Finding the (most efficient) way out of a maze is easier than asking (good) questions.

Nora Swaboda

Max Planck Institute for Human Development, Berlin

Björn Meder

Max Planck Institute for Human Development, Berlin and University of Erfurt

Azzurra Ruggeri

Max Planck Institute for Human Development, Berlin and Technical University Munich

Abstract

We investigate whether a spatial representation of a search task supports 4- to 7-year-old children's information-search strategies, relative to their performance in a question-asking game. In Experiment 1, children played two computationally and structurally analogous search games: a spatial search task, the maze-exploration game, in which they had to discover the path through a maze, and a verbal search task, the 20-questions game, where they had to identify a target monster from a set of eight monsters by asking yes-no questions. We found that children made more informative queries in the maze-exploration game than in the 20-questions game. Children's performance in the 20-questions game improved with age, whereas there were no age-related differences in the spatial task. In Experiment 2, we introduced a non-verbal version of the 20-questions game, in which children had to select which features to query (e.g., color) in order to identify the target monster. We found that children performed equally well in both tasks, with no age-related performance differences. Our results demonstrate that efficient search strategies emerge much earlier than previously assumed, suggesting that young children's difficulties in the 20-questions game are directly related to the verbal requirements of the task. These findings highlight the importance of developing age-appropriate paradigms that capture children's early competence, in order to gain a more comprehensive picture of their emerging information-search abilities.

Finding the (most efficient) way out of a maze is easier than asking (good) questions.

Introduction

It's Saturday morning and suddenly you remember that today is your godchild's birthday! Surely, any 4-year-old would love a unicorn float! Excited about your idea, you head to the nearest toy store. Once you enter, your spirits drop: how are you going to find what you are looking for within this maze of shelves storing thousands of colorful toys? You decide to explore the corridors yourself. An efficient way to find the unicorn float would be to think about the hierarchical categories it belongs to (e.g., outdoor vs. indoor toys, beach toys, a float) and search the store accordingly (i.e., find the section for outdoor toys, then beach accessories, and then floats). The ability to represent objects as embedded in a hierarchical categorical structure is also a crucial component of asking informative questions. Once you arrive at the party, your godchild curiously tries to guess what the present is ("Is it a book?", "Is it a jigsaw puzzle?"). You cannot help but think that their search would be more effective if they approached the problem top-down, just as you did at the store, by targeting higher-level categories first and narrowing down the space systematically question after question (e.g., "Is it an outdoor toy?", "Is it something for the beach?"). Also, you wonder if they would have been efficient at searching for the unicorn float at the store as, in this situation, asking question would not have been necessary. This paper investigates across two studies whether and how a *spatial* representation of a search task supports 4- to 7-year-old children's information-search strategies, relative to their performance in a question-asking game.

The emergence and development of effective information search

The development and quality of children's information-search strategies has frequently been investigated using the 20-questions game (e.g., Legare, Mills, Souza, Plummer, & Yasskin, 2013; Meder, Nelson, Jones, & Ruggeri, 2019; Mosher & Hornsby, 1966; Nelson, Divjak, Gudmundsdottir, Martignon, & Meder, 2014; Ruggeri & Feufel, 2015; Ruggeri & Lombrozo, 2014; Ruggeri, Lombrozo, Griffiths, & Xu, 2015, 2016). Its

goal is to identify a target object among a given set (e.g., “What present did you get for your godchild?”) by asking as few yes-no questions as possible. Initially, the question asker entertains a certain set of hypotheses (“hypothesis space”) that includes all the potential solutions to the problem at hand (e.g., all possible items from the toy store). Through a process of elimination, the initial hypothesis space is narrowed down until only one hypothesis, the correct solution, remains. Questions in this game have traditionally been classified into *hypothesis-scanning* questions, which target a single hypothesis within the given set of options (e.g., “Is it the yellow beach ball?”), and *constraint-seeking* questions, which target features shared by several hypotheses (e.g., “Is it an outdoor toy?”). Because constraint-seeking questions are able to rule out multiple hypotheses at each step of the search process (e.g., all indoor toys), they are typically considered more informative than hypothesis-scanning questions (although this is not always true, see Meder et al., 2019; Nelson, Meder, & Jones, 2018; Ruggeri et al., 2015; Ruggeri, Sim, & Xu, 2017).

