The Successful Use of a Search Strategy Improves with Visuospatial Working Memory in 2-to-4.5-Year-Olds

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Ethical Approval

This research was approved by Swedish Ethical Review Authority in Lund (DRN 2018/572). No sensitive data about participants were gathered, and only those children, whose parents submitted a written consent, either on paper or digitally, were included in the study.

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Conflict of Interest

None of the Authors have any competing interests to declare.

Data availability

The datasets generated during and analysed during the current study are available from the corresponding author on reasonable request. The study analysis code is available in Online Supplemental Material 1.

Abstract

Using spatial cues, such as shape, orientation, and pattern, aids visuospatial working memory, as it allows strategies that reduce the load on this cognitive resource. One such strategy, namely taking advantage of patterned spatial distributions, remains understudied to date. This strategy demands keeping track of already-searched locations and excluding them from further search, and so correlates with visuospatial working memory. The use of such strategies should, in principle, develop in early childhood, but, as most studies focus on chunking, the development of other strategies reducing the load on working memory is understudied in young children. Therefore, in this study, we tested whether children between 2 and 4.5 years (N = 97) could take advantage of spatial cues in their search, and whether this ability correlated with their age, verbal ability, and visuospatial working memory. The results showed that the ability to use a patterned spatial distribution (searching a row of locations from one side to the other instead of a random search) significantly improved with visuospatial working memory but not age or verbal ability. These results suggest that visuospatial abilities may rapidly develop between 2 and 4.5 years, and given their impact on later mathematic achievement, demand increased attention in cognitive developmental research and early childhood education.

Keywords: working memory, visuospatial skills, strategy, verbal ability, toddlerhood, preschool

Introduction

Working memory, the ability to hold and manipulate information acquired from the environment and information retrieved from long-term memory, is central to individual learning and academic achievement (Blankenship et al., 2015; Swanson & Alloway, 2012). In primary school, diverse aspects of working memory contribute to both reading (Blankenship et al., 2015; Carretti et al., 2009; Nouwens et al., 2017; Slattery et al., 2021) and mathematics achievement (Allen et al., 2020; Alloway et al., 2009; Friso-van den Bos et al., 2013; Peng et al., 2016), and children's working memory in the preschool years predicts reading, writing, and mathematics achievement at a later stage in school (reading: Nevo & Breznitz, 2011; writing: Bourke et al., 2014; mathematics: Bull et al., 2008; Fanari et al., 2019;). Working memory in a visuospatial setting, that is investigated in the current study, predicts a unique proportion of variance in spelling and independent text writing ability in 5-year-olds (Bourke et al., 2014), and longitudinally predicts mathematical ability (Allen et al., 2019; 2020; Bull et al., 2008).

Although, in the last decades, working memory was repeatedly measured in adults and children, no consensus was reached with regards to the nature of working memory and the mechanism driving its development (Simmering & Perone, 2013). According to componential theories (e.g., Tam et al., 2010; Baddeley & Hitch, 1974; Vandierendonck, 2020), working memory comprises multiple components, each of which is responsible for performing separate functions, such as dealing with visuospatial information, dealing with auditory information, or oversight of these two functions. On the contrary, attention-based theories conceptualize working memory as a general-purpose attentional resource (Cowan, 2016; Morra et al., 2021), whose capacity is driven by a fixed number of representations (Cowan, 2016) or by continuous adjustment of attention to incoming information (e.g., Hardman et al., 2017; Heyes et al., 2012; Morra et al., 2021).

Although many studies concur that, with age, children's performance on working memory tasks improves, the mechanism responsible for these improvements in working memory has been debated as well (Simmering & Perone, 2013). Working memory tends to improve with age, but children's performance on working memory tasks (e.g., in terms of memory span) varies on the individual level and within age groups. This cannot be sufficiently explained by single-cause accounts of working memory maturation, according to which improvements in working memory result from maturation of other cognitive processes such as processing speed, attention, retrieval, or strategy use (Dempster, 1981; Pascual-Leone, 1970). Therefore, the single-cause accounts were contested by a dynamic account of working memory maturation, suggesting that working memory capacity is rather a dynamic, emergent property of multiple aspects of individual cognition and behavior in relation to specific stimuli and task demands (Simmering & Perone, 2013). This means that, for instance, constraints on working memory are not fixed across tasks, and can vary in individual participants across diverse task demands.

Working Memory Strategies

Constraints on working memory, such as working memory capacity, can be mitigated by cognitive strategies, such as chunking (Cowan, 2001; Thalmann et al., 2019). Chunking allows for cutting a sequence of information into smaller portions, for instance, when grouping a long phone number into two- or three-digit chunks (Cowan, 2001; Miller, 1956). While chunking is an efficient way of dealing with sequences of information that lack obvious portioning, strains on the capacity of working memory can also be reduced in other ways, such as finding and taking advantage of patterns in spatial distribution of to-be-remembered items (Bobrowicz & Osvath, 2020a; Sanada et al., 2015; Zhang et al., 2022). In fact, adults spontaneously use chunking (Thalmann et al., 2019) and consistently take advantage of simple patterned spatial distributions as well, for instance, when retrieving items from a row of locations systematically, one by one, from one end of the row to the other (Bobrowicz & Osvath, 2020a). However, visuospatial search strategies extend beyond chunking, onto, for instance, holistic strategies (encoding a single visual image, comprising to-be-remembered items; Gonthier, 2021; Lecerf & De Ribaupierre, 2005), relational encoding strategies (encoding relations between items to base recall on their relative positions; Avons, 2007; Gonthier, 2021), and other strategies, which would rely on categorical encoding and rehearsal (Gonthier, 2021), possibly unavailable to children younger than 5 (Hitch et al., 1988; Morey et al., 2018). For instance, 5-year-old children, contrary to 10-year-olds, were found to rely on visual recall rather than auditory-verbal recall (Hitch, 1988).

Previous research shows that even infants and toddlers use chunking when dealing with arrays of items (Feigenson & Halberda, 2004; Mathy et al., 2016). Furthermore, with age, children's working memory may benefit from semantic knowledge of relevant strategies (Cowan et al., 1987; Cowan et al., 2006; Cowan, 2016; Flavell et al., 1966; Morra, 2000; Ornstein et al., 1975; Tam et al., 2010), and, albeit to a limited extent, from metacognitive awareness of working memory limitations (Applin & Kibbe, 2020). Furthermore, children were found to use multiple strategies in diverse cognitive tasks that require working memory, such as serial recall, arithmetic, or rule learning (Chen & Siegler, 2003). These strategies become more advanced with age and experience (Chen & Siegler, 2003), and more efficient and adaptive over trials on a given task (e.g., toy retrieval, Chen & Siegler, 2000; Torbeyns et al., 2004). Early in development, producing an appropriate memory strategy does not, however, guarantee its successful execution and benefits for recall. This temporary developmental phase, called a strategy utilization deficiency, was identified for numerous attention and memory tasks in preschool-aged children (e.g., Miller, 1990; Miller et al., 1994;

Bjorklund et al., 1997; Clerc, Miller & Cosnefroy, 2014), and may likewise apply to using simple spatial strategies, such as proceeding systematically through a line.

