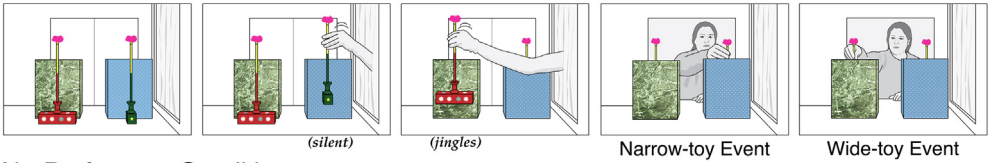
Fig. 1. Familiarization Trials 1 to 4 for all four conditions.

Test Trial

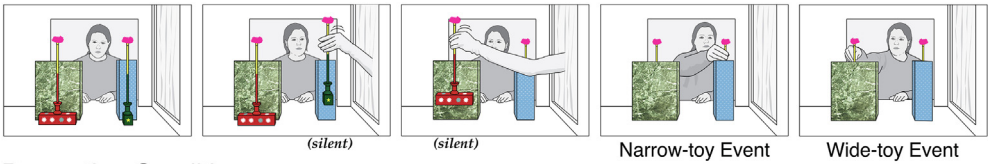
Inference Condition



Ignorance Condition



No-Preference Condition



Perception Condition

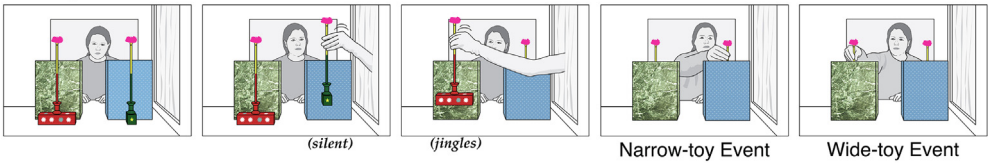


Fig. 2. Test trial in each of the four conditions. Each infant saw either the narrow-toy or the wide-toy event.

that wide objects can fit only into wide containers, and hence (d) expected her to reach for the handle protruding from the wide box and found it unexpected when she reached for the handle protruding from the narrow box instead.

Additional infants were tested in three conditions designed to support this interpretation of positive findings in the inference condition. The *ignorance* condition served to rule out one alternative interpretation of such findings: Perhaps infants in the inference condition acted egocentrically and attributed to the agent their *own* knowledge of the wide toy's location. This possibility seemed unlikely because 6-month-olds have been shown in a variety of tasks to non-egocentrically keep track of what others can see or have seen (Kim & Song, 2015; Luo & Johnson, 2009; Southgate & Vernetti, 2014). Nevertheless, to rule out this possibility, infants in this condition were tested using the same procedure as in the inference condition with one exception: In the test events, the narrow box was replaced with another wide box of the same color and pattern as the narrow box. If infants simply attributed to the agent their own knowledge of where the wide toy was hidden, results should be similar to those in the inference condition. On the other hand, if infants realized, non-egocentrically, that the agent had to be ignorant about the wide toy's location because there was no basis for her to infer this location (both boxes were wide enough to accommodate the wide toy and the handles protruding from them were identical), infants should look equally whether they were shown the narrow-toy or the wide-toy event.

The *no-preference* condition addressed another alternative interpretation of positive findings in the inference condition: Perhaps infants looked longer when the agent reached for the narrow box simply because they had a baseline preference for that box. To rule out this possibility, infants in this

condition were tested using the same procedure as in the inference condition except that the test events were modified in two ways: The agent was present throughout each event and watched as the hand shook each toy and placed it in its box, and the wide toy no longer jingled when shaken, as though it was broken. If infants simply had a baseline preference for the narrow box, results should be the same as in the inference condition. On the other hand, if infants were reasoning about which toy the agent would reach for, results might differ from those in the inference condition. Because the wide toy no longer jingled, infants might expect the agent's preference for that toy to dissipate, leaving them with no particular expectation about which toy she would select. Thus, infants should look equally at the narrow-toy and wide-toy events.