Previous research employing the 20-questions paradigm has shown that the informativeness of children’s questions steadily increases with age: until age 7, children almost exclusively ask hypothesis-scanning questions (Herwig, 1982; Mosher & Hornsby, 1966; Ruggeri & Feufel, 2015; Ruggeri et al., 2015, 2016). Children begin to rely more on constraint-seeking questions around age 10, until asking constraint-seeking questions becomes the dominant strategy in adulthood (Ruggeri & Feufel, 2015; Ruggeri et al., 2015). Recently, more computationally-oriented studies, which assess the informativeness of questions using quantitative measures such as expected stepwise *information gain* (e.g., Eimas, 1970), have confirmed this developmental trajectory (Kachergis, Rhodes, & Gureckis, 2017; Meder et al., 2019; Nelson et al., 2014; Ruggeri & Feufel, 2015; Ruggeri & Lombrozo, 2014; Ruggeri et al., 2016). Developmental research on question asking has also found that children’s performance in the 20-questions game is better when they can *select* among given questions, rather than having to *generate* them from scratch, potentially because this eliminates the need to identify and generate those categorical features (e.g., outdoor toys, beach toys) that can

be used to target different levels of the hierarchical structure (Herwig, 1982; Ruggeri & Feufel, 2015; Ruggeri et al., 2016). Indeed, Legare et al. (2013) showed that the ability to flexibly categorize objects based on alternative features (e.g., color or pattern) predicted how likely preschoolers were to generate informative questions. Along these lines, Jones, Pachur, Markant, and Ruggeri (2020) also demonstrated that the ability to appreciate the relationship between hypotheses, and therefore entertain abstract representations of the hypothesis space, develops between age 5 and 8, and can guide information search. However, a recent study suggests that the performance of 4- and 5-year-olds does not necessarily improve when they are given the labels for those object features that would be needed to ask effective constraint-seeking questions (Ruggeri, Walker, Lombrozo, & Gopnik, in preparation).

Goals and scope

We investigate across two studies whether and how highlighting the categorical relationships between hypotheses by representing them *spatially* supports 4- to 7-year-old children’s information-search strategies. In Experiment 1, we presented children with a novel spatial search task, the *maze-exploration* game, in which they had to discover the path through a maze, and a traditional version of the 20-questions game, where they had to identify a target monster from a set of eight monsters by asking yes-no questions. We developed the maze-exploration game to be structurally and computationally analogous to the 20-questions game, so that we could compare children’s search performance across both tasks. Just as in the 20-questions game, where the monsters varied across three hierarchically and symmetrically structured features (shape, pattern, and color; Figure 1a), giving rise to eight unique candidate monsters, the maze was symmetrically organized onto three hierarchical levels, with two passages on the higher, four passages on the middle, and eight passages on the lower level (Figure 1a). We hypothesised that children would conduct more informative queries in the maze-exploration game than in the 20-questions game, as in the spatial search task the structure of the hypothesis space may be more evident, and because

searching would not require children to ask questions.

Experiment 1

Method

Participants. Participants were 124 children, recruited at local museums and preschools in [BLIND FOR REVIEW]. An additional 21 children were excluded from analysis (7 due to experimenter error, 2 due to insufficient command of [BLIND FOR REVIEW], and 12 because they did not complete the task). Table 1 shows participant demographics, all *N*s refer to the sample size after excluding participants. Written informed consent of legal guardians was obtained prior to participation. Children were asked for verbal consent and received stickers as a reward for their participation (see Design and Procedure). The study was approved by [BLIND FOR REVIEW].

Table 1

Participant demographics

				Age (months)	
	Age group	<i>N</i>	Female	Mean	SD
Exp. 1	4-year-olds	29	13	55.15	3.56
Exp. 1	5-year-olds	32	15	66.89	5.46
Exp. 1	6-year-olds	32	17	78.20	3.62
Exp. 1	7-year-olds	31	18	92.82	5.56
Exp. 2	4-year-olds	35	17	55.46	5.29
Exp. 2	5-year-olds	31	17	65.59	4.62
Exp. 2	6-year-olds	29	16	76.90	4.94
Exp. 2	7-year-olds	40	17	94.02	7.85

Design and Procedure. Children performed two tasks (order counterbalanced): a 20-questions game and a maze-exploration game. In the 20-questions game, the goal was to find out which out of eight monsters activated a music machine by asking as few yes-no questions as possible. In the maze-exploration

Figure 1. Illustration of the 20-questions and maze-exploration games, designed to be structurally and computationally analogous. In the 20-questions game (a), the eight candidate monsters could be organized in a hierarchical structure consisting of three levels corresponding to three different features (shape, pattern, color; assignment of features to each level counterbalanced across participants). The maze (b) also consisted of three hierarchically-organized levels (higher, middle, lower). To ensure that the tasks were structurally and computationally analogous, the maze-exploration game featured two additional constraints: there was only *one correct path* through the maze and only *one open passage* on each level. The goal of the 20-questions game was to find out which monster activated a music machine. The goal of the maze-exploration game was to discover the path leading through the maze in order to move a marble through it, thereby giving it the power to activate the music machine.

game, children had to discover the path leading through a partially blocked two-dimensional maze by finding out which of its hidden passages were open. Children could then move a marble through the maze along the discovered path to “charge” it, giving it the power to activate the music machine. The two tasks were designed to be structurally and computationally analogous.