Location-bound Working Memory

Taking advantage of simple patterned spatial distributions, such as proceeding systematically through a row of locations, demands keeping track of already-searched and to-be-searched locations. In other words, the child needs to remember which locations have already been visited and no longer contain a reward and which locations have not yet been visited and still contain a reward, e.g., a sticker (Bobrowicz & Osvath, 2020a; Jayakody et al., 2018). This, in turn, requires dividing attention between maintaining representations that are already available in working memory and encoding additional representations, as the child progresses through the search (Kibbe & Leslie, 2013; Moher & Feigenson, 2013; Wheeler & Treisman, 2002). Although the ability to divide attention accordingly and update representations in working memory develops in infancy (Kibbe & Leslie, 2013), it continues to develop in toddlerhood and the preschool years, as the working memory representations become more robust and, therefore, less susceptible to interference (Cheng & Kibbe, 2022). However, it remains unclear at which point in development children can take advantage of patterned spatial distributions, opting for this less cognitively demanding solution and, thereby, releasing working memory resources.

Using simple patterned spatial distributions, such as a row of locations, is an effective search strategy because, in principle, it can rely on a habitual, low-cost strategy acquired through early exposure to reading, writing, and mathematics, and requires holding less information in working memory than searching at random. Browsing through picture books with adults and pretend-reading/pretend-writing may, therefore, underpin children's tendency to proceed systematically from left to right when tackling series of objects. If the systematic search strategy is habitual, the child only needs to remember the last searched location. Otherwise, the child needs to remember the last searched location paired with the direction of the search, left to right or right to left. We expected that this systematic search strategy will become increasingly popular among 2- to 4.5-year-olds given their increasing exposure to reading, writing and spatial material in general, that typically requires progressing from left to right and from top to bottom. This also coincides with the acquisition of counting principles such as the stable order principle, the one-to-one principle, and the cardinality principle (Butterworth, 2005; Gelman & Gallistel, 1978). Repeated exposure to counting objects (typically from one side to the other) when acquiring these principles may strengthen children's habit of proceeding from one side of the row of locations to the other. First, to acquire the stable order principle, children learn to verbally count with number words, always using the same order, e.g., one, two, three etc., and second, to acquire the one-to-one principle, they learn that each of this numbers should be assigned exactly to one object in a set. Finally, the cardinality principle relies on understanding that the last number used when counting a set of objects, typically from left to right, represents the set's numerosity (e.g., Gelman & Gallistel, 1978). Although children may count the objects in any order, they are most likely trained by adults to do this systematically to avoid missing any of the objects in the set. Children acquire the order-irrelevance principle later in development, learning that the order of objects while counting does not influence the outcome (Butterworth, 2005; Gelman & Gallistel, 1978). This principle, however, seems to be employed by children older than 2- to 4.5-years. For instance, order irrelevance was used only by some 10- and 11-year-olds in a sample of 5- to 11-year-olds in Kamawar et al. study (2010), while most of the participants favored counting from left to right, and from top to bottom.

Several recent studies showed that 5-year-olds can reliably remember which items were hidden in a maximum of four locations (Applin & Kibbe, 2020; Cheng & Kibbe, 2022).

With these findings in mind, in the present study, for the first time, we investigated whether 2- to 4.5-year-olds could organize their own search across an array of three to nine locations. We hypothesized that performance on a task that allows proceeding systematically through a line would correlate with knowledge of relevant search strategies (e.g., search from left to right or top to bottom) and the ability to keep track of one's own search behaviors. The use of relevant search strategies may correlate with child's age and semantic knowledge (Starr et al., 2020). However, age is likely not the only factor behind keeping track of children's own search behaviors, as this may rely on working memory capacity (e.g., Cowan et al., 2015) or verbal self-regulation of one's own search behaviors (e.g., Winsler, Carlton, & Barry, 2000).

Aims and Hypotheses

Given that taking advantage of spatial cues and reducing working memory load is important for both daily (e.g., searching for a book in a library) and academic activities (e.g., ordering numbers or quantities on a number line), we investigated whether proceeding systematically through a line is available to 2- to 4.5-year-olds, and whether the ability to use this strategy successfully (i.e., achieve the top score on the Find Them All task) increases with age, visuospatial working memory capacity, and verbal ability. Verbal ability may guide performance on the Find Them All task because self-regulatory (i.e., private) speech aids self-regulation during cognitive tasks in 2- to 4.5-year-olds (Bono & Bizri, 2014; Diaz & Berk, 1992; Winsler et al. 2003). Note that the Find Them All is somewhat similar to the Self-Ordered Pointing Task (SOPT), as both tasks require the ability to generate and monitor a sequence of responses (Edmunds et al., 2022). While Find Them All is a spatial version of the SOPT task with a single spatial setting, other spatial versions of the SOPT task may involve several separate spatial settings, as items are displayed across several pages (Cragg & Nation, 2007).

We differentiated between a consistent vs. a successful use of the strategy. The consistent use of the strategy entailed deploying the systematic search strategy (i.e., from left to right or right to left) in all trials; the successful use of the strategy entailed a high top score achieved when deploying the strategy. Note that the consistent use of the strategy did not need to result in a high top score, for instance, if the participant failed to monitor the deployment of the strategy and forgot which location had just been searched.

We assumed that:

(A1) The consistent use of the systematic search strategy would correlate with higher scores on the Find Them All task as compared to the inconsistent use because utilizing this strategy could potentially reduce the load on working memory to a single to-be-remembered item (the last searched location).

(A2) Children who did not use this strategy consistently would achieve higher scores on the Find Them All task on trials with the systematic search strategy than on trials without this strategy.

In terms of the consistent use of the systematic search strategy, we expected that:

(H1A) With age, children would be more likely to consistently use the search strategy, showing familiarity with such strategies.

In terms of the successful use of the systematic search strategy, we expected that:

(H1B) When using the systematic search strategy, older children would achieve higher scores on the Find Them All task than younger children because they may have (1) more habitual experience with deploying this strategy, (2) better control over the deployment of the search strategy, or (3) higher working memory capacity. (1) If older children have more experience with deploying the systematic search strategy than younger children, they may do so habitually throughout the trials, reaching high scores. (2) If older children have better control over the deployment of the search strategy than younger children, then, in the group of children who did not use the strategy consistently, older children should be more likely to employ this strategy on difficult trials than younger children. (3) If older children use the systematic search strategy more successfully than younger children due to a higher working memory capacity, an interaction effect between age and working memory on the top score with the systematic search strategy is expected.

(H2) When using the systematic search strategy, high working memory capacity would correlate with a high top score on the Find Them All task, showing that working memory aids keeping track of one's own search behavior.

(H3) When using the systematic search strategy, high verbal ability would correlate with a high top score on the Find Them All task, showing that verbalization, e.g., self-regulatory speech, may aid keeping track of children's own search behavior.