Finally, the *perception* condition was designed to support positive findings in the inference condition by showing that similar results were found when the agent directly observed the hiding of the two toys in the test events. Infants in this condition were tested using the same procedure as in the ignorance condition with one exception: The agent was present and watched as the hand shook each toy and placed it in its box. Based on prior findings that infants aged 6 months and older keep track of what events others have seen (Hyde et al., 2018; Kamps, Parise, Csibra, & Kovács, 2015; Kovács, Téglás, & Endress, 2010; Liszkowski et al., 2008; Luo & Johnson, 2009; Meristo & Surian, 2013; Southgate & Vernetti, 2014; Ting et al., 2019), infants should expect the agent to reach for the box that held her preferred toy, and they should find it unexpected when she reached for the box that held the other toy instead. Thus, as in the inference condition, infants should look significantly longer if shown the narrow-toy as opposed to the wide-toy event.

In short, finding positive results in the inference and perception conditions but negative results in the ignorance and no-preference conditions would indicate that from a young age, infants track not only what information agents can gather through perception but also what information they can gather through inference, by bringing to bear relevant general knowledge. Such results would cast doubt on the claim by two-system accounts that early psychological reasoning is inflexible and cognitively encapsulated and, by the same token, would support one-system accounts.

Method

Power analysis

Luo and Baillargeon (2007) compared infants' ability to keep track of what objects an agent could and could not see in the context of a preference task using live events and a 2×2 between-subject design; the Condition \times Event effect size (η_p^2) they obtained was .163. Using this value, we conducted an a priori power analysis with G*Power (Faul, Erdfelder, Lang, & Buchner, 2007) to estimate the appropriate sample size for our experiment. Although our overall design was a 4×2 between-subject design, our analysis plan also included comparing the inference condition with the other conditions in separate 2×2 analyses of variance (ANOVAs). With power set at .80 and alpha set at .05, the minimum number of infants required per cell (i.e., per combination of condition and event) for these comparisons was 10 or 11. In line with this estimate, we tested 12 infants per cell for a total of 24 per condition and 96 overall.

Participants

Participants were 96 healthy term 5-month-old infants (46 male; age range = 4 months 5 days to 7 months 4 days, $M = 5$ months 13 days). Another 14 infants were tested but excluded from the analyses. Of these, 12 (distributed across the four conditions) were fussy ($n = 8$), drowsy ($n = 2$), or distracted (e.g., by their shoes; $n = 2$), and the other 2 infants looked more than 3 standard deviations above the mean in the test trial (1 in the inference condition and 1 in the perception condition; both infants saw the wide-toy test event). Twenty-four infants were randomly assigned to each of the four conditions. In the inference, ignorance, and perception conditions, 12 infants saw the narrow-toy test event and 12 saw the wide-toy test event; in the no-preference condition, the corresponding numbers were 13 and 11.

Infants' names were obtained from a university-maintained database of parents interested in participating in child development research. Parents were offered a small gift (e.g., a children's book) and travel reimbursement but were otherwise not compensated for their participation. Each infant's parent gave written informed consent, and the protocol was approved by the Institutional Review Board of the University of Illinois at Urbana-Champaign.

Apparatus and stimuli

The apparatus consisted of a brightly lit display booth (201 cm high \times 102 cm wide \times 58 cm deep) with a large opening (55 \times 95 cm) in its front wall; between trials, a supervisor lowered a curtain in front of this opening. Inside the apparatus, the side and back walls were white and the floor was covered with a lightly patterned adhesive paper.