20-Questions game. At the beginning of the game, the experimenter presented children with a set of eight monster cards and demonstrated that one monster (the target monster) activated a music machine when inserted into it (without showing

which monster it was). The eight monsters varied across three hierarchically structured features (shape, pattern, and color), such that four of the eight monsters shared the higher-level feature (two variants; e.g., square and circle), two monsters shared the middle-level feature (four variants; e.g., solid, dots, hearts, and stripes), and each monster was unique with respect to the lower-level feature (eight variants; e.g., blue, yellow, brown, pink, orange, purple, red, and green, see Figure 1a). We counterbalanced the level to which each feature was assigned across six sets of monsters (see Supplementary Materials). The monster set and target monster were assigned to children pseudo-randomly. The experimenter then shuffled the monster cards and arranged them in a 2×4 grid on a table, visually organized according to their hierarchical structure (e.g., square monsters on the left, round monsters on the right; solid monsters on top, dotted monsters on the bottom, see Supplementary Materials). Children were instructed to find the target monster by asking as few yes-no questions as possible. Children could ask as many questions as they wanted, but had to pay a sticker for every question, out of a set of eight stickers they were initially given. They could take home all remaining stickers at the end of the game. Following each question, the experimenter removed all eliminated monsters from the display (i.e., those inconsistent with the obtained information). This procedure was repeated until the child had identified the target monster, that is, when only one monster remained. The child could then insert the target monster into the music machine to activate it.

Maze-exploration game. At the beginning of the game, the experimenter demonstrated how a small marble could activate the music machine. She then pointed to the maze, whose passages were concealed with yellow cards (Figure 1b), and explained that once the marble activated the machine, it lost its special powers, but that it could get recharged by going through the maze. The maze was symmetrically organized onto three hierarchical levels, with two passages at the higher, four passages at the middle, and eight passages at the lower level (Figure 1b). To achieve structural and computational equivalence with the 20-questions game, there was only one correct path through the maze and only one open passage per level (i.e., no dead ends).

Consequently, there were exactly eight possible maze configurations (i.e., eight potential paths through the maze, each leading to one of the eight lower level passages), to which children were assigned pseudo-randomly. To rule out a potential bias to start from the top (e.g., due to expectations about gravity), the maze was rotated 90°, so that the hierarchical levels were organized right-to-left or left-to-right (orientation counterbalanced, see Supplementary Materials). For simplicity and consistency with the 20-questions game, we will refer to the levels according to their default, unrotated hierarchical position as “higher” (two passages), “middle” (four passages), and “lower” (eight passages) levels.

To familiarise children with the structure of the maze and the constraints (e.g., exactly one open passage per level), children were then presented with pictures illustrating all eight possible fully-revealed maze configurations (presented in random order, and in the same rotated orientation as the real maze) and were asked to indicate the path through each of them by tracing it with their fingers. Subsequently, the experimenter pointed to the real maze and explained that, to find the path through this particular maze, children would have to find out which of the hidden passages were open or closed, and that they could do so by removing the yellow cards that were covering them. As in the 20-questions game, children were allowed to make as many queries as they wanted, but were incentivized to find the path with as few queries as possible by having to pay a sticker (from an initial set of eight stickers) for each query. Once children had revealed a passage, the experimenter provided feedback by pointing out whether the discovered passage was open or closed. In addition, just as she removed the eliminated monsters from the display in the 20-questions game, she uncovered those passages of the maze children could make inferences about due to implicit horizontal and vertical dependencies. For instance, if a child discovered that the right passage was open on the higher level, the experimenter revealed the remaining closed passage on the left, as well as all closed passages on the middle and lower level below it. This is equivalent to discovering that the target monster is a square and removing all four round monsters from display (for the full set of dependencies, see Supplementary

Materials). After children had found the correct path, the experimenter placed the silver marble at the entrance of the maze, so that children could move it across and use it to turn on the music machine.