Materials and Methods

Participants

In total, 123 children were recruited from eleven public preschools in urban and semi-urban areas of southern Sweden. Children 24–55 months of age were included (M = 40.09; SD = 7.85 months). Parental education was high, with 86.6% having a college or university degree, which means that the sample had an above-average parental education level, as, according to a recent OECD report, 44% of Swedes between 25 and 64 achieved the tertiary level of education (OECD, 2020). Data from 97 children (44 boys/53 girls; 24–55, M = 40.60, SD = 7.49 months) were included, while data from 26 children were excluded because of (a) considerably older age (60 months, n = 1); (b) missing only a score on Find Them All (n =16) due to experimenter's mistake in administration of the task (n = 5), children's unwillingness to participate specifically in this task (n = 8), children's unwillingness to participate in the second day of testing (n = 1), a missing video from the second day of testing

(n = 2); (c) missing only a score on Corsi Block Tapping (n = 3) due to experimenter's mistake in administration of the task (n =1) or children's unwillingness to participate specifically in this task (n = 2); (d) missing a score on both Find Them All and Corsi Block Tapping due to children's refusal of participation in both tasks (n = 4); and (e) missing a score on several measures included in this study (n =2) due to experimenter's mistake in administration (n = 1) or children's refusal of participation in several tasks (n = 1). The sample size was pre-determined by a power calculation for other analyses (see Bobrowicz et al., 2020b, 2022)[1], but post-hoc power was calculated for the analyses conducted in this study (see Results). This research was approved by Swedish Ethical Review Authority in Lund (DRN 2018/572). No sensitive data about participants were gathered, and only those children, whose parents submitted a written consent, either on paper or digitally, were included in the study.

Measures

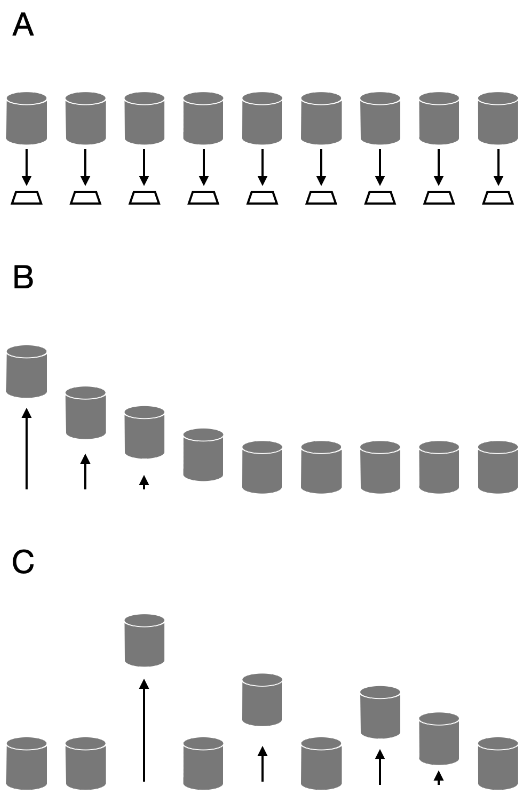
Strategic search. Find Them All, a task used to address the consistent use of a search strategy, required keeping track of one's own, not the experimenter's, actions (Jayakody et al., 2018). The child was asked to check three to nine locations arranged in a row and retrieve the items hidden there, one at each location (Figure 1). The child was allowed to plan and perform searches across a row of locations and may have chosen to do so systematically (e.g., from left to right) or not. After a practice trial with three locations, the number of locations was gradually increased in test trials. Testing was interrupted after two incorrect responses (missing at least one of the locations at the end of the search or returning to an already visited location) on trials with the same number of locations. The largest number of items retrieved

[1] Data from the same primary dataset were used in two published studies (Bobrowicz et al., 2020b; 2022), but focused on analogical transfer and executive functions (including working memory), not on visuospatial skills.

within a trial was recorded as the child's score (max. 9). This means that children would receive up to two trials on the same number of locations, if they have not solved it on the first trial. Note that we differentiated between consistent and successful use of the strategy. Consistent use of the strategy entailed deploying the systematic search strategy in all trials; successful use of the strategy entailed a high top score (maximum level) on the task, achieved when deploying the strategy.

Figure 1.

An overview of possible search behaviors in the Find Them All task. (A) A sticker was hidden under each box; the number of boxes increased from 3 to 9. (B) Searching from left to right (or from right to left) was considered a systematic search strategy, proceeding systematically through a line. (C) Searching in other ways was not considered a systematic search strategy.



Visuospatial working memory. Two tests of visuospatial working memory were employed: Corsi Block Tapping and Find The Toy.

Corsi Block Tapping, developed to measure working memory capacity in a visuospatial setting (Farrell Pagulayan et al., 2006, Gade et al., 2017), was used. Although multiple other tests of working memory for the target age group were devised in the past, Corsi Block Tapping allowed us to maintain a comparable setup to Find Them All (9 locations) and was relatively brief compared to other, similar tasks, e.g., Memory Span Spin-the-Pots (Morra et al., 2021). In Corsi Block Tapping, the child was asked to reproduce the order in which the experimenter had tapped a number of identical items right before (Farrell Pagulayan et al., 2006). The task consisted of a 9-item tray, allowing the manipulation of the difficulty level across trials. The standard arrangement was used, but black blocks were substituted with white inverted cups placed on a blue tray, with numbers on the experimenter's side (Kessels et al. 2000). The child first received a practice trial, and thereafter testing began with taps on two items and increased gradually to nine taps. Each numerosity was repeated twice, and testing was interrupted after two incorrect responses on the same number. The highest number of items tapped in the correct order was recorded as the child's score (max. 9). To distinguish between children who were able to touch one of the boxes or none of the boxes correctly when attempting the two-box sequence (e.g., touched box 3 in a modeled sequence of 3 and 7), children who touched one box correctly received a score of 1. Otherwise, they received a score of 0.

Find the Toy was developed to measure working memory in a visuospatial setting in 18- to 24-month-olds (Bernier et al., 2010, Pauen and Bechtel-Kuehne, 2016). In the task, the child is asked to retrieve an item hidden by the experimenter in one of three, six, or nine locations (Pauen & Bechtel-Kuehne, 2016). The retrieval is allowed after 3, 5, or 8 s (compared to 5 or 8 s in Pauen & Bechtel-Kuehne, 2016). For 36-month-old and younger children, after a practice trial with three items, twelve test trials followed, six with 3 locations (thrice with a 3 s delay, and thrice with a 5 s delay) and another six with 6 locations (thrice with a 3 s delay, and thrice with a 5 s delay). For children older than 36 months, after a practice trial with six items, twelve test trials followed, six with 6 locations (thrice with a 3 s delay, and thrice with a 5 s delay) and another six with 9 locations (thrice with a 5 s delay, and thrice with an 8 s delay). Testing was interrupted after three incorrect responses. The sum of all items found over the trials was recorded as the child's score (max. 12).

Verbal ability. Word Recognition, a subtest from the Swedish version of the Wechsler Preschool and the Primary Scale of Intelligence Test (WPPSI-IV, Wechsler, 2014) was administered, as a proxy of the child's verbal ability. In the Word Recognition sub-test, children were asked to point at the picture corresponding to a word among four pictures. The child received a point for each correct answer and could accumulate a total of 31 points.

Procedure

Children completed the tasks in two separate sessions carried out on two consecutive days: Word Recognition and Find the Toy on Day 1, and Corsi Block Tapping and Find Them All on Day 2. Only children who agreed to participate in the tasks were tested, in a room arranged for the purposes of testing at children's respective preschools. All children received a toy at the end of testing. Trials of Find the Toy, Corsi Block Tapping, and Find Them All were video recorded, capturing the experimental setup and the participant's hands; results of Word Recognition were recorded in a paper-and-pencil manner by the experimenter in real time.

Five additional measures were gathered but not analyzed in this study: the Information subscale from WPPSI, Head-Toes-Knees-Shoulders, a novel measure of

Analogical Transfer, and Attentional Focusing and Inhibitory Control subscales from the Early Child Behavior Questionnaire and the Children's Behavior Questionnaire (see also Bobrowicz et al., 2020b, 2022).