Two female assistants served as the agent and the experimenter. The agent wore a gray shirt and sat at a window (50 \times 50 cm) in the back wall of the apparatus; this window was located 7 cm from the right wall and could be closed by two small white doors. The experimenter wore a white shirt and a long white glove on her left hand and arm, and she knelt at a window (51 \times 38 cm) in the right wall that was filled with a white fringe curtain; she introduced her gloved hand into the apparatus through the curtain. Behind the two assistants, white ceiling-to-floor curtains hid the testing room from infants' view. During the trials, the agent followed the gloved hand's actions, looked at the objects she acted on, and otherwise looked at a neutral point on the apparatus floor; she never made eye contact with infants.

The wide toy had a rectangular base (4 \times 15 \times 4 cm) that was covered with a red adhesive paper and decorated with various colorful stickers. At the back of the base, out of infants' view, was a Velcro strip with four metal bells that jingled when shaken (this strip was removed prior to the test trial in the no-preference condition). A spool (5 cm tall and 4 cm in diameter), also covered with a red adhesive paper, was centered on the top of the base. A thin rod (25 cm tall and 0.5 cm in diameter) protruded from the center of the spool; its lower half was covered with a red adhesive paper and its top half was covered with a yellow adhesive paper. At the top of the rod was a section of a bright pink Koosh ball (2 cm tall and 2.5 cm in diameter) that helped to make the rod more noticeable for infants. The narrow toy was similar with the following exceptions: Its base was narrower (4 cm wide); it had no bells; its base, its spool, and the lower half of its handle were covered with a dark green adhesive paper; and the front of its base was decorated with a large gold star. The total height of each toy was 36 cm.

Strictly speaking, our experimental design did not require the use of handles for the toys given that the agent and the gloved hand could have acted directly on the toys' bases or on the boxes. There were several reasons for using handles. First, when the toys were in the boxes, their protruding handles ensured that they remained partly visible to infants, thereby reducing information-processing demands (Hauf, Paulus, & Baillargeon, 2012; Hespos & Baillargeon, 2006; Lin, Li, Gertner, Fisher, & Baillargeon, 2021). Second, having the agent reach for a handle rather than for a box in the test trial prevented any confusion about whether she was now interested in the box as opposed to the toy. Finally, because the handles of the two toys were identical, the agent's actions were highly similar in the paused scenes at the end of all test events (i.e., she always grasped an identical handle and paused).

The rectangular mats used in the first two familiarization trials (0.5 \times 19 \times 9.5 cm) were covered with a white, blue, and green plaid-patterned adhesive paper, and the round mats used in the last two familiarization trials (0.2 cm tall and 19 cm in diameter) were covered with a brown wood-patterned adhesive paper. Across conditions, three tall boxes (each 26 cm tall \times 9.5 cm deep) were used in the test trial. Two of the boxes were wide (21 cm); one was covered with a light green marble-pattern adhesive paper, and the other was covered with a light blue adhesive paper decorated with a subtle white dot pattern. The last box was narrow (9 cm) and was covered with the same light blue adhesive paper. At the start of the trials, the toys stood centered 5 cm in front of the rectangular mats or boxes, which themselves stood 12 cm apart, centered in front of and 17 cm from the agent's window; the corresponding values for the rounded mats were 0.5, 12, and 12 cm.

During each testing session, two cameras captured images of the infant and events; the two images were combined, projected onto a monitor located behind the apparatus, and checked by the supervisor to confirm that the events followed the prescribed scripts. Recorded sessions were also checked offline for experimenter accuracy.

Procedure

Each infant sat on a parent's lap centered in front of the apparatus; parents were instructed to remain silent and neutral throughout the session and to close their eyes during the test trial. Each infant's looking behavior was monitored by two naïve observers hidden behind cloth-covered panels on either side of the apparatus; looking times during the initial and final phases of each trial were computed separately using the primary observer's responses. Interobserver agreement was calculated for each trial by determining the proportion of 100-ms intervals in which the two observers agreed during the final phase of the trial. Agreement was calculated for 92 of 96 infants (only one observer was present for the other infants) and averaged 92% per trial per infant.