Results

Mean information gain of participants' queries. We calculated the expected stepwise information gain (see Supplementary Materials for details) of each participant's queries in the two tasks (Figure 2 left). A mixed-model ANOVA with task (20-questions game vs. maze-exploration game) and age group (4 vs. 5 vs. 6 vs. 7 years) as predictors and expected information gain as dependent variable revealed a main effect of task ($F(1, 120) = 109.52, p < .0001, \eta_G^2 = .26$): participants' mean information gain was higher in the maze-exploration ($M = 0.88, 95\% \text{ CI} [.86, .90]$) than in the 20-questions game ($M = 0.72, 95\% \text{ CI} [.71, .75]$). In addition, we found a main effect of age group ($F(3, 120) = 3.08, p = .03, \eta_G^2 = .05$), and an interaction of task and age group ($F(3, 120) = 8.97, p < .0001, \eta_G^2 = .08$). Bonferroni-corrected post-hoc pairwise t -tests revealed that 4-year-olds made less informative queries than 6- ($t(120) = -2.65, p = .05$) and 7-year-olds ($t(120) = -2.66, p = .05$). To explore the interaction effect, we looked at task effects separately for the four age groups. Post-hoc pairwise t -tests (Bonferroni-corrected) revealed that 4- ($t(120) = 8.00, p < .001$), 5- ($t(120) = 6.25, p < .001$) and 6-year-olds ($t(120) = 5.55, p < .001$) made more informative queries in the maze than in the 20-questions game. Seven-year-olds performed equally well in both tasks ($t(120) = 1.07, p = .29$).

Children's first queries. Figure 2 (right) shows the proportion of children targeting each level with their first query in the two tasks. To analyse these proportions, we first looked at whether children performed the most informative first query (i.e., targeted the highest level of the hierarchy, see Table 2). We performed a mixed-model logistic regression with level of first query (1 = higher level/most informative, 0 = other levels) as dependent variable and task (20-questions game vs. maze-exploration game) and age group (4 vs. 5 vs. 6 vs. 7 years) as predictors. Both

(a) 20-questions game (question generation)

(b) Maze-exploration game

Figure 2. Informativeness of queries in the 20-questions (a) and in the maze-exploration (b) games. Children asked more informative questions in the maze-exploration than in the 20-questions game: Their queries had higher information gain (left) and were more likely to target higher levels of the hierarchy with their first query (right). Box plots show interquartile range with mean (diamond) and median (horizontal bar); the dots show individual participants.

task and age group were significant predictors of whether children performed the most informative first query: children had an increased likelihood of targeting the higher level

of the hierarchy in the maze compared to the 20-questions game, and older children were more likely to do so than younger children (Table 3).

Table 2

Proportion of Children Performing the Most Informative First Query (Experiment 1).

Age group	20Q	Maze
4	3.4 %	13.8 %
5	9.4 %	37.5 %
6	12.5 %	37.5 %
7	22.6 %	38.7 %

Table 3

Results of a Logistic Regression on Optimality of Children’s First Query (Experiment 1)

Predictor	<i>B</i>	<i>SE</i>	<i>z</i> value	<i>p</i>	<i>OR</i>	95% <i>CI OR</i>
Intercept	-3.87	0.82	-4.72	< .001	0.02	[0.00, 0.10]
Task: Maze	1.56	0.42	3.68	< .001	4.74	[2.07, 10.84]
Age group: 5 years	1.48	0.71	2.07	0.04	4.39	[1.08, 17.81]
Age group: 6 years	1.59	0.72	2.22	0.03	4.93	[1.21, 20.08]
Age group: 7 years	1.95	0.72	2.69	0.01	7.02	[1.70, 28.99]

Note. Optimality of children’s first query was dummy coded as 1 (optimal) and 0 (non optimal). The reference levels for the two predictors were 20-questions game (task) and 4-year-olds (age group).

Proportion of children employing the optimal strategy. In both tasks, the optimal strategy consisted of a “top-down” approach, sequentially targeting the higher, middle, and lower level. We classified children according to whether they implemented the optimal strategy, therefore achieving a mean information gain of 1, and those who did not. Table 4 shows the proportion of children employing the optimal strategy in the 20-questions versus the maze-exploration game.¹ We then conducted a

¹ Note that these numbers reflect children who employed the optimal strategy in one *or* the other task, or in both. Only 4 children (two 6-year-olds and two 7-year-olds) followed the optimal strategy in both

mixed-model logistic regression with implementation of the optimal strategy as dependent variable, and task (20-questions game vs. maze-exploration game) and age group (4 vs. 5 vs. 6 vs. 7 years) as predictors. The analysis revealed that both task and age group were significant predictors: Children were more likely to implement the optimal strategy in the maze-exploration than in the 20-questions game, and older children were more likely to do so than younger ones (see Table 5).

Table 4

Proportion of Children Employing the Optimal Overall Strategy (Experiment 1).

Age Group	20Q	Maze
4	0 %	10.3 %
5	9.4 %	28.1 %
6	6.2 %	31.2 %
7	12.9 %	35.5 %

Table 5

Results of Logistic Regression on Optimality of Children's Overall Search Strategy (Experiment 1)

Predictor	<i>B</i>	<i>SE</i>	<i>z</i> value	<i>p</i>	<i>OR</i>	95% <i>CI OR</i>
Intercept	-4.32	0.87	-4.94	< .001	0.01	[0.00, 0.07]
Task: Maze	1.71	0.46	3.75	< .001	5.53	[2.26, 13.52]
Age group: 5 years	1.61	0.75	2.15	0.03	5.02	[1.16, 21.82]
Age group: 6 years	1.61	0.75	2.15	0.03	5.00	[1.15, 21.68]
Age group: 7 years	2.00	0.75	2.66	0.01	7.40	[1.70, 32.23]

Note. Optimality of children's overall search strategy was dummy coded as 1 (optimal strategy) and 0 (non optimal strategy). The reference levels for the two predictors were 20-questions game (task) and 4-year-olds (age group).