Statistical Analysis

All analyses were conducted in R (v.3.5.1, the R Foundation for Statistical Computing: http://www.R-project.org). Significance level was set at 0.05. There was no missing data, apart from values on two variables, with data on children's score on Find Them All with strategy and with data on children's score on Find Them All without using the strategy. Two children who never used the strategy had a missing value in the score on Find Them All with strategy. Children who always used the strategy (n = 41), searching locations systematically, one by one, from one end of the row to the other, had a missing value in the score on Find Them All without strategy by design. The distribution of all variables was inspected visually ("hist" function from the "graphics" package (R Core Team, 2021) and "qqPlot" function from the "car" package (Fox & Weisberg, 2019), and thereafter skewness (Pearson's mode coefficient calculated in R) and kurtosis of each variable were inspected ("kurtosis" function from "moments" package, Komsta & Novometsky, 2022; see Table 1). Further, we examined whether Corsi Block Tapping, not used with children younger than 4 years before (Grossi, Orsini, Monetti, & De Michele, 1979; Orsini, Grossi, et al., 1987), resulted in a large low-scoring sample to account for this in further analyses.

To address Assumption A1, i.e., assuming that the consistent use of the systematic search strategy would correlate with higher scores on the Find Them All task as compared to the inconsistent use, the two-sided Welch's t-test ("t_test" function from the "rstatix" package with the "var.equal" parameter set to "FALSE"; Kassambara, 2022) was employed to determine whether the children who consistently used the systematic search strategy achieved higher results in the Find Them All task than those who did not consistently use the systematic search strategy. This analysis was performed to ensure that the consistent use of systematic search strategy aided children's performance.

To address Assumption A2, the paired t-test ("pairwise_t_test" from "rstatix"; Kassambara, 2022) was used to determine whether, among children who did not use the strategy consistently, higher scores were achieved on trials when such children used the systematic search strategy compared to the scores achieved on trials when such children did not use the systematic search strategy. This was performed to check whether children who did not use the strategy consistently nevertheless would maximize the outcome when using the strategy. In principle, the inconsistent use of strategy could be underpinned by other factors than low working memory or low verbal ability, for instance, by a lack of motivation or a lack of understanding of strategy efficiency.

Finally, for children who did not use the strategy consistently, another variable was computed to test whether these children switched to the use of the systematic search strategy on more difficult trials. Among children who did not use the systematic search strategy consistently, the mode of scores on trials, in which strategy was not used, equaled 5, so the difficulty cut-off for easy/difficult trials was set at 5 locations. Trials with up to 5 locations were considered easy ("low" difficulty) and the remaining trials, with 6 locations or more, were considered difficult ("high" difficulty). A child could use the strategy on easy trials but then refrain from using it on difficult trials (strategy only on easy trials; low difficulty group). Alternatively, a child could refrain from using the strategy on easy trials but then switch to the use of the strategy on difficult trials (strategy only on difficult trials, high difficulty group). If the child did not use the strategy on at least one easy and at least one difficult trial, their performance was considered "mixed". One-way ANOVAs ("aov" function from the "rstatix" package; Kassambara, 2022) were used to determine whether there was a significant difference in Age, Corsi Block Tapping, Find The Toy and WPPSI Word Recognition score across the three groups of children (low difficulty, high difficulty and mixed). Note that this analysis also hinted on the reasons behind the effect of Age on Find Them All with strategy stated in hypothesis H1B.

With regard to our hypotheses, we employed the following statistical methods. To address hypothesis H1A and test whether the consistent use of strategy correlated with Age, a two-sided Welch's t-test ("t_test" function from the "rstatix" package with the "var.equal" parameter set to "FALSE"; Kassambara, 2022) and a linear model were used (family gaussian; "lm" function, from the "stats" package; R Core Team, 2021). Two variables were used to do so: one dichotomous, capturing whether the child consistently (always) used the systematic search strategy or not (Welch's test), and one continuous (linear regression; family "gaussian"), capturing the proportion of trials on which the child used the systematic search strategy to all trials completed by the child (see Table 1). All variables were centered and standardized in the linear model ("scale" function from the "base" package; R Core Team, 2021).

To address hypotheses H1B, H2 and H3 and test whether successful strategy use (FTA top score with strategy; see Table 1) correlated with Age, Corsi Block Tapping, and WPPSI Word Recognition, a multiple regression was used (family gaussian; type 3 "Anova" function from the "car" package; Fox & Weisberg, 2019). Age, Corsi Block Tapping, and WPPSI Word Recognition, as well as two interactions, Age x Corsi Block Tapping and Age x WPPSI Word Recognition, were introduced as predictor variables. Initially, Find the Toy was also considered as a potential predictor, but it did not correlate with any of these measures (Tables 2 & 3), and, further, adding this measure to the model resulted in overfitting that can produce biased regression coefficients and p-values (e.g., Babyak, 2004). The multiple regression was applied to two datasets: one including children who scored higher than 0 on

Corsi Block Tapping, and one including all children who used the systematic search strategy at least once, regardless of their score on Corsi Block Tapping. All predictors were centered and standardized in the model (“scale” function from the "base” package; R Core Team, 2021).

The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request. The study analysis code is available in Online Supplemental Material 1.

Results

Descriptive Statistics

For an overview of descriptive statistics on all variables see Table 1. All children but two used the systematic search strategy at least once (n = 95), and 42.27% of children (n = 41) always used the systematic search strategy (Table 1). Testing on Find Them All was interrupted for six children and their results were retained in the dataset because it was not clear whether they became bored or whether the task became too difficult for them as they did proceed to further testing on other tasks. None of them used the systematic search strategy on Find Them All consistently.

Overall, 32.99% of children (n = 32) received a score of 0 on Corsi Block Tapping (24-52 months, *Mage* = 37.06, SD = 7.34 months). Given that we do not have sufficient evidence that these children understood the task instruction, two multiple regressions were performed in response to Hypotheses H1B, H2 and H3: one without children who scored 0 on Corsi Block Tapping, and one with all children, regardless of this score. This was done to better understand how exclusion of null-scoring children influenced the results. For an overview of correlations between the variables included in the statistical analyses see Tables

2 (all participants) and 3 (only participants who scored higher than 0 on Corsi Block Tapping).

Table 1.

Descriptive Statistics of Measures Used in the Current Study (N= 97)

Measure	Details	Lowest score	Highest score	Mean	SD	Skewness	Kurtosis
Find Them All	Top score (*N* = 97)	3	9	7.91	1.70	-0.642	3.978
	Top score with the use of the systematic search strategy (*n* = 95)	3	9	7.842	1.734	-0.668	3.552
	Top score with the consistent use of the systematic search strategy (*n* = 41)	3	9	8.780	0.725	-0.303	19.990
	Top score without the consistent use of the systematic	2	9	7.268	1. 921	-0.902	2.353

	search strategy (*n* = 56)						
	Ratio of trials with the systematic search strategy to all trials (*n* = 54*)*	0	1	0.643	0.234	-0.926	3.017
Corsi Block Tapping	Top score (*N* = 97)	0	7	1.897	1.692	1.121	2.294
Find The Toy	Top score (*N* = 97)	0	12	5.928	3.333	-0.622	1.928
WPPSI Word Recognition	Score (*N* = 97)	0	29	15.412	6.582	0.822	2.497

Table 2.