Each trial began with a paused pretrial that ended when the infant had cumulated 2 s of looking, to allow the infant to orient to the apparatus before the trial proper began. The durations of the initial phases in the familiarization (25-s) and test (23-s) trials were fixed and computer-controlled; the two assistants' actions followed a precise second-by-second script, and a metronome beat softly once per second to help them adhere to the script. Infants were highly attentive during these initial phases; across conditions, they looked, on average, for 97% of the initial phase in each familiarization trial and for 97% of the initial phase in the test trial. The final phases of the familiarization trials ended when infants (a) looked away for a consecutive 2 s after having looked for at least a cumulative 5 s or (b) looked for a cumulative maximum of 60 s. Such criteria are commonly used in infancy research and give infants ample opportunity to become familiar with the events shown. The final phase of the test trial ended when infants (a) looked away for 0.5 s after having looked for at least 8 s or (b) looked for a maximum of 30 s. The 8-s minimal value was chosen to give our young participants sufficient time to process the agent's toy selection before the trial could end. In addition, a 0.5-s look-away criterion was used because the agent paused at a different point in the test trial than she did in the familiarization trials. In the latter trials, she shook the wide toy four times and then paused; in the test trial, however, she grasped the handle of one of the toys and then paused. Therefore, infants tended to look back at the paused scene because their attention was recaptured as they waited for the agent to shake the toy as she had done before. By using a short 0.5-s look-away criterion, we could assess infants' initial response to the agent's selection of the wide or narrow toy (for other studies using a 0.5-s look-away criterion, see, e.g., Scott & Baillargeon, 2013; Stavans & Baillargeon, 2018).²

To reduce positive skewness, all looking times were log-transformed and analyses were conducted on the log-transformed data (Csibra, Hernik, Mascaro, Tatone, & Lengyel, 2016). For ease of communication, however, raw looking times are provided in the text and figures. Preliminary analyses of the test data revealed no significant interaction of condition and event with infants' sex, $F(3, 80) = 1.00, p = .396$; the data were therefore collapsed across this factor in subsequent analyses.

² A concern some readers might have about our procedure is that it used a variant of the violation-of-expectation method that is commonly used to study early psychological reasoning (e.g., infants saw a single test event, which was shown only once, followed by a paused scene; Luo & Baillargeon, 2007; Onishi & Baillargeon, 2005; Scott et al., 2010; Surian et al., 2007; Vouloumanos et al., 2014). By contrast, when the violation-of-expectation method was first introduced several decades ago to study early physical reasoning, infants often saw two different test events on alternate trials, and in each trial the event was repeated continuously until the trial ended (Aguilar & Baillargeon, 2002; Baillargeon & DeVos, 1991; Baillargeon, Spelke, & Wasserman, 1985; Kotovsky & Baillargeon, 1998; Needham & Baillargeon, 1993). Because the current research examined the integration of psychological and physical reasoning in young infants, this juxtaposition might give rise to the worry that infants could fail in the inference condition, not because they were unable to track information gathered through inference but rather because the procedure chosen was less than optimal for revealing their physical-reasoning capacity. In recent years, however, several reports have used a single-event, paused-scene procedure to study various facets of infants' physical reasoning with no ill effects (Lin et al., 2021; Stavans & Baillargeon, 2018; Stavans, Lin, Wu, & Baillargeon, 2019; Wang & Goldman, 2016; Wang, Zhang, & Baillargeon, 2016). Thus, there was little a priori reason for concern, and the positive results of the inference condition confirmed that the procedure selected was appropriate for the current research.

The data are available via the Open Science Framework (https://osf.io/u9gda/?view_only=92c4b3ac3d9949f084b0b623406c9b53).

Results

Infants' looking times during the final phases of the four familiarization trials were averaged and analyzed by means of a 4×2 ANOVA with condition (inference, ignorance, no-preference, or perception) and test event (narrow-toy or wide-toy) as between-subject factors. The Condition \times Event interaction was not significant, $F(3, 88) = 0.51, p = .674, \eta_p^2 = .017$, nor was either main effect (both $ps > .692$), suggesting that infants tended to look equally during the familiarization trials (inference: $M = 26.25, SD = 13.16$; ignorance: $M = 26.47, SD = 11.19$; no-preference: $M = 26.33, SD = 13.59$; perception: $M = 23.83, SD = 9.61$).

