

Children's use of reasoning by exclusion to infer objects' identities in working memory

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Abstract

Reasoning by exclusion allows us to form more complete representations of our environments, “filling in” inaccessible information by ruling out known alternatives. In two experiments (Experiment 1: $n=34$ 4-6-year-olds; Experiment 2: $n=85$ 4-8-year-olds), we examined children’s ability to use reasoning by exclusion to infer the identity of an unknown object, and investigated the role of working memory in this ability. Children were asked to encode a set of objects that were then hidden, and after a brief retention interval children were asked to select the identity of the object hidden in one of the locations from two alternatives. On some trials, all of the images were visible during encoding, so selecting the correct identity when probed required successful working memory storage and retrieval. On other trials, all but one of the images was visible during encoding, so selecting the correct identity when probed also required maintaining a representation of an *unknown* object in working memory and then using reasoning by exclusion to fill in the missing information retroactively to complete that representation by ruling out known alternatives. To investigate the working memory cost of exclusive reasoning, we manipulated the working memory demands of the task. Our results suggest that children can use reasoning by exclusion to retroactively assign an identity to an incomplete object representation at least by age 4, but that this ability incurs some cognitive cost, which eases with development. These results provide new insights into children’s representational capacities and on the foundational building blocks of fully developed exclusive reasoning.

Keywords: Working memory, reasoning by exclusion, logical inference, object representations, representational uncertainty

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We live in an ever-changing world in which the amount of access we have to information varies considerably across space and time. To achieve cognitive goals in the face of incomplete information, we can use logical reasoning to make inferences about what we do not know based on what we already know. Reasoning by exclusion is the process of inferring unobserved information by eliminating known alternatives (Premack, 1995). For example, imagine you are at a buffet dinner at which there are two covered dishes, both unlabelled. You lift the lid of one of the dishes and see chicken. You are then told that there is one chicken option and one vegetable option. Without lifting the lid of the other dish, you immediately make the inference that the other dish must contain the vegetable option. You were able to make this inference using knowledge of the situation at hand to exclude possibilities for the contents of the unknown dish, effectively reasoning about its likely identity. Reasoning by exclusion therefore is a powerful means of resolving representational uncertainty without having to exert excess physical effort (like walking over to the other dish and lifting the lid) in order to do so.

Recent work has shown that the foundations of our exclusive reasoning abilities about objects and their spatial locations are laid early in development (e.g., Aust, Range, Steurer, & Huber, 2008; Feiman, Mody, & Carey, 2022; Ferrigno, Huang, & Cantlon, 2021; Hill, Collier-Baker, & Suddendorf, 2011; O'Hara et al., 2016; Völter, Sentis, & Call, 2016). For example, around age 3, children who know a reward is hidden in one of two locations, and who observe that one of the locations is empty, will search for the reward in the other location (Mody & Carey, 2016; see also Hill et al., 2012; Gautam, Suddendorf, & Redshaw, 2020; Grigoroglou, Chan, & Ganea, 2019), suggesting that they are using the observed information (the emptiness of the revealed location) to reason about the possible contents of the unobserved location. Younger children also can make inferences about the contents of a location when given verbal input about another location (e.g. "It's not in this bucket"; Austin, Theakston, Lieven, & Tomasello,

2014; Feiman, Mody, Sanborn, & Carey, 2017; Grigoroglou, Chan, & Ganea, 2019), and can infer the identity of an ambiguous object when given information rules out alternative identities (Cesana-Arlotti et al., 2018).

Successful reasoning by exclusion requires children to rely on working memory. Consider the child who is tasked with finding a toy in one of two locations (e.g. Mody & Carey, 2016). The child sees two possible locations, which are then occluded, and then they see that a toy is placed somewhere behind the occluder. The child is now faced with the maximum amount of uncertainty they will encounter in this particular task: *while the two possible locations of the toy are known, the exact location of the toy is unknown*. The child is then given information that reduces that uncertainty: one of the locations is revealed to be empty. In this scenario, the child needs to represent the two locations, and the object (the toy) unbound (or ambiguously bound) to a particular location, and store those representations in working memory. After getting new information about the contents of the scene (the toy is not in location A), they can then *update* their stored representations, binding the representation of the toy to its only possible location in space (Location B). Thus, successful exclusive reasoning requires that children have sufficient working memory resources to track known information and to update uncertain or unknown representations.

In children, working memory is severely capacity-limited, and undergoes substantial developmental increases in capacity between infancy and late childhood (Cheng & Kibbe, 2022; Cowan, 2016; Kibbe, 2015; Simmering, 2012). Despite the fact that reasoning by exclusion relies on working memory, little is known about how working memory and reasoning by exclusion abilities may interact across development. What is the cognitive cost of reasoning by exclusion, and how might working memory capacity constrain reasoning by exclusion abilities in young children?

On the one hand, the ability to reason by exclusion about uncertain/unknown object locations or identities may impose greater demands on working memory than simply storing

representations of a known array of items. This is because reasoning by exclusion tasks often require children to store uncertain or unknown representations in working memory, and then *update* those representations once they receive the relevant disambiguating information. Previous work has shown that when children have to update the contents of working memory (i.e., to reflect real-world changes to object locations), children make more errors and can store fewer items in memory than when they are only asked to store information in working memory without updating (Cheng & Kibbe, 2022). The reasoning by exclusion process itself also may incur some cognitive cost above and beyond the costs of updating in working memory, as children may have to expend cognitive effort to make inferences about unknown information from known alternatives. Previous work with adults has shown that reasoning tasks (e.g., syllogistic reasoning) draw substantially on working memory resources (Gilhooly et al., 1993), and children with higher working memory capacity do better on analogical reasoning tasks (Simms et al., 2018; see also Richland et al., 2006). Inferring unknown object properties from known alternatives may therefore be more demanding and more error-prone than storing known information in working memory, and as working memory load increases, children's reasoning by exclusion abilities may be more limited. However, as children develop greater working memory capacity, their reasoning by exclusion abilities also should increase.

On the other hand, previous work with adults has shown that reasoning by exclusion may be deployed automatically when working memory is taxed, reducing the overall burden on working memory (see e.g., van den Berg & Ma, 2018; Emrich et al., 2017). For example, as working memory load increases, an efficient strategy is maintaining a subset of to-be-remembered items rather than the entire set, and then using the remembered subset to infer the identities of the remaining object(s). Like other working memory strategies that occur automatically when working memory is taxed (e.g., chunking or recoding; Miller, 1956; Chase & Simon, 1973; Thalmann et al., 2019), reasoning by exclusion may be fundamental to working memory. Since young children have been shown to use a variety of efficient working memory

processes (including chunking, recoding, and metacognitive awareness; see e.g., Kibbe & Feigenson, 2014; Applin & Kibbe, 2020), reasoning by exclusion as an efficient working memory process could be operational even in young children. Under this possibility, reasoning by exclusion may not impose significant additional demands on working memory, and reasoning by exclusion should not be negatively impacted by increasing working memory load (or indeed, reasoning by exclusion may even become more reliable as working memory is taxed), and we would be unlikely to see improvements in reasoning by exclusion abilities as working memory capacity increases with development.

The present experiments

The goal of the present experiments was to systematically examine the cognitive cost of reasoning by exclusion by investigating the role of working memory in reasoning by exclusion abilities across development. In two experiments, we used a modified version of an identity-location binding working memory task (Cheng & Kibbe, 2022), in which sets of images of objects were occluded and children were asked to remember the locations of specific objects. In our modified task, children completed trials in which one of the object's identities was *unknown*, and children had to infer its identity using reasoning by exclusion to eliminate known alternatives. We manipulated working memory load in both experiments, and measured the impact of these manipulations on children's reasoning by exclusion abilities.