Correlations among Age, Corsi Block Tapping, Find The Toy, WPPSI Word Recognition and Find Them All (Pearson's r). The group of participants who scored 0 on Corsi Block Tapping was included in this analysis. N = 97 for Age, FTA top score overall, CB, WR and FTT; n = 95 for FTA top score with strategy; n = 56 for FTA top score without strategy.

	FTA top score with strategy	FTA top score without strategy	FTA top score overall	CB	WR	FTT

Age	0.54***	0.05	0.38***	0.52***	0.54***	-0.04
FTA top score with strategy		0.27*	0.96***	0.42***	0.43***	0.07
FTA top score without strategy			0.47***	-0.03	0.01	0.35**
FTA top score overall				0.37***	0.41***	0.07
CB					0.54***	0.17
WR						0.14

Note: FTA with strategy = Find Them All with the consistent use of the systematic search strategy. FTA without strategy = Find Them All without the consistent use of the systematic search strategy. FTA top score = Find Them All regardless of strategy use. CB = Corsi Block Tapping. WR = WPPSI Word Recognition and FTT = Find the Toy.

** = p < .05; ** = p < .01; *** = p < .001*

Table 3.

Correlations among Age, Corsi Block Tapping, Find The Toy, WPPSI Word Recognition and Find Them All (Pearson's r). The group of participants who scored 0 on Corsi Block Tapping was excluded from this analysis. N = 65 for Age, FTA top score overall, CB, WR and FTT; n = 64 for FTA top score with strategy; n = 33 for FTA top score without strategy.

	FTA top score with strategy	FTA top score without strategy	FTA top score overall	CB	WR	FTT
Age	0.16	0.22	0.3	0.55***	0.4***	-0.03
FTA top score with strategy		0.26	0.97***	0.43**	0.38**	0.04
FTA top score without strategy			0.38*	0.07	0.06	0.21
FTA top score overall				0.38**	0.4**	0
CB					0.48***	0.2
WR						0.19

Note: FTA with strategy = Find Them All with the consistent use of the systematic search strategy. FTA without strategy = Find Them All without the consistent use of the systematic search strategy. FTA top score = Find Them All regardless of strategy use. CB = Corsi Block Tapping. WR = WPPSI Word Recognition and FTT = Find the Toy.

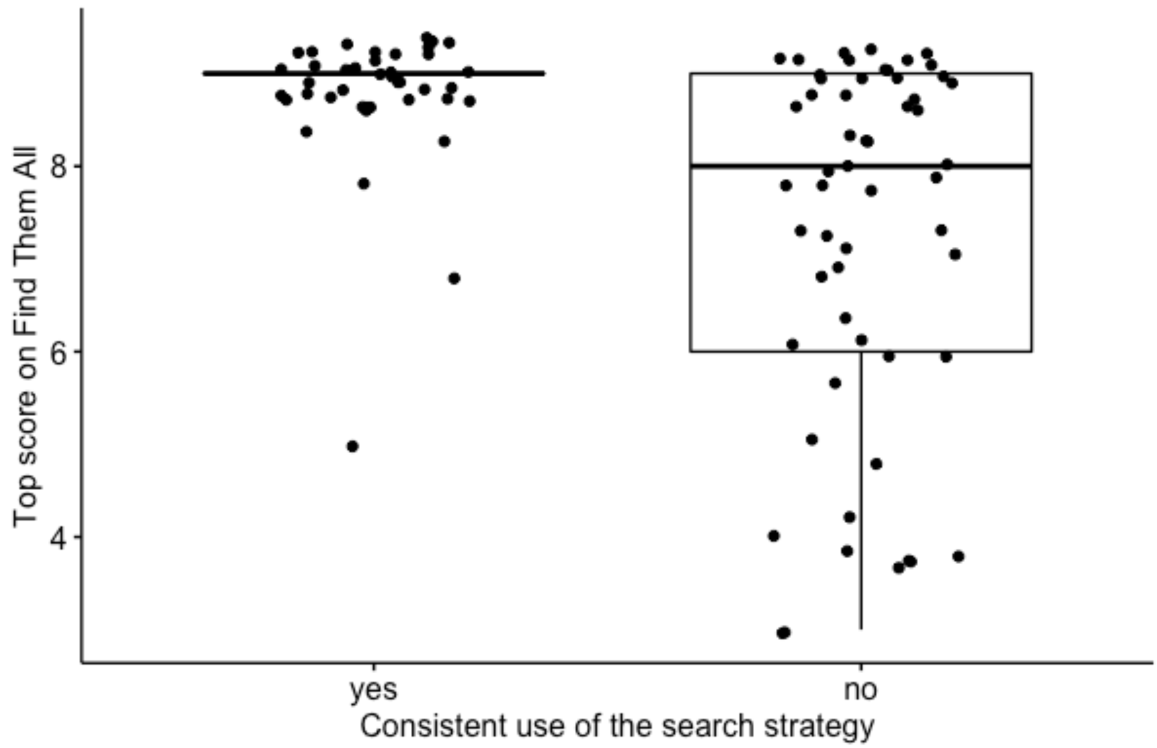
** = $p < .05$; ** = $p < .01$; *** = $p < .001$*

(A1) Correlation Between the Consistent Use of the Search Strategy and Score on the Find Them All Task

First, a two-sided Welch's t-test was used to determine whether the children who used the systematic search strategy consistently achieved higher top score on Find Them All than those who did not use it consistently. The mean score in the group with consistent use of strategy ($n = 41$) was 8.78 ($SD = 0.725$), whereas the mean score in the group that did not use the strategy consistently ($n = 56$) was 7.27 ($SD = 1.92$). The difference between these two groups was significant ($t(74.6) = -5.38$, $p < 0.0001$, $d = -1.04$; Figure 2).

Figure 2.

A boxplot of top scores achieved by children who used the systematic search strategy in all trials and those who used the systematic search strategy only on some of the trials.