Infants' looking times during the final phase of the test trial (Fig. 3) were analyzed in the same manner as above. The analysis yielded a significant main effect of event, $F(1, 88) = 5.49, p = .021$, as well as a significant Condition \times Event interaction, $F(3, 88) = 6.18, p = .0007, \eta_p^2 = .174$. To examine this interaction, we conducted four planned comparisons, one per condition (with a Bonferroni-adjusted α level of $.05/4 = .0125$). Infants in the inference condition looked significantly longer if shown the narrow-toy event ($M = 19.18, SD = 8.41$) as opposed to the wide-toy event ($M = 10.41, SD = 2.43$), $F(1, 88) = 15.25, p = .0002, d = 1.462$; infants in the ignorance condition looked equally at the narrow-toy event ($M = 13.21, SD = 7.16$) and wide-toy event ($M = 14.78, SD = 6.75$), $F(1, 88) = 0.93, p = .338, d = -0.309$; infants in the no-preference condition also looked equally at the narrow-toy event ($M = 11.27, SD = 3.16$) and wide-toy event ($M = 12.78, SD = 3.51$), $F(1, 88) = 0.82, p = .367, d = -0.468$; and infants in the perception condition looked significantly longer if shown the narrow-toy event ($M = 17.54, SD = 4.45$) as opposed to the wide-toy event ($M = 12.16, SD = 2.97$), $F(1, 88) = 7.06, p = .009, d = 1.438$. Nonparametric Wilcoxon rank-sum tests (two-sided) confirmed the results of the inference condition ($z = 2.80, p = .005$), ignorance condition ($z = -1.13, p = .260$), no-preference condition ($z = 0.96, p = .339$), and perception condition ($z = 3.06, p = .002$).

Finally, 2×2 ANOVAs indicated that test responses in the inference condition differed significantly from those in the ignorance condition [Condition \times Event interaction: $F(1, 44) = 8.46, p = .006, \eta_p^2 = .161$] and the no-preference condition [$F(1, 44) = 12.71, p = .0009, \eta_p^2 = .224$], but not those in the perception condition [$F(1, 44) = 0.89, p = .352, \eta_p^2 = .020$]. In line with prior findings, test responses

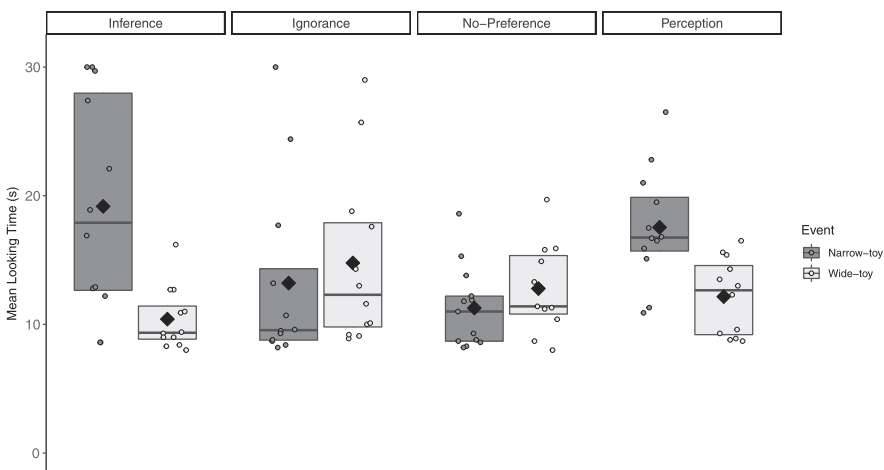


Fig. 3. Looking times at the test events by condition. Each dot represents a single infant, diamonds indicate means, boxes represent the interquartile ranges between the first and third quartiles, and the horizontal line inside each box indicates the median.

in the perception condition also differed significantly from those in the ignorance condition [$F(1, 44) = 6.00, p = .018, \eta_p^2 = .120$] and the no-preference condition [$F(1, 44) = 10.58, p = .002, \eta_p^2 = .194$].