In Experiment 1, 4-6-year-old children viewed sets of virtual "cards" depicting images of different animals, which were then occluded. We then probed a location and asked children which image was hidden behind that occluder. Children responded by selecting one of the two images, either the correct target image or an incorrect distractor image of another animal that was hidden on that trial. In one block of trials, children performed a straightforward working memory task: all of cards in the set were presented "face up" before becoming occluded, such that the images on their faces were visible for children to encode. To succeed on these trials,

children needed to encode the location of each image, hold the location-identity bound representations in working memory during the maintenance period, and then recall the information when prompted for a response. In the other block of trials, all but one of the card faces were visible during the encoding period, while the remaining card was presented “face down” such that the image on its face was *unknown* during encoding (e.g., children observed a card with a bear on it and a face-down card). After the cards were occluded, children were probed on either a face-up card or on the face-down card. Success on trials in which children were probed on a face-down card required children to use reasoning by exclusion: children needed to remember the location and the identity of the card(s) that was(were) face up during encoding, and then use that information to rule out known alternatives and infer the identity of the probed card (“it’s not the bear, so it has to be the cat!”). We manipulated working memory load by varying the number of cards in the set.

In Experiment 2, we expanded our age range to include 4-8-year-old children and modified the method used in Experiment 1 to increase working memory load: children again completed two blocks of trials (a straightforward working memory task block and a reasoning by exclusion block), but the locations of the objects swapped places during the maintenance period, requiring children to *actively update* the contents of working memory by updating their representations of the locations of each object. On trials with a card facing down during encoding, this meant tracking and updating the location of the card with an unknown identity.

Together, the two experiments were designed to shed light on the cognitive cost of reasoning by exclusion in working memory across development. Specifically, we predicted different performance depending on the two possibilities we presented above for how reasoning by exclusion and working memory may interact. If reasoning by exclusion is an automatic strategy that children can deploy to make working memory more efficient, once children show the ability to reason by exclusion, then we would expect: 1) children should perform *better* on trials that require reasoning by exclusion compared to same set-size trials that only tap working

memory storage or updating; 2) on trials with a face-down object, children should perform similarly regardless of whether targets were presented face-up or face-down during encoding. Alternatively, if reasoning by exclusion imposes cognitive costs, we would predict that 1) children should perform worse on trials that require reasoning by exclusion compared to same set-size trials that only tap working memory storage or updating; 2) on trials with a face-down object, children should perform worse when probed on the face-down target compared to when they are probed on a target that was available during encoding. We also predicted that, if reasoning by exclusion and working memory share a common pool of cognitive resources, we should observe poorer performance on trials that require reasoning by exclusion as working memory load increases.

Finally, while previous work has studied the emergence of children's ability to reason by exclusion about object locations (e.g., Mody & Carey, 2016; see also Hill et al., 2012; Gautam, Suddendorf, & Redshaw, 2020; Grigoroglou, Chan, & Ganea, 2019), less is known about children's ability to reason by exclusion about unknown objects' *identities*, nor whether children's reasoning by exclusion abilities may change with development. An additional goal of the present experiments was to examine whether children can indeed reason by exclusion about unknown objects' identities, and whether the ability to use reasoning by exclusion to infer unknown identities may emerge across our age range.

Experiment 1

Method

Participants

Participants were 34 4- to 6-year-old children (mean age: 5 years, 6 months; range: 4 years, 1 month – 6 years 9 months; 17 girls). The size of the sample was determined prior to data collection based on a power analysis using G*Power 3.1 and was sufficient to yield 80% power to detect a medium-sized effect ($d = .5$) of a comparison between the Unknown-object

and Face-up blocks on children's performance using a paired samples t-test ($\alpha = .05$, two-tailed). Due to COVID-19 pandemic restrictions, participants were tested individually online via Zoom videoconferencing software (see Cheng & Kibbe, 2020, for a similar procedure). Children were recruited via recruitment events in the greater Boston area and participated in the current study after completing a separate, unrelated study. All participating families received a \$10 Amazon gift card for their participation. The study was approved by the Boston University Charles River Campus Institutional Review Board.

Apparatus and Stimuli

Children participated remotely from in a quiet room in their own homes using their own device with a screen at least 10 inches (32 used a laptop or a desktop computer, 1 used an iPad, and 1 used a Chromebook). Parents were asked before the start of the experiment to ensure that siblings were not present in the room during testing. Stimuli were designed and presented in Keynote presentation software running on the experimenter's computer, and were displayed to children using Zoom's screen sharing feature. Before the study began, parents were asked to hide the self-view video window and to position the experimenter's video window at the top center of the screen.

On each trial, children were asked to remember the animal characters depicted on 2 or 3 virtual "cards", which were selected from a total of 12 possible unique cards. The animal characters were images from the World of Eric Carle Mini Memory Match Game (Mudpuppy Toys) (see Figure 1; similar stimuli were used by Cheng & Kibbe, 2022). Sessions were recorded and saved to a secure campus server for later coding. The stimuli, data, and R analysis code for Experiments 1 and 2 can be found at

https://osf.io/m6qsb/?view_only=45d3934fbff2443da25e1c4f3fb28c8f.

Design

Test trials were divided into two blocks, a Face-up block and an Unknown-object block. On each Test trial, children viewed sets of either two cards (Set Size 2 trials) or three cards (Set

Size 3 trials) presented in a horizontal row. We chose these set sizes because previous work showed that children performed worse at Set Size 3 trials compared to Set Size 2 trials where there was a working memory updating component to the task (Cheng & Kibbe, 2022). We reasoned that, if reasoning by exclusion is impacted by working memory load, these set sizes would be sufficient to reveal those effects without inducing floor-level performance.

In the Face-up block, all of the cards were presented with their images visible (see Figure 1, panel a). In the Unknown-object block, all but one of the cards in the set had visible images, while the remaining card was presented “face down”, such that the image on the card was not visible (see Figure 1, panels b and c). The Face-up block was a straightforward measure of working memory ability: children needed to encode which object was hidden in which location, and maintain that information in working memory over a brief retention interval. The Unknown-object block, by contrast, included trials that also required reasoning by exclusion – the to-be-remembered set included an unknown image at encoding, and children were probed either on a previously-observed image in the array or on the unknown image, the identity of which could be inferred by ruling out the known alternatives.

Children were allowed to view the array for a total duration of 1 second per face-up card, after which the cards were hidden by occluders that descended from the top of the screen. The cards remained occluded for 1 s. Children were then probed to report the identity of one of the cards: an animated hand pointed to one of the locations and two images appeared above the probed location, the image that was hidden in that location (target) and an image that was hidden elsewhere in the array (distractor). The card on the left was labelled with a 1 and the card on the right was labelled with a 2. Children were asked to select which of the two cards was hidden in that location by verbally responding “1” or “2”. Whether the target appeared on the left or the right of the distractor was counterbalanced across trials.

Children completed one practice trial at the beginning of the study, and two additional practice trials before the Unknown-object block. Block order was counterbalanced across

children: half of children completed the Face-up block first, and the other half completed the Unknown-object block first. The entire task took about 10-15 minutes to complete.

Procedure

Initial practice trial. The experimenter told children “We are going to play a hide-and-seek game.” She showed children the entire set of 12 possible images and told children, “Each time, a few of my friends will appear, then they will then hide behind blocks. Your job is to help me figure out who is hiding where.” Children then saw two cards appear on screen for 2 s. The experimenter then said, “Now they are going to hide!”, after which children saw the occluders descend from the top of the screen. After 1 s, one of the locations was probed, and the experimenter asked, “Which one hides here?” Children selected their response from two images, the target image that had been hidden in that location or the image that had been hidden in the other location. The experimenter provided feedback on children’s responses by revealing the hidden target. If children answered correctly, the experimenter proceeded to the Test trials, otherwise the experimenter repeated the practice trial to ensure children understood the task. Thirty out of 34 children responded correctly on the first try. The remaining four children succeeded after repeating the trial once.