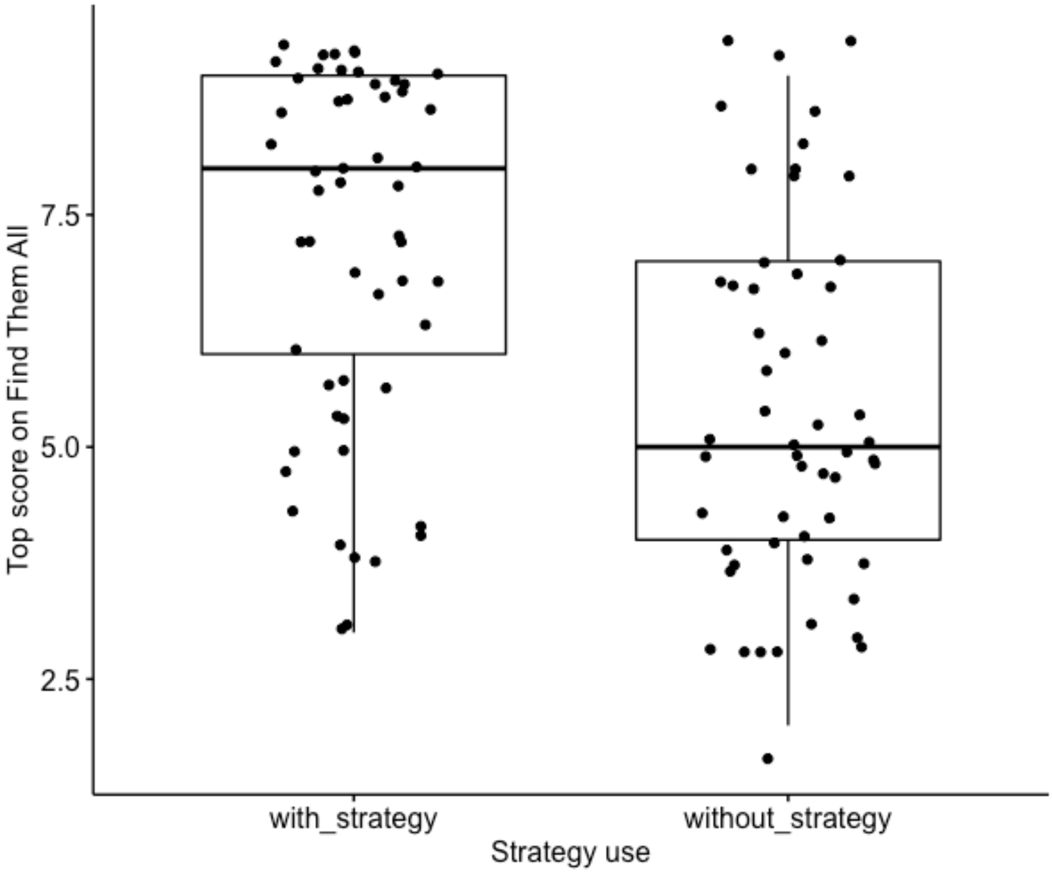
(A2) Correlation Between the Systematic Use of the Search Strategy and Score on the Find Them All Task

A two-sided paired-sample t-test was used to determine whether, among children who did not use the systematic search strategy consistently, these children achieved higher scores when using the systematic search strategy compared to the scores achieved without using the strategy. Note that two children never employed the systematic search strategy. Among children who did not use the systematic search strategy consistently, the mean score for trials in which children employed the search strategy was 7.13 ($n = 54$, $SD = 1.93$), whereas the mean score for the remaining trials was 5.44 ($n = 54$, $SD = 1.93$). The paired-sample t-test showed that the difference was significant ($t(53) = 5.32$, $p < 0.0001$, $d = 0.723$; Figure 3).

Among children who did not use the systematic search strategy consistently and employed the systematic search strategy on at least one trial ($n = 54$), the mode of scores on trials without the use of the strategy equaled 5, so the difficulty cut-off for easy/difficult tasks was set at 5 locations. Among these children, 14 children ($M_{age} = 37.93$, $SD = 8.8$) used the strategy on at least one trial with 6 or more locations but never on trials with 5 or fewer locations. 21 children ($M_{age} = 41.19$, $SD = 6.94$) used the strategy on at least one trial with 5 or fewer locations but never on trials with 6 or more locations. The remaining 19 children ($M_{age} = 37.21$, $SD = 7.36$) used the systematic search strategy on at least one trial with 5 or fewer and at least one trial with 6 or more locations. The one-way ANOVA showed that the difference in Age across the three groups was not significant ($F(2; 51) = 1.537$, $p = 0.225$; $\eta 2= 0.06$). This was also the case for Corsi Block Tapping ($F(2; 51) = 1.123$, $p = 0.333$; $\eta 2= 0.04$), Find the Toy ($F(2; 51) = 0.604$, $p = 0. 515$; $\eta 2= 0.02$) and WPPSI Word Recognition ($F(2; 51) = 0.625$, $p = 0.539$; $\eta 2= 0.02$).

Figure 3.

A boxplot of top scores on Find Them All on trials where the strategy was used and on trials where the strategy was not used, achieved by children who have not consistently used the *systematic search strategy and employed the strategy at least once (n = 54). The result shows that using the strategy was associated with higher scores in this group.*



(H1A) The Effect of Age on Consistent Strategy Use

First, a two-sided Welch's t-test was used to determine whether, with Age, children were more likely to consistently use the systematic search strategy. The mean Age in the group with consistent use of strategy was 43.34 (*SD* = 6.13), whereas the mean Age in the group that did not use the strategy consistently was 38.59 (*SD* = 7.80). The difference between these two groups was significant ($t(94.5) = -3.36$, $p < 0.01$, $d = -0.678$). Furthermore, a generalized linear model was fitted to determine the effect of Age (in months) on Strategy Use in the Find Them All Task. With Age, the proportion of trials with the systematic strategy to all trials likewise increased ($\beta = 0.336$; $SE = 0.01$, $p < 0.001$; $R2 = 0.096$; $f2 =$

0.106). Therefore, the older children were more likely to consistently use the systematic search strategy than the younger children.

(H1B, H2, H3) The Effects of Age, Visuospatial Working Memory, and Verbal Ability on Successful Strategy Use

Two multiple regression models were run in order to determine whether Age, Corsi Block Tapping and WPPSI Word Recognition correlated with the top score on Find Them All with the systematic search strategy: one with children who used the systematic search strategy at least once and scored higher than 0 on Corsi Block Tapping (n = 64; adjusted R^2 = 0.233, $f2$ = 0.304), and another with all such children regardless of their score on Corsi Block Tapping (n = 95; adjusted R^2 = 0.247, $f2$ = 0.328).