Discussion of Experiment 1

The results of Experiment 1 show that children employed more informative search strategies in the maze-exploration game than in the 20-questions game: they achieved higher mean information gain, and were more likely to make the most informative first query and to employ the overall optimal strategy. Indeed, the maze was so effective that it boosted younger children’s search performance up to the level achieved by 7-year-olds. This indicates that, under the right conditions, the ability to conduct informative queries may emerge at an earlier age than previously assumed. In contrast, and in line with previous research, the quality of children’s questions in the 20-questions game increased with age (Herwig, 1982; Mosher & Hornsby, 1966; Ruggeri & Feufel, 2015; Ruggeri et al., 2015, 2016). In this sense, younger children especially benefited from the maze, with performance differences between tasks decreasing with age and disappearing by age 7. This interestingly corresponds to one of the milestones in the development of children’s information-search strategies (Jones, Swaboda, & Ruggeri, 2020), the point when children begin to ask more informative constraint-seeking questions (Herwig, 1982; Mosher & Hornsby, 1966; Ruggeri & Feufel, 2015; Ruggeri et al., 2015, 2016). On the one hand, because performance of 7-year-olds in our 20-questions game was already very high, there might not have been enough room to observe a beneficial effect of the spatial layout. On the other hand, our findings may indicate that the support offered by the spatial layout of the maze-exploration game might not be helpful anymore after a certain stage of development.

The spatial search task could have supported younger children’s search strategies in two ways: by highlighting the hierarchical, nested structure of the hypothesis space – an aspect that is known to develop across these childhood years (Jones, Pachur, et al., 2020), or by eliminating verbal requirements from the search (Ruggeri et al., 2017). To disentangle these alternative explanations, we conducted a follow-up study in which we compared children’s performance in the the same maze-exploration game, and in a novel non-verbal *feature-selection* version of the traditional 20-questions game. In this version, children were presented with three cards illustrating the different monster features (i.e.,

shape, color and pattern, see Figure 3) and could point at the feature they wanted to query, similarly to pointing at the passage in the maze they wanted to reveal. If the performance boost observed in the spatial search task in Experiment 1 was driven by the fact that it did not rely on their verbal skills, younger children in Experiment 2 should achieve the same informativeness in both games. In contrast, if the maze-exploration game was beneficial because its spatial layout highlights the hierarchical structure of the hypothesis space, then task-dependent differences should persist.

Experiment 2

Method

Participants. Participants in Experiment 2 were 135 children, recruited at the same local museums as children in Experiment 1. An additional 11 participants were excluded due to experimenter error ($n = 6$) and video failure ($n = 5$). Table 2 shows participant demographics, all Ns refer to the sample size after excluding participants.

Materials, Design and Procedure. The materials and procedure were largely identical to those of Experiment 1, with two differences. First, in the feature-selection game, a completely non-verbal version of the 20-questions game, children were presented with three *feature cards*, each depicting all variants of one feature (i.e., shape, color, pattern; see Figure 3a), and had to select (point at) the feature and variant they wished to query. The monsters ruled out by the question, as well as the feature cards for which the target variant had been identified, were removed.

Second, in the maze-exploration game, we introduced three red arrows pointing at the three different levels (Figure 3b), to ensure that the procedure was analogous to that of the feature-selection game. When making a query, children first selected the arrow pointing at the level they wished to query, and then selected the passage on the chosen level they wished to reveal. As in the feature-selection game, the arrows were removed from display once the open passage on that level had been found.

Figure 3. Task setup of Experiment 2. In the feature-selection game, children made their queries by selecting one of three feature cards showing the three monster features (arranged in hierarchical order, matching the maze's orientation) and then pointing at the variant they wanted to know about. In the maze-exploration game, children pointed at the arrows indicating the level they wished to query and then at the passage on that level.

Results

Mean information gain of participants' queries. Figure 4 (left) shows the information gain of participants' queries in Experiment 2. A mixed-model ANOVA with the predictors task (feature-selection game vs. maze-exploration game) and age group (4 vs. 5 vs. 6 vs. 7 years), and mean information gain as dependent variable produced a main effect of age group ($F(3, 131) = 4.11, p = .008$), but no main effect of task ($F(1, 131) = 1.82, p = .18$) and no interaction ($F(3, 131) = 0.85, p = .47$). Post-hoc pairwise t-tests revealed that 4-year-olds made less informative queries than 6-year-olds ($t(131) = -2.85, p = .03$, Bonferroni-corrected) and 7-year-olds ($t(131) = -3.10, p = .01$, Bonferroni-corrected). The other age groups did not differ from each other.