Face-up block. The Test trials in the Face-up block were similar to the initial practice trial, except that after the experimenter revealed the face of the card (giving children feedback on whether they responded correctly), children were not given the opportunity to repeat trials if they responded incorrectly. Children completed eight Test trials: four Set Size 2 trials, followed by four Set Size 3 trials (see Figure 1 for an example trial). The location of the probed card was counterbalanced across trials. When probed, children were always given a choice between two objects that had been observed on that trial.

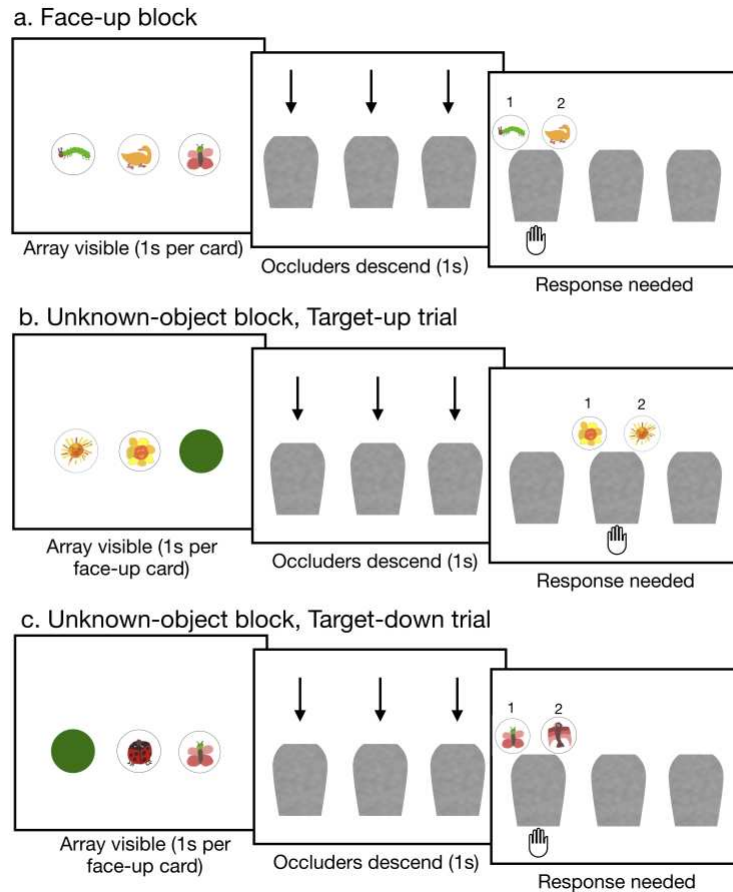


Figure 1. Example of Set Size 3 trials in the Face-up block (panel a) and Unknown-object block (panels b and c) of Experiment 1. In the Unknown-object block, the target was presented face-up during encoding on half of the trials (Target-up trial, panel b), and face down during encoding on the other half of trials (Target-down trial, panel c), requiring reasoning by exclusion to respond correctly (in this example, if children remembered the known location of the butterfly, they could use that knowledge to rule out the butterfly and select the bird). Children also completed Set Size 2 trials, not pictured. Note the actual images used in the experiments were not granted copyrights for publication, therefore the images displayed in Figure 1 and Figure 3 were recreated by the first author to be similar to the actual images.

Unknown-object block. The Unknown-object block began with two additional practice trials to familiarize children the fact that the virtual “cards” could be presented face up or face down. First, children saw an array of two cards, both facing down. The experimenter said, “Here are my two friends. But this time only one of them will turn around,” and children saw one of the cards flip over to reveal an animal image. The experimenter continued, “The other friend is going to be sneaky and he won’t turn around. He will only turn around once he hides behind the

block. Now they are going to hide like this!" The cards were then occluded, and children were probed on the occluded face-up card, choosing between the target and a previously unseen image (32/34 children succeeded the first time; for the remaining two children, the experimenter repeated the trial an additional two times before the children responded correctly.) This "flipping over" animation only occurred in the practice trial.

Next, the experimenter told children, "Sometimes we are going to look for the one that we did not see before." Children then saw two different cards, one facing up and one facing down, which were then occluded. Children were first probed on the occluded face-up card, choosing between a target and a previously unseen image (32/34 children answered correctly, the remaining two children succeeded after one repetition). Children were then probed on the occluded face-down card with the same two image choices (all children responded correctly the first time). The experimenter then explained, "Because we already knew that the [face-up card] is right over here [the experimenter circled the location of the face-up card with her mouse cursor], so it cannot be here under this block [she circled the location of the face-down card], so it had to be the other one, and that's the [face-down card]!"

Children then completed eight Unknown-object Test trials, four Set Size 2 trials then four Set Size 3 trials. Each trial proceeded similarly to the Face Up trials, except that one of the cards was presented face down and the rest were presented face up. Within each Set Size, children were probed on the face-up card on half of the trials (Target-up trials), and were probed on the face-down card on the other half of trials (Target-down trials). On Set Size 2 Target-up trials, children always chose between the target image and the unobserved image. On Set Size 3 Target-up trials, children chose between the target image and the unobserved image in one trial, and between the target image and the other visible image on the other trial¹. After children

¹ There was no difference in children's performance on Set Size 3 Target-up trials as a function of which image was the distractor, the unobserved image (27/34 children correctly chose the target) or the other visible image (29/34 children correctly chose the target) (Fisher's exact test $p = .75$)

responded, the experimenter revealed the card face, effectively giving children feedback on whether they responded correctly. Children completed one of two trial orders: Set Size 2 Target-up, Target-down, Target-down, Target-up followed by Set Size 3 Target-down, Target-up, Target-up, Target-down; or Set Size 2 Target-down, Target-up, Target-up, Target-down followed by Set Size 3 Target-up, Target-down, Target-down, Target-up.

Results

Analyses were conducted on children's responses on each trial (correct responses were coded as 1 and incorrect responses were coded as 0).

We first confirmed that children in our task could use reasoning by exclusion to infer the identity of the unknown object in the Unknown-Object block. Children's mean proportion correct across trials was significantly above chance (.5) at both set sizes in Target-up trials (in which they saw the image on the target card at encoding; mean proportion correct: $M_{ss2} = .97$, $M_{ss3} = .82$) and in Target-down trials (in which the target image was hidden during encoding and therefore needed to be inferred; $M_{ss2} = .85$, $M_{ss3} = .85$) (all $p < .001$, $BF_{10} > 1000$), suggesting that children were successfully using reasoning by exclusion to infer the identity of the unknown object. Further analyses confirmed that even the youngest children in our sample (4-year-olds) successfully inferred the identity of the unknown object in the Target-down trials ($p < .001$, $BF_{10} = 231.54$). All children also were significantly above chance in the Face-up block ($M_{ss2} = .80$, $M_{ss3} = .79$, both $p < .001$, all $BF_{10} > 1000$). See Table S1 for full results.