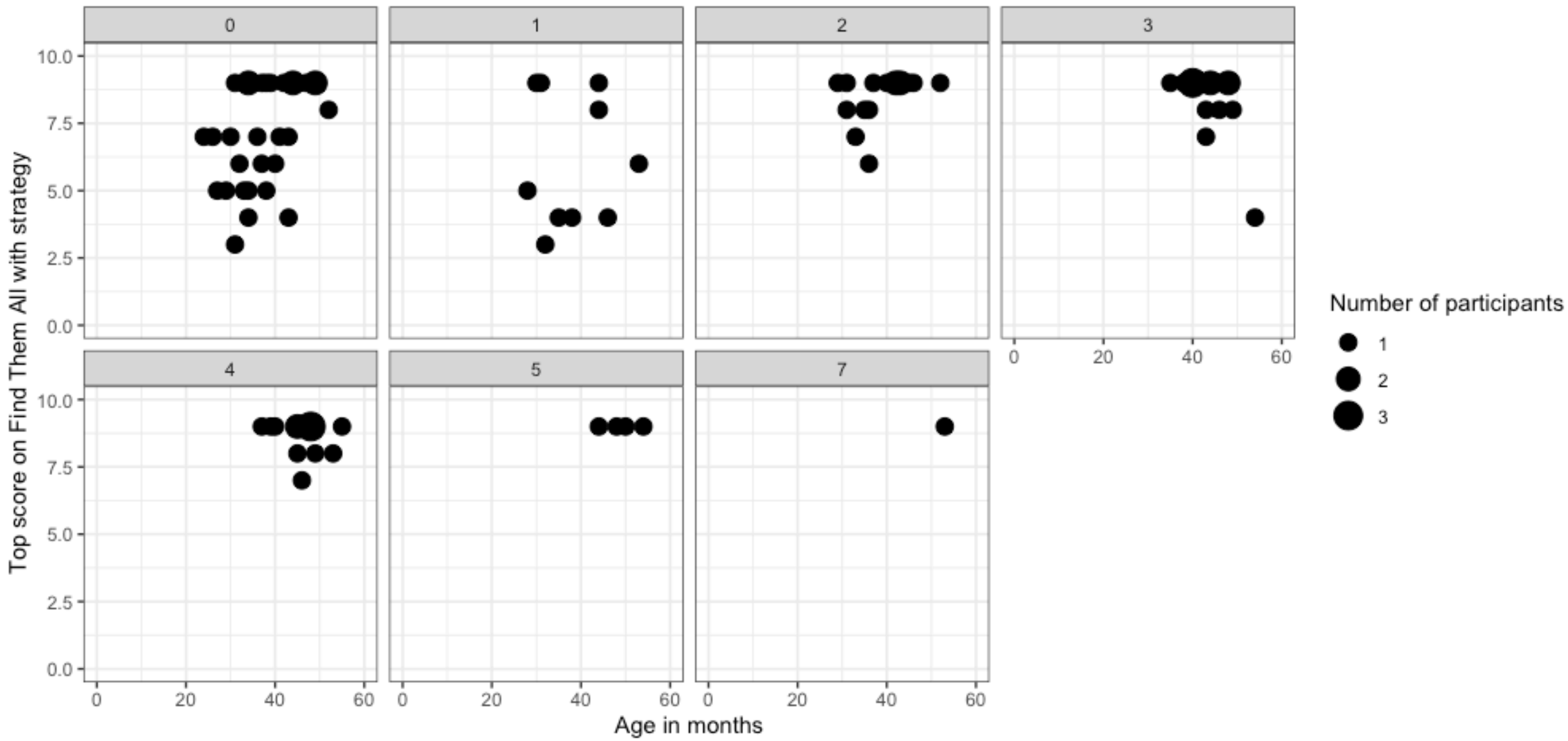
Among children who scored higher than 0 on Corsi Block Tapping, there was only a main effect of Corsi Block Tapping (β = 0.486, SE = 0.149, p = 0.002). Therefore, a 1 SD increase in the top score on Find Them All with strategy was associated with a 0.486 SD increase in the score on Corsi Block Tapping. None of the other effects were statistically significant (Age: β = -0.24, SE = 0.14, p = 0.092, WPPSI Word Recognition: β = 0.271, SE = 0.136, p = 0.051, Age x Corsi Block Tapping: β = -0.244, SE = 0.133, p = 0.07, Age x WPPSI Word Recognition: β = 0.064, SE = 0.143, p = 0.653)

Among all children who used the systematic search strategy at least once, there was a main effect of Corsi Block Tapping (β = 0.368, SE = 0.124, p = 0.004), a main effect of WPPSI Word Recognition (β = 0.254, SE = 0.116, p = 0.031), and an interaction effect of Age and Corsi Block Tapping (β = -0.317, SE = 0.128, p = 0.015). There was neither a main effect of Age (β = 0.023, SE = 0.113, p = 0.842) nor an interaction effect of Age and WPPSI Word Recognition (β = 0.176, SE = 0.119, p = 0.144).

To better understand the interaction effect between Age and Corsi Block Tapping on the top score on Find Them All reached with the systematic search strategy regardless of the score on Corsi Block Tapping, the relationship between these variables was visualized (Figure 4). The negative interaction effect seems to have resulted from a negative correlation between Age and Corsi Block Tapping among children who scored 0 to 3 on Corsi Block Tapping, and a low variance in the Find Them All score among the older children, scoring 4 to 7 on Corsi Block Tapping.

Figure 4.

An overview of the relation between the top score on Find Them All task, achieved with the systematic search strategy, the score on Corsi Block Tapping and child's Age in months. Note that numbers from 1 to 7 on top of the individual graphs represent the score on Corsi Block Tapping.



Discussion

In this study, we aimed to investigate whether 2- to 4.5-year-olds were able to perform a systematic search across a row of locations, proceeding systematically through a line. Furthermore, we tested whether consistent use of the systematic search strategy increased with age, and whether the successful use of this systematic search strategy increased with age, visuospatial working memory and verbal ability. Our results suggest that a spontaneous use of search strategies, drawing on patterned spatial distributions, begins in toddlerhood. In the current study, one of such strategies aided keeping track of searched locations, as the consistent use of the strategy correlated with higher top scores on a task that required retrieval of stickers from beneath identical boxes arranged in a row. Interestingly, even children who did not use the strategy consistently were able to benefit from the systematic search strategy, as they achieved significantly higher scores on trials where the strategy was used than on trials where the strategy was not used.

Overall, the present results showed that the ability to proceed systematically through a line significantly improved with visuospatial working memory, but not with age or verbal ability, in 2- to 4.5-year-olds who sufficiently showed that they understood task instruction. The ability to use the relevant search strategy, i.e., searching a row of locations from left to right, correlated with age, suggesting that the use of such strategies is related to previous knowledge or experience. The successful use of the relevant search strategy, however, did not correlate with age but did correlate with working memory as measured by Corsi Block Tapping. This suggested that employing a familiar strategy was not sufficient for a successful search; the strategy had to be paired with the ability to keep track of already-searched and/or to-be-searched locations, relying on working memory resources. Surprisingly, among children with low visuospatial working memory, the older children struggled with the successful implementation of the search strategy more than the younger children.

While verbal ability significantly correlated with the successful use of the systematic search strategy in the Find Them All task, it was not a significant predictor of this success alongside Corsi Block Tapping, a measure of visuospatial memory, in children who sufficiently showed that they understood the task instruction on Corsi Block Tapping. Verbal ability was, however, a significant predictor of the successful use of the systematic search strategy in the Find Them All task, when the null-scoring children were included in the analysis. Finally, although two measures of visuospatial working memory were included in the present study, only Corsi Block Tapping but not Find The Toy correlated with the successful use of the systematic search strategy in the Find Them All task. Note, however, that Find the Toy did positively correlate with the score on Find Them All on trials without the use of the systematic search strategy.

Consistent Use of Strategy Increased with Age

The ability to use strategies that organize incoming information, such as chunking, develops early. Seven- and 15-month-olds were shown to use chunking if the objects shared salient common features (Moher et al., 2012; Feigenson & Halberda, 2004). With age, this early sensitivity to chunks gives rise to an ability to recode information in a top-down manner to increase memory efficiency (Mathy et al., 2016). The ability to increase memory efficiency, through increasing the number of chunks, continues to develop in primary school (Mathy et al., 2016). Although several other early working memory strategies were investigated in the past (Chen & Siegler, 2003), taking advantage of simple patterned distributions, e.g., proceeding systematically through a line, in the preschool years remains understudied. Here, we showed for the first time that nearly all children between 2 and 4.5 would at least once use one such strategy, proceeding systematically through a row of to-be-searched locations. Furthermore, with age, children were increasingly likely to use this strategy consistently, that is, on all trials, regardless of the number of locations. This may have resulted from children's familiarity with proceeding from left to right when dealing with series of objects. Between 2 and 4.5 years of age, children are increasingly exposed to serial stimuli and accumulate experience with pretend-reading, pretend-writing, and spatial material in general, that typically requires progressing from left to right and from top to bottom. This also coincides with children's arithmetical development which may strengthen children's habit of proceeding from one side of the row of objects/locations to the other. This habit may remain strong even in older children that those tested in the current study, namely in 5- to 11-year-olds (Kamawar et al., 2010).