Discussion

In the present research, 5-month-olds received familiarization trials in which an agent first saw an experimenter shake a wide toy, which jingled when shaken, and a narrow toy, which did not; the agent then grasped the wide toy and shook it. In the test trial, while the agent was absent, the experimenter shook each toy as before and hid the wide toy in a wide box and the narrow toy in a narrow box (inference condition). When the agent returned, infants looked significantly longer if she reached for the narrow as opposed to the wide toy, suggesting that they (a) attributed to the agent a preference for the wide, jingling toy during the familiarization trials, (b) assumed that she shared the knowledge that wide objects can fit only into wide containers, (c) expected her to apply this knowledge in the test trial to infer which box held the wide toy, and hence (d) found it unexpected when she reached for the narrow toy instead. This effect was eliminated when both of the boxes used in the test trial were wide, leaving the agent with no basis for inferring the wide toy's location (ignorance condition). Negative results were also found when the agent witnessed the hiding of the toys into the wide and narrow boxes but the wide toy no longer jingled when shaken by the experimenter, causing the agent's preference for the toy to dissipate (no-preference condition). Finally, positive results were again found when the agent witnessed the hiding of the toys into the two wide boxes and thus saw where the experimenter hid her preferred toy (perception condition).

Together, these results rule out several low-level interpretations of the positive results in the inference condition, such as that infants attributed to the agent their own knowledge of the wide toy's location (had that been the case, positive results would have also been found in the ignorance condition), that infants simply had a baseline preference for the narrow box (positive results would have also been found in the no-preference condition), or that infants themselves could remember the location of the agent's preferred toy only when the two boxes differed in width (negative results would have been found in the perception condition). In addition, our design rules out low-level hypotheses that similar results were found whenever the agent was absent at the start of the test trial (results were positive in the inference condition but were negative in the ignorance condition), whenever the agent was present at the start of the trial (results were positive in the perception condition but were negative in the no-preference condition), whenever the two boxes differed in width (results were positive in the inference condition but were negative in the no-preference condition), or whenever the two boxes were identical in width (results were positive in the perception condition but were negative in the ignorance condition).

Our results provide converging evidence for prior findings in early psychological reasoning. In particular, the results of the perception condition confirm that young infants who see an agent consistently choose one object over another attribute to the agent a preference for that object and expect her to continue acting on this preference when the objects' locations are changed in her presence (Baillargeon et al., 2016; Luo, 2011; Luo & Baillargeon, 2005; Spaepen & Spelke, 2007; Woodward, 1998, 1999). Moreover, the results of the ignorance condition provide additional evidence that young infants are not egocentric: When an agent's representation of a scene is less complete than their own, they use her incomplete representation to interpret, predict, evaluate, and respond to her actions (Kim & Song, 2015; Liszkowski et al., 2008; Luo & Baillargeon, 2007; Luo & Johnson, 2009; Meristo & Surian, 2013; Ting et al., 2019).

Our results also extend prior research in two significant ways. First, they expand our understanding of early epistemic reasoning (i.e., reasoning about knowledge and ignorance states). Specifically, they reveal that when determining what an agent knows about a scene, 5-month-old infants take into account not only what information the agent can obtain through direct perception but also what information she can garner through inference, via the application of relevant physical rules; they then expect the agent to act in a manner consistent with her knowledge, irrespective of how it was attained. From this perspective, our findings add to the evidence that early psychological reasoning is guided by a principle of rationality and its corollaries of consistency (agents act in a manner consis-

tent with their mental states) and efficiency (agents expend as little effort as possible to achieve their goals) (Baillargeon, Scott, & Bian, 2016; Gergely & Csibra, 2003; Ting, Buyukozer Dawkins, Stavans, & Baillargeon, 2020; Ting & Baillargeon, 2020). In the inference condition, infants expected the agent to act in a manner consistent with her motivational state (she preferred the wide, jingling toy) and her epistemic state (she could infer that it was in the wide box), and they detected a consistency violation when she reached for the narrow toy instead.