We next asked whether children's performance varied as a function of Working Memory Load (Set Size 2 or Set Size 3), Block (Face-up or Unknown-object), or Age (in years, continuous) using a generalized linear mixed-effects model (GLMM; R lme4 package; Bates et al. 2014) in which we entered Block, Block Order (Face-up Block first or Unknown-object Block first), Age, and Working Memory as fixed factors and participant and trial number as random factors. The best-fit model included the interaction between Block and Block Order (see

Supplemental Material Table S2 and S3 full GLMM results). We observed a main effect of Age ($\chi^2(1) = 17.12, p < .001, \beta = .66, SE = .16$) but no main effect of Working Memory Load ($\chi^2(1) = 1.82, p = .178, \beta = -.33, SE = .25$); children's overall performance in the task increased across our age range (see Figure 2, top panel). We also observed a main effect of Block ($\chi^2(1) = 13.71, p < .001, \beta = -1.41, SE = .38$), a main effect of Block Order ($\chi^2(1) = 7.55, p = .006, \beta = -1.21, SE = .44$), and an interaction between Block and Block Order ($\chi^2(1) = 8.82, p = .003, \beta = 1.53, SE = .52$). Children performed significantly better in the Unknown-object block when they completed this block *after* the Face-up block compared with children who completed the Unknown-object block first ($t(32) = -2.201, p = .035, d = .78$), while children performed similarly on the Face-up block regardless of trial order ($t(32) = 1.08, p = .288, d = .38$); see Figure 2, bottom left panel.

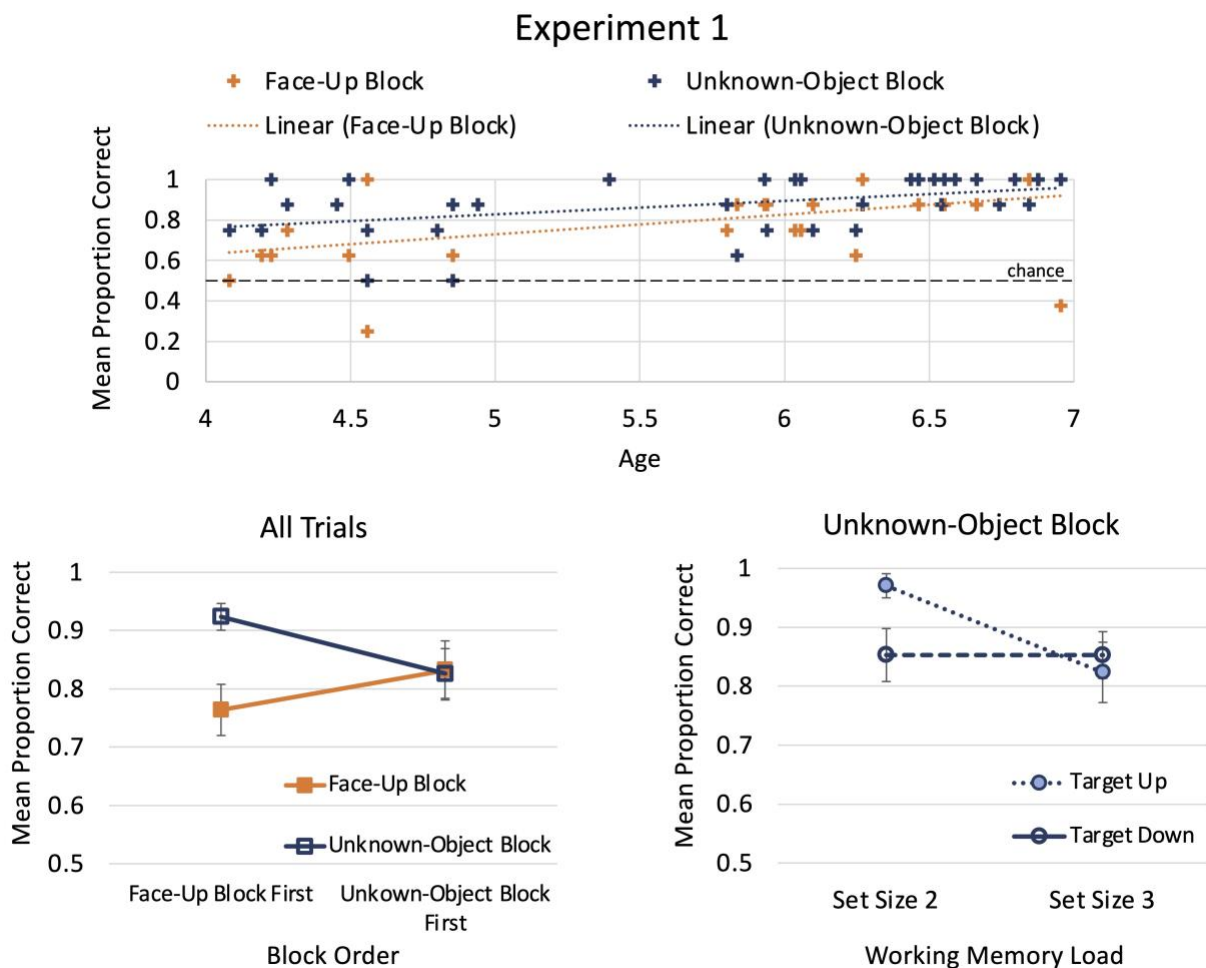


Figure 2. Summary of the results from Experiment 1. The top panel shows individual children's mean proportion correct in the Face-up and Unknown-object blocks (averaged across working memory load) as a function of age. The bottom left panel shows children's mean proportion correct on the Face-up and Unknown-object blocks as a function of Block Order. The bottom right panel shows children's mean proportion correct on Target-up and Target-down trials in the Unknown-Object block as a function of working memory load. Error bars represent ± 1 standard error of the mean.

Finally, we examined the extent to which reasoning by exclusion impacted performance in the Unknown-Object block. The design of the Unknown-Object block allowed us to directly measure the impact of reasoning by exclusion on children's ability to report the identity of the probed target. We compared children's performance in trials in which the target object had been observed before occlusion (Target-up trials) to their performance on trials in which the identity of the target object had to be inferred (Target-down trials). A central aspect of the design is that, in both trial types, children did not know ahead which object would be probed during the response period. If reasoning by exclusion does not impose additional demands on working memory, we predicted that children should perform similarly in Target-down and Target-up trials (since both trial types require encoding one unknown and either one (Set Size 2) or two (Set Size 3) known objects). If children show poorer performance in the Target-down trials, it would suggest that reasoning by exclusion may be more challenging than simply recalling the presented information.

We submitted Block Order, Age (continuous, in years), Working Memory Load (Set Size: 2 vs. 3), and the target's availability during encoding (Target Availability: Target-up or Target-down) as fixed factors, and participant and trial number as random factors, to a generalized linear mixed-effects model. The best fit model included interactions between Target Availability and Working Memory Load (full model results are shown in Supplemental Materials Table S4 and S5). Again, we observed a main effect of Age ($\chi^2(1) = 10.64$, $p < .001$, $\beta = .74$, $SE = .23$), with children's performance increasing with age, a main effect of Block Order ($\chi^2(1) = 5.16$, $p = .023$, $\beta = -.99$, $SE = .44$), with children who completed the Face-up block first performing

better overall, and no main effect of Working Memory Load ($\chi^2(1) < .001$, $p > .99$, $\beta < |.001|$, $SE = .51$), with children performing similarly well in both Set Size 2 and Set Size 3 blocks. Crucially, we observed a main effect of Target Availability ($\chi^2(1) = 5.08$, $p = .024$, $\beta = 1.83$, $SE = .81$) and an interaction effect between Target Availability and Working Memory Load ($\chi^2(1) = 4.75$, $p = .029$, $\beta = -2.07$, $SE = .95$): at Set Size 2, children performed better in Target-up ($M = .97$) compared to Target-down ($M = .85$) trials (paired samples $t(33) = 2.48$, $p = .019$, $d = .86$); at Set Size 3, children performed similarly in Target-up trials ($M = .82$) and Target-down trials ($M = .85$) (paired samples $t(33) = .57$, $p = .57$, $d = 0.20$). In Target-up trials, children performed worse at Set Size 3 compared to Set Size 2 (paired samples $t(33) = 2.96$, $p = .006$, $d = 1.03$), while children's performance in Target-down trials was similar between Set Size 2 and Set Size 3 (paired samples $t(33) = 0$, $p = 1$, $d = 0$). These results are depicted in Figure 2, bottom right panel.