(a) 20-questions game (feature selection)

(b) Maze-exploration game

Figure 4. Experiment 2: Search performance in the feature-selection (a) and in the maze-exploration game (b). The information gain of children’s queries did not differ (left) and children were equally likely to target the higher level of the hierarchy with their first query (i.e., make the most informative first query) in both games. Box plots show interquartile range with mean (diamond) and median (horizontal bar); dots show individual participants.

Children’s first queries. Figure 4 (right) shows the proportion of children targeting each level with their first query in the two tasks in Experiment 2. As in

Experiment 1, we were interested in whether children made the optimal first query and performed a mixed-model logistic regression with level of first query (1 = higher level/optimal, 0 = other levels/non optimal) as dependent variable, and task (feature-selection game vs. maze-exploration game) and age group (4 vs. 5 vs. 6 vs. 7 years) as predictors. This revealed that neither age group nor task were significant predictors of whether children made the optimal first query (see Table 7).

Table 6

Proportion of Children Employing the Optimal First Query (Experiment 2).

Age group	20Q	Maze
4	20.0 %	34.3 %
5	35.5 %	16.1 %
6	37.9 %	44.8 %
7	35.0 %	40.0 %

Table 7

Results of Logistic Regression on Optimality of Children's First Query (Experiment 2)

Predictor	<i>B</i>	<i>SE</i>	<i>z</i> value	<i>p</i>	<i>OR</i>	95% <i>CI OR</i>
Intercept	-1.06	0.32	-3.35	< .01	0.35	[0.19, 0.65]
Task: Maze	0.10	0.26	0.40	0.69	1.11	[0.66, 1.86]
Age group: 5 years	-0.07	0.40	-0.17	0.86	0.93	[0.42, 2.06]
Age group: 6 years	0.65	0.39	1.66	0.10	1.92	[0.89, 4.12]
Age group: 7 years	0.48	0.36	1.33	0.18	1.62	[0.80, 3.31]

Note. Optimality of children's first query was dummy coded as 1 (optimal) and 0 (non optimal). The reference levels for the two predictors were feature-selection game (task) and 4-year-olds (age group).

Proportion of children employing the optimal strategy. Table 8 shows the proportion of children employing the optimal strategy in the two tasks. A mixed-model logistic regression with implementation of the optimal strategy dummy

coded as 1 (optimal strategy) and 0 (non optimal strategy), and task (feature-selection game vs. maze-exploration game) and age group (4 vs. 5 vs. 6 vs. 7 years) as predictors revealed that children were equally likely to employ the overall optimal strategy in both tasks, and that 7-year-olds were more likely than 4-year-olds to employ the optimal strategy (Table 9).

Table 8

Proportion of children employing the optimal overall strategy (Experiment 2)

Age group	20Q	Maze
4	8.6 %	20.0 %
5	25.8 %	16.1 %
6	27.6 %	31.0 %
7	20.0 %	37.5 %

Table 9

Results of Logistic Regression on Optimality of Children's Overall Search Strategy (Experiment 2)

Predictor	<i>B</i>	<i>SE</i>	<i>z</i> value	<i>p</i>	<i>OR</i>	95% <i>CI OR</i>
Intercept	-2.18	0.46	-4.71	< .001	0.11	[0.05, 0.28]
Task: Maze	0.41	0.31	1.35	0.18	1.51	[0.83, 2.76]
Age group: 5 years	0.50	0.51	0.97	0.33	1.64	[0.60, 4.47]
Age group: 6 years	0.98	0.50	1.95	0.05	2.67	[1.00, 7.16]
Age group: 7 years	0.96	0.47	2.02	0.04	2.61	[1.03, 6.60]

Note. Optimality of children's overall search strategy was dummy coded as 1 (optimal strategy) and 0 (non optimal strategy). The reference levels for the two predictors were feature-selection game (task) and 4-year-olds (age group).

General Discussion

We investigated whether laying out the structure of a search task *spatially* improves the effectiveness of 4- to 7-year-old children’s search strategies. To do so, we contrasted children’s performance on a novel spatial search task (maze-exploration game) with their information-search behavior in two versions of a structurally and computationally analogous hierarchical 20-questions game. In Experiment 1, we found that, as predicted, children overall made more informative queries in the maze-exploration game than in the traditional 20-questions game. In line with previous studies (Herwig, 1982; Mosher & Hornsby, 1966; Ruggeri & Feufel, 2015; Ruggeri & Lombrozo, 2014; Ruggeri et al., 2015, 2016), the results of Experiment 1 also revealed a developmental increase in the informativeness of children’s questions in the 20-questions game. However, there were no age-related performance differences in the maze-exploration game, with younger children’s performance being on par with that of older ones. In Experiment 2, children achieved the same performance on the non-verbal feature-selection version of the 20-questions game as on the maze-exploration game, with no differences between age groups. This suggests that the beneficial effect of the maze-exploration game was directly related to its non-verbal nature.