Second, our results bear on the ongoing debate between two-system and one-system accounts of early psychological reasoning. As was discussed in the Introduction, two-system accounts assume that infants' primitive early-developing system is sufficient to track information registered through direct perception but is too inflexible and encapsulated to track information supplied by other cognitive processes (Apperly & Butterfill, 2009; Butterfill & Apperly, 2013; Low et al., 2014, 2016; Low & Watts, 2013). According to one-system accounts, in contrast, infants' psychological-reasoning system is neither inflexible nor cognitively encapsulated and can integrate inputs from other cognitive processes, at least under optimal conditions (Baillargeon et al., 2016; Carruthers, 2016; Hyde et al., 2018; Leslie et al., 2004; Scott et al., *in press*). Thus, our finding that infants as young as 5 months were able to attribute to an agent knowledge she could attain only by applying relevant physical rules to the scene provides new evidence for one-system accounts.

In a recent review, Scott et al. (*in press*) presented evidence of substantial cognitive integration in psychological reasoning during the second year of life: Infants integrated inputs from several different cognitive processes, including language, ostensive cues, categorization, and sociomoral reasoning, when reasoning about others' motivational and epistemic states (Choi & Luo, 2015; Egyed, Király, & Gergely, 2013; Forgács et al., 2020; Jin & Song, 2017; Jin et al., 2019; Martin, Onishi, & Vouloumanos, 2012; Scott et al., 2010; Spaepen & Spelke, 2007). Thus, the current findings, together with those of Vouloumanos et al. (2014) described in the Introduction, extend this evidence by showing that infants' psychological reasoning already shows some degree of cognitive integration with physical-reasoning and language processes during the first half-year of life.

Future research can build on our findings in several directions. First, it will be important to confirm our findings with other physical rules. For example, the rule that tall objects can become fully hidden in tall containers but not short containers is typically acquired by 7 months of age (Hespos & Baillargeon, 2001); would 8-month-olds expect an agent who is searching for a tall object hidden in her absence to approach a tall as opposed to a short container? Second, it would be useful to ascertain whether infants expect an agent to draw physical inferences from what she sees even when these inferences no longer apply. To illustrate, imagine that the inference condition was modified so that in the test trial the red toy was now as narrow as the green toy. When the agent arrived and saw the handles protruding from the wide and narrow boxes, would infants expect her (a) to falsely assume, based on the familiarization trials, that a wide toy and a narrow toy were hidden in the boxes and (b) to falsely infer that her preferred wide toy must be in the wide box? Positive results not only would add to the evidence of false-belief understanding in young infants (Hyde et al., 2018; Kamps et al., 2015; Kovács et al., 2010; Southgate & Vernetti, 2014) but also would make clear that infants expect an agent to draw physical inferences from her representation of a scene even when this representation is faulty, making these inferences invalid.

Conclusion

In the present research, 5-month-old infants watched an agent search for a wide toy that had been hidden in her absence in one of two boxes. Infants always knew in which box the toy was hidden; they expected the agent to correctly infer the toy's location when only one of the boxes was wide enough to hide the toy, but to be ignorant about this location when both boxes were wide enough to hide the toy. These results indicate that when forming expectations about an agent's actions in a scene, infants consider not only what she sees but also what physical inferences she can derive from what she sees. As such, our results provide new evidence for one-system accounts and for the claim that far from being inflexible and encapsulated, infants' psychological reasoning already shows signs of integration with other cognitive processes during the first half-year of life.

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