Discussion

Experiment 1 required 4-6-year-old children to encode and maintain a set of images in working memory for a brief retention interval, and to then report on the identity of one of the objects by choosing from two alternative choices. Children completed two blocks of trials, a Face-up block in which all the objects were visible during encoding (a straightforward working memory task), and an Unknown-object block in which one of the objects was not visible during encoding, requiring children either to recall a previously observed object (Face-up trials) or to infer an unknown object's identity using reasoning by exclusion (Unknown-object trials).

We found that children were able to select the correct identity of the probed object at rates significantly above chance, both when they were probed on an object that was available during encoding and when the identity of the object had to be inferred, suggesting they were able to use reasoning by exclusion to infer unknown object identities. We also found that

children's overall performance was not affected by increasing memory load in either block. Since children's accuracy was high at both set sizes regardless of whether children were completing the straightforward working memory task or whether they had to use reasoning by exclusion, we speculate that the working memory loads we chose may not have been sufficient to elicit differences in performance. Further, children's performance in both blocks increased with age, but did not vary differentially across blocks, suggesting that children's exclusive reasoning abilities across this age range may be primarily constrained by their working memory capacities rather than limitations on reasoning abilities themselves, at least under the conditions tested here.

Importantly, we found that when the task required reasoning by exclusion, children performed differently than when they were simply asked to store information in working memory, in a few ways. First, we found that children who completed the Face-up block *before* completing the Unknown-object block performed better in the Unknown-object block compared to the Face-up block, while children who completed the Unknown-object block first showed similar performance across both blocks. We speculate that children who completed the Face-up block first may have benefitted from getting practice with the straightforward working memory task before having to deploy reasoning strategies in the Unknown-object block. For example, children may have benefitted from having experience with the effort involved in encoding and maintaining sets of objects (see Applin & Kibbe, 2020), and may have been more apt to make efficient use of reasoning by exclusion as a strategy following that experience.

Second, children's performance in the Unknown-object block yielded important insights into how reasoning by exclusion may interact with working memory in children. Children's ability to select the correct target in Target-up trials (no reasoning by exclusion required to succeed) and Target-down trials (reasoning by exclusion required to succeed) was dependent on working memory load. When memory load was lower (Set Size 2 trials), children performed near perfectly in trials in which the target was presented face-up at encoding, but took a hit to

performance when the target was presented face-down. However, when memory load was higher (Set Size 3 trials), children's performance in Target-up trials was similar to Target-down trials. Further, children's performance in Target-up trials was impacted by set size, consistent with previous work that examined working memory in children this age (e.g., Cheng & Kibbe, 2022), while children's performance in Target-down trials was not impacted by the increase in working memory load.

There may be several possibilities that could account for these results. One possibility is that these results may be a product of the fixed order in which the set sizes were presented within each block (Set Size 2, followed by Set Size 3). By completing Set Size 2 first, children had the opportunity to "practice" solving the Target-down trials at a relatively lower cognitive load, and this practice allowed them to carry this effective strategy over to Set Size 3 trials with less cost.

A second possibility is that these results may suggest a strategy for how children are solving the task. Specifically, in the context of our task, the process of ruling out known alternatives to identify the unknown target may be dependent on two factors: a) keeping track of the *location* of the unknown object and b) keeping track of the *identities* of the known objects (but not necessarily their specific locations). At Set Size 2, where there was only one possible location for the known identity, children were nearly perfect at selecting the target identity when probed on the object that was face-up at encoding, but took a hit to performance when probed on the object that was face-down at encoding, suggesting that the reasoning by exclusion process incurred some cognitive cost. At Set Size 3, where there were two possible locations for the known objects, children performed worse than at Set Size 2 when the objects were face-up at encoding, but performed similarly to Set Size 2 trials when probed on the object that was face-down at encoding.

We speculate that, at Set Size 3, children could have used a strategy of *quarantining* the unknown location from the known locations, and when probed on that location, used what they

remembered about the known identities (unbound to spatial location) to reason by exclusion about the identity of the unknown object, incurring a similar cognitive cost as in Set Size 2 trials. However, when they were probed to recall the *specific bindings* between identities and locations of the face-up objects, they may have produced binding errors that resulted in slightly lower performance – essentially, a set size effect but only for the objects that were *visible* at encoding.

To give an example of this strategy, take the case of a child who is completing the trial depicted in Figure 1c. In this trial, the child viewed a face-down card (on the left) and two face-up cards: a ladybug and a butterfly. Faced with this information, children could maintain in working memory the *location* of the face-down card (“the leftmost spot”) and the identities of the face-up cards (“the ladybug and the butterfly”), but may not reliably encode the locations of the face-up cards (e.g., the child does not encode that the ladybug is in the middle and the butterfly on the right). When probed on the face-down card, children can successfully and easily rule out the ladybug or the butterfly, performing similarly to Set Size 2 Target-down trials. However, if probed on one of the face-up cards, children may be more likely to answer incorrectly, because they may not have encoded the precise locations of the cards in working memory. This strategy would therefore yield a “set size effect” between Set Size 2 and Set Size 3 trials, but only the cards that were face-up at encoding.

In Experiment 2, we examined the impact of working memory load on children’s ability to use reasoning by exclusion to infer unknown identities using a task that made such a quarantining strategy much more difficult to deploy. The task was similar to Experiment 1, except we introduced dynamic change in the objects’ locations (Cheng, Káldy, & Blaser, 2019; Cheng & Kibbe, 2022; Feigenson & Yamaguchi, 2009; Kibbe & Leslie, 2013; Pailian et al., 2020): after the images were occluded, the occluders swapped locations one or two times, requiring children to not only store information about which image was hidden in which location and which location contained an unknown identity, but to also update that information as the locations shifted. As previous work showed that children’s working memory updating undergoes

protracted development from 6 to 8 years (Cheng & Kibbe, 2022; Pailian et al., 2020), to capture a more complete developmental picture we expanded our age range to include 7- and 8-year-olds in addition to 4-, 5-, and 6-year-olds, and increased our sample size within each age group. Our goal for Experiment 2 therefore was to extend the results of Experiment 1, modifying the task to make greater demands on working memory and to make relying on alternative strategies more difficult.

Experiment 2

Method

Participants

Eighty-five 4- to 8-year-old children (mean age: 6 years, 3 months; range: 4 years, 0 months – 8 years 11 month; 43 girls) participated in the study. We first recruited a sample of 4-6-year-olds with a sample size determined to yield 80% power to detect small effects ($f = .2$) on children's performance using linear multiple regression with Block (Unknown-object or Face-up), Working Memory Load (Set Size 2, two swaps; Set Size 3, one swap; Set Size 3, two swaps), and Age as factors, and participant as a random factor (suggested sample size $n=59$). After data collection began, we decided to expand the age range to include 7-8-year-olds in order to better understand any developmental trends that we might observe in the data, aiming to have roughly equal numbers of children in each age year. The final sample included 19 4-year-olds, 18 5-year-olds, 16 6-year-olds, 16 7-year-olds, and 16 8-year-olds. We excluded two additional children from analysis because they did not complete the study. Due to COVID-19 pandemic restrictions, children were tested online using Zoom videoconferencing software. Children completed this study after completing a separate, unrelated study, and received a \$10 Amazon gift card for their participation. The study was approved by the Boston University Charles River Campus Institutional Review Board.

Apparatus and Stimuli

The stimuli were similar to those used in Experiment 1. Children participated in the study from their homes. Eighty-two children used a laptop or a desktop computer, and three children used a tablet.

Design

Children completed a Face-up block and an Unknown-Object block, with block order counterbalanced across participants. The task was similar to Experiment 1, except during the maintenance period the occluders swapped locations by physically moving across the screen (Figure 3). In Set Size 2 trials, the two occluders swapped places with each other. In Set Size 3 trials, for each swap, a subset of occluders was chosen pseudo-randomly to swap.