The finding that 4-year-olds performed as well as much older children in the two non-verbal tasks indicates that even young children possess more effective and sophisticated information-search strategies than previously assumed. This result adds to a growing body of research pointing towards the early emergence of effective search and exploration strategies (e.g., Bonawitz, van Schijndel, Friel, & Schulz, 2012; Cook, Goodman, & Schulz, 2011; Domberg, Koksuba, Rothe, & Ruggeri, 2020; Kushnir & Gopnik, 2005; Ruggeri et al., 2017; Ruggeri, Swaboda, Sim, & Gopnik, 2019; E. Schulz, Wu, Ruggeri, & Meder, 2019a; L. E. Schulz & Bonawitz, 2007) and supports the view that children are skilled active learners from a very young age (e.g., Gopnik, Meltzoff, & Bryant, 1997; Gopnik & Wellman, 2012). It also strongly suggests that younger children’s difficulties in the 20-questions game are directly attributable to the verbal requirements related to question generation (e.g., Ruggeri et al., 2017). Thus, the

wealth of developmental studies employing the traditional 20-questions game likely paints an incomplete picture of the effectiveness of children’s information search strategies – especially in young children, whose verbal skills are still developing. Our findings highlight the importance of investigating children’s information search using a broader array of paradigms and tasks that are better tailored to the cognitive abilities and constraints of the targeted age groups, and which are therefore more suitable to capture the early emergence of effective search.

In this project, we have tested children on *two* non-verbal tasks. The feature-selection paradigm, although crucial for identifying the reasons why the maze-exploration game supported children’s information search strategies, has very limited ecological validity. In contrast, despite the constraints introduced in the maze-exploration game to make it comparable to the 20-questions game, our spatial search task is generally ecologically valid, and we believe it to be a very promising paradigm. Indeed, similar maze paradigms have previously been used successfully with even younger children and primates to study their ability to plan ahead (Völter & Call, 2014). Our addition of an information search component opens up a range of possibilities for the development of non-verbal active search tasks. Using a combination of behavioral analyses and computational modeling, future work could for instance investigate how children explore more complex mazes, and search through maze-like configurations in real-life search paradigms. Building on previous work (Völter & Call, 2014), our paradigm may also be used to study how children and adults search for information to plan ahead, for example to examine whether effective information search contributes to successful planning. In addition, this paradigm provides possibilities for studying toddlers’ ecological learning and adaptiveness (Ruggeri et al., 2015, 2017, 2019), dynamic learning over trials, as well as exploration vs. exploitation strategies in spatial (Meder, Wu, Schulz, & Ruggeri, 2020; E. Schulz, Wu, Ruggeri, & Meder, 2019b) and non-spatial domains (Wu, Schulz, Garvert, Meder, & Schuck, 2020). Finally, future work may also attempt to further reduce verbal demands in spatial search tasks, for instance using eye tracking or EEG measures, to explore active information search in

infants. Employing experimental paradigms that minimize additional demands, such as verbal skills, can provide a much more nuanced understanding of young children's information-search abilities. This approach is therefore crucial to enrich our understanding of the developmental trajectory of children's active learning strategies and to paint a more comprehensive picture of young children's cognitive development.

References

- Bonawitz, E. B., van Schijndel, T. J., Friel, D., & Schulz, L. (2012). Children balance theories and evidence in exploration, explanation, and learning. *Cognitive Psychology*, 64(4), 215–234.
- Cook, C., Goodman, N. D., & Schulz, L. E. (2011). Where science starts: Spontaneous experiments in preschoolers' exploratory play. *Cognition*, 120(3), 341–349.
- Domberg, A., Koksuba, K., Rothe, A., & Ruggeri, A. (2020). Goal-adaptiveness in children's cue-based information search. In *Proceedings of the 42nd annual conference of the cognitive science society*.
- Eimas, P. D. (1970). Information processing in problem solving as a function of developmental level and stimulus saliency. *Developmental Psychology*, 2(2), 224.
- Gopnik, A., Meltzoff, A. N., & Bryant, P. (1997). *Words, thoughts, and theories* (Vol. 1). MIT Press Cambridge, MA.
- Gopnik, A., & Wellman, H. M. (2012). Reconstructing constructivism: Causal models, bayesian learning mechanisms, and the theory theory. *Psychological Bulletin*, 138(6), 1085.
- Herwig, J. E. (1982). Effects of age, stimuli, and category recognition factors in children's inquiry behavior. *Journal of Experimental Child Psychology*, 33(2), 196–206.
- Jones, A., Pachur, T., Markant, D. B., & Ruggeri, A. (2020). How the hypothesis space is represented: Evidence from young children's active search and predictions in a multiple-cue inference task. *OSF Preprints*. doi: 10.31219/osf.io/wh2pr
- Jones, A., Swaboda, N., & Ruggeri, A. (2020). Developmental changes in question-asking. In L. P. Butler, S. Ronfard, & K. H. Corriveau (Eds.), *The questioning child: Insights from psychology and education* (pp. 118–143). Cambridge University Press.
- Kachergis, G., Rhodes, M., & Gureckis, T. (2017). Desirable difficulties during the development of active inquiry skills. *Cognition*, 166, 407–417.
- Kushnir, T., & Gopnik, A. (2005). Young children infer causal strength from