We varied the working memory load within each block by varying both the set size and the number of times the cards swapped places. Working memory load was chosen based on preliminary testing of $n=36$ 4-6-year-olds in the laboratory (prior to the onset of COVID-19 restrictions) on a face-up version of the task using a range of updating loads. We used these preliminary data to determine three updating loads that were not too easy nor too difficult for children in this age range, but that also appeared to yield some variability in performance. These working memory loads were Set Size 2 two swaps, Set Size 3 one swap, and Set Size 3 two swaps. Critically, because the objects swapped places during the maintenance period, children in Experiment 2 would have more difficulty using a “quarantining” strategy in which they kept their representation of the unknown object separate from their representations of the known objects.

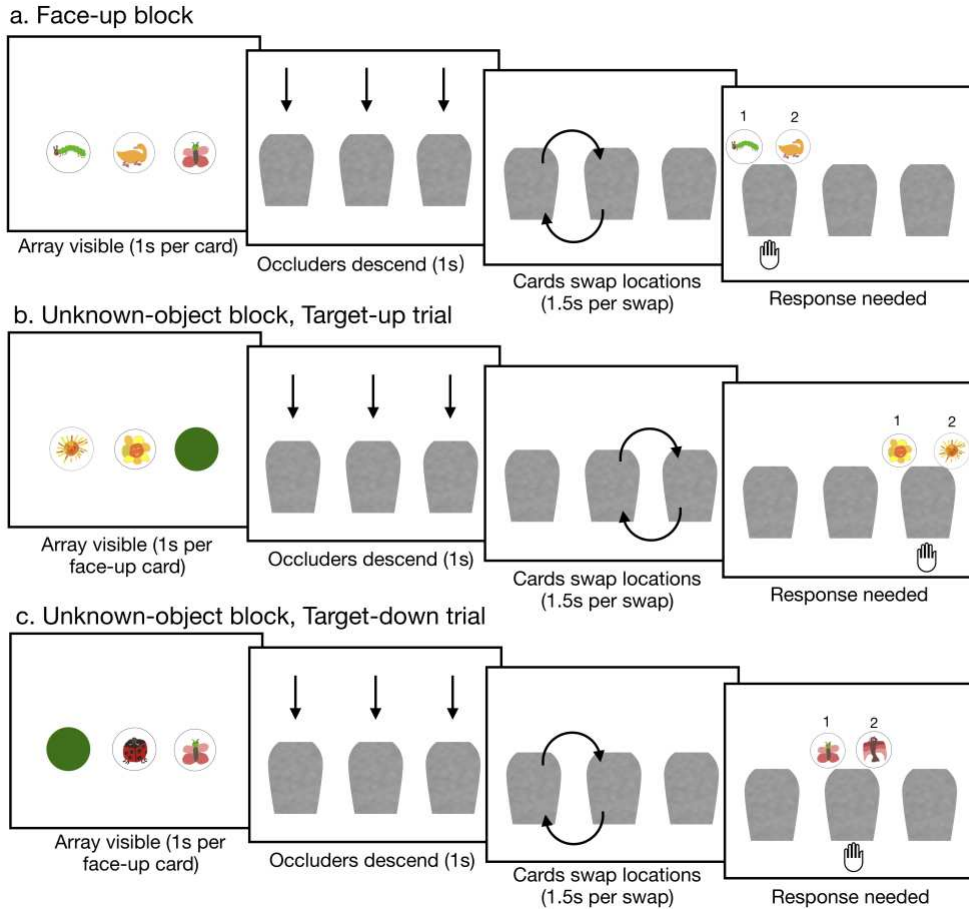


Figure 3. Examples of Set Size 3 one swap trials in the Face-up block (panel a) and Unknown-object blocks (panels b and c) of Experiment 2. In the Unknown-object block, children completed trials in which the probed card was visible during encoding (Target-up trial, panel b) and trials in which the probed card was face-down during encoding (Target-down trial, panel c).

Procedure

Initial practice trials. The first practice trial was the same as in Experiment 1 (81/85 children chose correctly the first time, the remaining four children succeeded after repeating the trial once). In the second practice trial, children were introduced to the swap movement. The experimenter explained, “Let’s try this one. Here are my two friends, they are going to hide again, but this time after they hide they are going to move, and we have to keep track of where they are hiding. Here we go!” Children saw two cards appear on the screen, which were then occluded. The occluders then swapped locations once (taking the cards with them). Children were then probed to select the identity of the card hidden behind one of the occluders from two

alternatives, and were given feedback on their responses. Seventy-four out of 85 children succeeded the first time. The remaining 11 children succeeded after one repetition of the trial.

Face-up block. Test trials in the Face-up block were similar to the second practice trial, except that, after the experimenter revealed the face of the probed card, children did not have the opportunity to repeat trials if they had answered incorrectly. There were 12 Face-up trials in total. Children first completed four Set Size 2 two swaps trials, followed by four Set Size 3 one swap trials, and finally four Set Size 3 two swaps trials. The location of the probed image and whether the target image appeared on the left or the right of the distractor image were counterbalanced across trials. Figure 3 (panel a) shows an example Set Size 2 two swaps Face-up trial.

Unknown-object block. Children first completed two Unknown-object practice trials, which proceeded similarly to the Unknown-object practice trials in Experiment 1, except that the objects swapped locations once following occlusion. Feedback was provided and the trial was repeated if children's responses were incorrect. In the first Unknown-object practice trial, children were probed to select the identity of the face-up card (72/85 children succeeded the first time, the remaining 13 children succeeded after one repetition). In the second practice trial, the experimenter first probed the location where the face-up card was hidden (78/85 children succeeded the first time, and the remaining children responded correctly after the second presentation), then the location of the face-down card with the same two alternatives (all children correctly chose the previously unseen image the first time).

The test trials proceeded similarly to the practice trials except that after given feedback they were not allowed to repeat a trial if they responded incorrectly. As in the Face-up block, the location of the probed card and whether the target image appeared on the right or left of the distractor image were counterbalanced across trials. Children completed 12 trials, four trials each of Set Size 2 two swaps, Set Size 3 one swap, and Set Size 3 two swaps, presented in blocks, with block order fixed across participants (children always completed Set Size 2 two

swaps first, followed by Set Size 3 one swap, then Set Size 3 two swaps). Within each block, two trials were Target-up trials (see Figure 3, panel b for an example) and two were Target-down trials (see Figure 3, panel c, for an example). In Set Size 3 Target-up trials, children chose between the target image and the unobserved image in half of the trials, and between the target image and the other visible image on the other half of the trials². The probed card was always involved in at least one swap movement, but in Set Size 3 two-swap trials, the probed card sometimes swapped during the first swap movement and sometimes during the second swap movement. The order of the trials within each block were counterbalanced following the ABBA or BAAB pattern.

Results

We first confirmed that children could use reasoning by exclusion to infer the identity of the unknown object in a task that made more demands on working memory. We found that, overall, children performed significantly above chance in the Unknown-Object block in both Target-Up and Target-Down trials, suggesting successful reasoning by exclusion (all $p < .001$, $BF_{10} > 1000$; similar results were observed for the Face-up Block). However, when we binned children into groups based on their age in years and compared each group's performance on Target-down trials to chance, we found that only children 6 years and older showed above-chance performance (all $p < .001$, $BF_{10} > 69$), while 4- and 5-year-olds' performance on Target-Down trials was not different from chance (see Supplemental Materials Table S6).