- probabilities and interventions. *Psychological Science*, 16(9), 678–683.
- Legare, C. H., Mills, C. M., Souza, A. L., Plummer, L. E., & Yasskin, R. (2013). The use of questions as problem-solving strategies during early childhood. *Journal of Experimental Child Psychology*, 114(1), 63–76.
- Meder, B., Nelson, J. D., Jones, M., & Ruggeri, A. (2019). Stepwise versus globally optimal search in children and adults. *Cognition*, 191, 103965.
- Meder, B., Wu, C. M., Schulz, E., & Ruggeri, A. (2020, Apr). Development of directed and random exploration in children. *PsyArXiv*. doi: 10.31234/osf.io/7zhxv
- Mosher, F., & Hornsby, J. (1966). On asking questions. In J. Bruner, R. Oliver, & P. Greenfield (Eds.), *Studies in cognitive growth*. Wiley New York, NY.
- Nelson, J. D., Divjak, B., Gudmundsdottir, G., Martignon, L. F., & Meder, B. (2014). Children’s sequential information search is sensitive to environmental probabilities. *Cognition*, 130(1), 74–80.
- Nelson, J. D., Meder, B., & Jones, M. (2018). Towards a theory of heuristic and optimal planning for sequential information search. *PsyArXiv*. doi: 10.31234/osf.io/bxdf4
- Ruggeri, A., & Feufel, M. (2015). How basic-level objects facilitate question-asking in a categorization task. *Frontiers in Psychology*, 6, 918.
- Ruggeri, A., & Lombrozo, T. (2014). Learning by asking: How children ask questions to achieve efficient search. In *Proceedings of the 36th Annual Meeting of the Cognitive Science Society* (Vol. 36).
- Ruggeri, A., Lombrozo, T., Griffiths, T. L., & Xu, F. (2015). Children search for information as efficiently as adults, but seek additional confirmatory evidence. In *Proceedings of the 37th Annual Meeting of the Cognitive Science Society*.
- Ruggeri, A., Lombrozo, T., Griffiths, T. L., & Xu, F. (2016). Sources of developmental change in the efficiency of information search. *Developmental Psychology*, 52(12), 2159.
- Ruggeri, A., Sim, Z. L., & Xu, F. (2017). “Why is Toma late to school again?” Preschoolers identify the most informative questions. *Developmental Psychology*, 53(9), 1620.

- Ruggeri, A., Swaboda, N., Sim, Z. L., & Gopnik, A. (2019). Shake it baby, but only when needed: Preschoolers adapt their exploratory strategies to the information structure of the task. *Cognition*, *193*, 104013.
- Ruggeri, A., Walker, C., Lombrozo, T., & Gopnik, A. (in preparation). Strategic use of questions to solve a causal inference task in early childhood.
- Schulz, E., Wu, C. M., Ruggeri, A., & Meder, B. (2019a). Searching for rewards like a child means less generalization and more directed exploration. *Psychological Science*, *30*(11), 1561–1572.
- Schulz, E., Wu, C. M., Ruggeri, A., & Meder, B. (2019b). Searching for rewards like a child means less generalization and more directed exploration. *Psychological Science*, *30*(11), 1561–1572.
- Schulz, L. E., & Bonawitz, E. B. (2007). Serious fun: preschoolers engage in more exploratory play when evidence is confounded. *Developmental Psychology*, *43*(4), 1045–1050.
- Völter, C. J., & Call, J. (2014). Younger apes and human children plan their moves in a maze task. *Cognition*, *130*(2), 186–203.
- Wu, C. M., Schulz, E., Garvert, M. M., Meder, B., & Schuck, N. W. (2020). Similarities and differences in spatial and non-spatial cognitive maps. *bioRxiv*. doi: 10.1101/2020.01.21.914556