Next, we ran a GLMM with Block (Face-up or Unknown-object), Block Order (Face-up block first or Unknown-object block first), Age (continuous, in years), and Working Memory Load

² There was no difference in children's performance on Set Size 3 Target-up trials as a function of which image was the distractor, in one swap trials, 65/85 children correctly chose the target when paired with the unobserved image, and 55/85 children correctly chose the target when paired with the visible image (Fisher's exact test $p = .13$); in two swaps trials, 57/85 children correctly chose the target when paired with the unobserved image, and 66/85 children correctly chose the target when paired with the visible image (Fisher's exact test $p = .17$)

(Set Size 2 two swaps, Set Size 3 one swap, Set Size 3 two swaps), entered as fixed factors and participant and trial number as random factors. The best fit model included an interaction between Age and Block (see Supplemental Material Table S7 and S8 for full GLMM results). We observed a main effect of Age ($\chi^2(1) = 70.45, p < .001, \beta = .60, SE = .07$), a main effect of Block ($\chi^2(1) = 6.14, p = .013, \beta = 1.19, SE = .48$), and an interaction between Block and Age ($\chi^2(1) = 5.23, p = .022, \beta = -.18, SE = .078$), and no other main effects or interactions were significant; while children performed better overall in the Face-up block compared to the Unknown-object block (regardless of working memory load), performance in both blocks converged with age (see Figure 4, top panel).

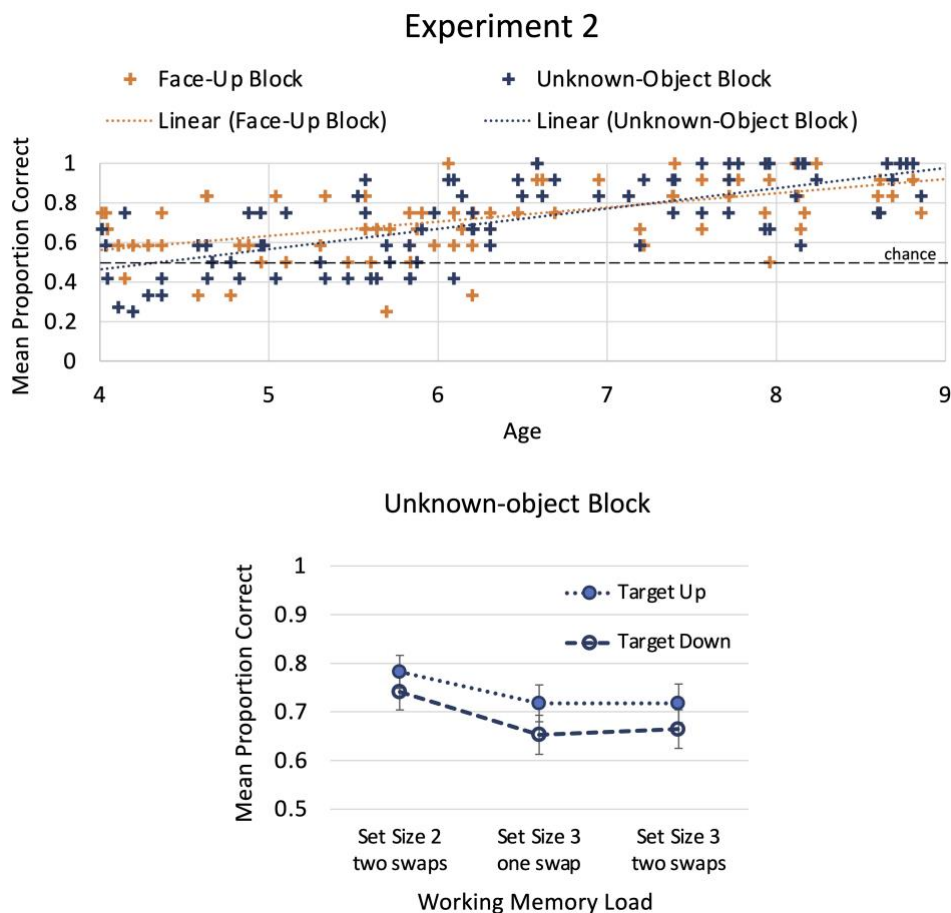


Figure 4. Summary of the results from Experiment 2. The top panel shows individual children's mean proportion correct in the Face-up and Unknown—object blocks (averaged across working memory load) as a function of age. The bottom panel shows children's mean proportion correct

in the Target-up and Target-down trials in the Unknown-object block as a function of working memory load. Error bars represent +/-1 standard error of the mean.

Finally, we analyzed children's performance in the crucial Unknown-object block. We entered Working Memory Load (Set Size 2 two swaps, Set Size 3 one swap, Set Size 3 two swaps), Target Availability at encoding (Target-up trial or Target-down trial), Age (continuous, in years) and Order (Face-up block first or Unknown-object block first) as fixed factors and participant and trial number as random factors into a GLMM. The best fit model did not include any interactions between variables (see Supplemental Material Table S9 and S10 for full GLMM results). We again observed a main effect of Age ($\chi^2(1) = 69.24, p < .001, \beta = .60, SE = .072$), but also a main effect of Working Memory Load ($\chi^2(2) = 8.16, p = .017$), with children performing better overall on Set Size 2 two swaps trials compared to both Set Size 3 trials. Crucially, we observed a main effect of Target Availability ($\chi^2(1) = 4.10, p = .043, \beta = .31, SE = .15$); children's performance was higher in the trials where the probed card was visible during encoding compared with trials where the probed card was not visible during the encoding period (Figure 4, bottom panel), and this pattern was consistent across our age range. Indeed, inspection of Figure 4 shows children's performance in Target-up trials was consistently higher than Target-down trials across working memory loads.

Discussion

In Experiment 2, we increased working memory load by introducing dynamic change in the locations of the objects during the retention interval. In addition to making the working memory task more demanding, the dynamic motion of the objects during the maintenance period made it more difficult for children to use a strategy of "quarantining" the unknown object from the known objects: children had to bind both the *known* and *unknown* identities of objects to specific locations, and then track and update those locations to successfully identify the target, either by retrieving it from memory (Face-up block; Unknown-object block Target-up

trials) or by inferring its identity by ruling out known alternatives (Target-down trials). We also expanded our age range to include children ages 4-8 years.

We found that, overall, children performed better in the Face-up block than in the Unknown-object block overall, suggesting that maintaining an array of known identities in working memory is less error-prone than maintaining an array with an unknown identity. It is important to note that children had to remember *more* identities at the outset in the Face-up block compared to the Unknown-object block. Children's poorer performance in the Unknown-object block suggests that the costs of maintaining/inferring an unknown identity in working memory is higher than the cost of maintaining an additional *known* identity in working memory. We also failed to replicate the block order effect from Experiment 1: children in Experiment 2 no longer benefitted from completing the Face-up block first, perhaps due to the higher working memory loads in Experiment 2.

The expansion of our age range in Experiment 2 revealed a developmental trend: performance on the Face-up and Unknown-object blocks began to converge around ages 6-7 years, with older children achieving similar performance across the two blocks. This result suggests that the costs associated with maintaining/inferring an unknown object's identity ease with development, perhaps as children develop further executive control abilities (see General Discussion for further discussion).

We also found that, in the Unknown-object block, when the dynamic change in the objects' locations made using a "quarantining" strategy difficult, children performed better when they were probed on a known-identity target than when they were probed on a target whose identity they needed to infer, and this difference in performance was consistent working memory loads and across age. We discuss the broader implications of these results in the General Discussion.

General Discussion

Reasoning by exclusion often necessitates reliance on limited working memory – to successfully rule out known alternatives, children must hold those alternatives in mind, along with a representation of the unknown object or location. In two experiments, we examined the cognitive cost of reasoning by exclusion in working memory by investigating the impact of working memory load on reasoning by exclusion abilities during a period of childhood in which working memory is undergoing considerable development. Our results suggest three main takeaways about the cognitive cost of reasoning by exclusion in working memory across development.

First, we found that reasoning by exclusion to infer unknown identities by ruling out stored alternatives in working memory is not cost-free for children. While previous work suggested that adults may use reasoning by exclusion to make working memory *more* efficient and *less* effortful (e.g., van den Berg & Ma, 2018; Emrich et al., 2017), children appeared to take a “hit” to performance when they had to reason by exclusion compared to when they were asked to simply report the identity of a stored item in working memory. And children’s overall worse performance on Unknown-object trials in which the target object’s identity had to be inferred compared to when they were probed on a known object suggested that, even if children remember the identit(ies) of the known alternative(s), they do not necessarily use those representations reliably to make the correct inference. Our results suggest that the reasoning by exclusion may incur a one-time cognitive cost -- working memory load appeared to impact performance on both Target-up and Target-down trials similarly (particularly evident in Experiment 2 in which a strategy of “quarantining” the unknown object from the known objects was significantly more difficult).

Second, we also found that children’s performance in trials that required reasoning by exclusion to infer an unknown identity appeared to improve with development. In Experiment 2, in which we extended our age range to include children ages 4-9 years, we found that around age 6-7 years children’s performance on the straightforward working memory task (the Face-up

block) and their performance on the reasoning by exclusion task (the Unknown-object block) began to converge. Indeed, while the development of working memory capacity itself may be one limiting factor in reasoning by exclusion across development, these results suggest that the sources of children's limitations on reasoning by exclusion may be more nuanced.

One possible source of the cognitive cost of reasoning by exclusion may come from the way children distribute limited working memory resources across the items in the array. While younger children may have distributed their working memory resources evenly across all of the items in the display, older children may be able to use a strategy of tracking only the objects for which they observed identities, which would require children to proactively plan which item(s) they should attend to (Chevalier et al., 2014) while inhibiting and actively not tracking the unknown object (Zelazo et al., 2014), and then using reasoning by exclusion only when probed on the unknown (and untracked) object. Previous work suggests children shift from more reactive to more proactive working memory recall strategies (Chevalier et al., 2014) and show improved metacognitive awareness of working memory limitations between 5 and 7 years of age (Applin & Kibbe, 2020), consistent with a possible strategy shift around age 6-7.

In fact, children's pattern of performance in Experiment 1 shows some hints that such strategies may be deployed even by younger children under the right circumstances. In Experiment 1 (in which children did not have to dynamically update their representations in working memory), children performed *better* in the Unknown-object block when they completed this block after completing the more straightforward working memory task block (the Face-up block). Since both the Face-up and Unknown-object blocks required children to maintain sets of static objects, children may more easily have been able to recognize the similarity between the tasks - children may thus have been able to use the static working memory task to get their feet under them, allowing them to subsequently realize that they could deploy a more efficient strategy for reasoning by exclusion in the Unknown-object block. Second, the interaction between working memory load and target availability in Experiment 1 suggested that children

may indeed have used a strategy of inhibiting or quarantining the unknown object when the demands of the task made it relatively easy to do so (as when children only needed to maintain static arrays). Further work is needed to understand the strategies that children use when reasoning by exclusion under varying task demands, and how those strategies may shift with the development of working memory or cognitive control.

Another possible source of cognitive effort in our task is related with how children represent the face-down card: what do children represent about an object that has an unknown identity? In our study, younger children's ability to track and update working memory for known object identities may be less robust under conditions with unknown identities (see Kovacs et al., 2021 for similar evidence in an uncertain belief updating task), particularly in Experiment 2 when the location of the unknown object needs to be dynamically tracked along with other, known objects. In Unknown-object trials, children may have deployed object-file representations for each object (known and unknown) in order to track all of these objects as they moved through space. Younger children's ignorance of the identity of one of the object-file representations may have interfered with maintaining and tracking identity-bound object representations of the other object(s) as they moved (see Ma & Flombaum (2013) for evidence of unknown number of targets impacting multiple object tracking in adults). Children's difficulty in dynamically tracking the locations of object files with unknown identities in working memory may be resolved by the maturation of attentional or representational resources with age, as evidence by the age-related improvement in children's performance in the Unknown-object block of the Experiment 2. More work is needed to understand how representing object files with unknown identities impacts object tracking, storage, and updating in working memory, and how this ability might change with development.

To summarize, we observed a developmental increase in children's ability to infer an unknown identity using reasoning by exclusion. Yet, there are many potential sources of the observed developmental increase, including but not limited to children's ability to remember,

track, and update known and unknown object identities, improved flexibility in planning, and development in the ability to reason by exclusion. Future work is needed to identify the role of a range of cognitive factors to the developmental improvement we observed.

Third, our study provides an additional data point on early reasoning by exclusion abilities in children. Previous work that investigated the emergence of reasoning by exclusion abilities in development suggested that 3-year-old children can use reasoning by exclusion to infer the location of a hidden object (e.g., Mody & Carey, 2016; Grigoroglou et al., 2019) and infants can resolve ambiguity in the identity of a partially visible object prospectively (Cesana-Arlotti et al., 2018, 2020) when all possible alternatives are already known at the outset. Our results extend this previous work by showing that, by at least age 4 (the youngest age tested here), children can exclude known alternatives to infer the identity of an unknown object (albeit at a cost) and that these abilities interact with working memory load and undergo developmental change across early to middle childhood. Future work would examine the emergence of this reasoning by exclusion about unknown identities in younger children. Future work also should examine the development of reasoning by exclusion to make inferences about locations or other aspects of objects. Since previous work has shown that working memory for object locations may be less effortful and may follow a different developmental trajectory than working memory for identity-location bound objects (Kibbe & Applin, 2022; Kibbe, 2015), reasoning by exclusion over these different types of information in working memory also may undergo different developmental trajectories.

Could children have been using strategies other than reasoning by exclusion to do the task? Whenever children were probed an unknown object, they were presented with two alternative choices: an image that had appeared on that trial and an image that did not appear on that trial. Children could potentially have succeeded at selecting the correct image using a strategy of choosing novelty (or avoiding familiarity), rather than reasoning by exclusion. However, while possible, there are reasons to think that children were not doing this. First, if

children were using such a strategy, their performance on Target-up trials and Target-down trials should be similar, since the ability to choose novelty (or avoid familiarity) would be entirely dependent on the ability to remember the other targets that appeared on that trial, regardless of working memory load, and should be relatively easy to do if one can remember the other objects. However, we observed poorer performance when children were probed on the unknown object compared to known object, inconsistent with such a strategy. Further, if children were choosing novelty or avoiding familiarity, the ability to do so should become more difficult across trials; because objects were drawn from a finite set, the likelihood of proactive interference from previous trials increased across trials (Hamilton et al., 2022), and objects became less novel overall. Thus, if children were using a “choose novelty” strategy, we might expect children to perform worse when the Unknown-object block was presented second. However, we found that in Experiment 1 children performed *better* in the Unknown-object block after completing the Face-up block first, and we did not observe any reliable order effects in Experiment 2. While it is still possible that children may have used a mix of strategies on our task, we think it is unlikely that they were using purely non-exclusion-based strategies. Future work would investigate the kinds of strategies children may use when approaching a cognitively effortful task involving reasoning or inference.

Conclusions

The ability to make inferences about unknown or uncertain information by ruling out known alternatives is a powerful means of resolving representational uncertainty in our environments, and this ability makes working memory operate more efficiently in adulthood. Previous work suggested that the ability to use reasoning by exclusion to infer object locations emerges early in development. Our results suggest that the ability to reason by exclusion about object identities may operate at a cost early in development. While even young children can retroactively assign an identity to an unknown object by ruling out known identities stored in

working memory, this ability was more error-prone than recalling information stored in working memory. With age, children's ability to reason by exclusion in working memory converged with their working memory recall abilities.

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