The increase in the consistent use of the systematic search strategy with Age may have been reinforced by the development of the ability to implement systematic behavior in compliance with task demands, alongside the development of effective strategy use. We speculate that the increase in the use of the systematic search strategy with Age could have been underpinned by children's metacognitive awareness of working memory limitations (Applin & Kibbe, 2020; Marulis et al., 2016). Such metacognitive awareness would have resulted in intentional deployment of the systematic search strategy on all or only difficult trials. However, the results of the present study do not provide conclusive evidence in terms of metacognitive awareness (monitoring), given that indeed, older children were more likely to consistently employ the systematic search strategy, but it seems that age did not correlate with the deployment of the systematic search strategy only on the difficult trials.

Furthermore, children, who did not use the systematic search strategy consistently, achieved higher top scores on trials during which they used the strategy than on trials during which they did not. This suggests that these children were able to maximize their results when using the systematic search strategy, but perhaps lacked motivation to perform well on all trials or showed utilization deficiency. As the study was always interrupted if the child was no longer motivated to participate, it is more likely that children, who did not use the strategy consistently, either did not deploy the strategy intentionally or failed to monitor its deployment on each trial. In principle, as children who did not use the strategy consistently, achieved diverse scores, from low to high (see Figure 3), this group may have consisted of two sub-groups: children who indeed did not understand that the strategy would secure top scores and children whose working memory capacity was so high that they would not need to use the strategy on all trails. However, this is unlikely, given that children, who used the strategy consistently, achieved higher scores than children who did not, and that successful use of the strategy correlated with working memory capacity.

Successful Use of Strategy Correlated with Working Memory

In line with our hypotheses, children were more likely to achieve high scores with the increasing visuospatial working memory capacity. This result is consistent with previous studies, showing that maintaining and updating representations in working memory, critical to keeping track of one's own search behavior, develops in toddlerhood and preschool years (Kibbe & Leslie, 2013; Moher & Feigenson, 2013; Wheeler & Treisman, 2002).

Interestingly, among all children who used the systematic search strategy at least once in the present study, we found a negative interaction effect between visuospatial working memory as measured by Corsi Block Tapping and Age in months on the successful use of the systematic search strategy. It seems that, among children scoring low on visuospatial working memory (0 to 3), older children used the systematic search strategy less successfully than younger children (see Figure 4). This was not, however, the case for children scoring high on visuospatial working memory (4, 5 or 7). This result is somewhat puzzling but may suggest that older children tried to compensate lower working memory capacity with other, unsuccessful strategies, or that they have not received a sufficient support earlier in development, and now are falling behind their peers. The present result remains inconclusive and needs closer examination in the future.

In principle, metacognitive awareness of working memory limitations may have allowed children to tailor their strategies to task demands, solving the Find Them All task from left to right and, e.g., visualizing patterns of locations sequentially tapped by the experimenter in the Corsi Block Tapping task. However, it remains unclear whether the correlation between visuospatial working memory capacity and performance on the Find Them All task was underpinned by children's metacognitive awareness of working memory limitations (Applin & Kibbe, 2020; Marulis et al., 2016) as metacognition was not measured in the present study. Such awareness would have resulted in a higher probability of deploying of the systematic search strategy only on difficult trials by children with higher visuospatial working memory scores, but this was not the case in the present study.

Contrary to our hypothesis, children's verbal ability was a statistically significant predictor of change in performance on the Find Them All task only among all children, including those who did not sufficiently show that they understood task instruction on Corsi Block Tapping. This suggests that their exclusion from the final regression model was a correct choice. Children's verbal ability was not a statistically significant predictor of change in performance on the Find Them All task among children who sufficiently showed that they understood task instruction on Corsi Block Tapping. This, in turn, suggests that children may have not benefitted from the self-regulatory potential of private speech. The experimenters have indeed not noted such speech in the study, and previous findings showed that three- and four-year-olds were the least likely to engage in such speech in the presence of the adult and during activities that they have not selected themselves (e.g., Winsler, Carlton, & Barry, 2000).

Working Memory Capacity

According to previous research, by age 5, children can maintain on average, between 1.1 and 4.6 representations in their visuospatial working memory on simple span tasks but this result considerably varies across different working memory tasks (Simmering & Perone, 2013). In the present study, children's average score on Corsi Block Tapping task, an established task measuring visuospatial working memory, equaled 1.897 (2.831 among children who scored higher than 0 on the task) and 5.928 on the Find the Toy task. However, top score on the Find Them All task on trials, where the systematic search strategy was not used, equaled, on average, 7.268. This suggests that when children are allowed to organize their own search behavior, they might, in principle, be able to support the capacity limit using several other, non-salient strategies (Chen & Siegler, 2003). Such strategies could be further investigated in the future, either in an individual version of Find Them All or in a social version of this task (Bobrowicz & Osvath, 2020a). In the social version of the task, the child sees a partner removing items from several locations and needs to remember which locations have been depleted before starting their own search for the remaining items. The social version of the task could be used to investigate the link between children's working memory and collaborative learning skills, as it demands keeping track of both partner's and one's own actions.

Limitations

In this study, Corsi Block Tapping served as a test of visuospatial working memory because this task allowed us to maintain a comparable setup for both CBT and the Find Them All task (9 locations). Namely, in both tasks, children were tested with nine boxes, either arranged without any explicit pattern and not allowing for self-structured search (CBT) or arranged in a row and allowing for self-structured search (Find Them All). Furthermore, both tasks should involve similar cognitive processes as both require spatial reasoning (mental manipulation of objects). Finally, Corsi Block Tapping was relatively brief compared to some other nonverbal tests of working memory (e.g, Memory Span Spin-the-Pots, Morra et al., 2021) and, in principle, should not have required high verbal ability, as this test relied on imitation of the experimenter's hand movements. However, we found that many children (32.99%) may have struggled with the task instruction. While the decision to exclude these children from the analyses has not masked the effect of age on the successful use of the systematic search strategy, it seems to have masked the effect of verbal ability. In the future, multiple other nonverbal tests of working memory may be implemented to measure visuospatial working memory in children between 2 and 4.5 years, such as the Imitation Sorting Task (Alp, 1994; Fitzpatrick & Pagani, 2012; Morra et al., 2021), Memory Span Spin-the-Pots task (Morra et al., 2021), the Missing Scan Task (Roman et al., 2014), Mr. Cucumber Test, and Direction Following Task (Panesi & Morra, 2016), the modified version of the Change Detection Task (Simmering, 2012), the Copy Hand Movement task (Slot & Suchodoletz, 2018), or finally Nine Boxes, Nebraska Barnyard Task or Delayed Alternation task (Wiebe et al., 2011).

Although two measures of visuospatial working memory were used in the present study, only one, Corsi Block Tapping, correlated with age. Find the Toy did not, suggesting that this measure failed to reflect improvements in visuospatial working memory with age. This measure was previously tested with toddlers between 18 and 24 months of age (Bernier et al., 2010, Pauen and Bechtel-Kuehne, 2016), and perhaps was too easy for older children despite the adaptation of the difficulty level to age, embedded in the task instruction. Note that the adaptation of the difficulty level to age in this task may have underpinned the lack of correlation between Age and the score on Find the Toy. Find the Toy may have also measured rather short-term than working memory as it required maintaining information in mind, rather than operating on it. This explanation would be consistent with previous studies, showing that working and short-term memory tasks do not have to correlate with one another in children, adolescents, and adults (Diamond, 2013). Interestingly, Find the Toy correlated only with one measure in the current study, namely the top score on Find Them All without the use of the systematic search strategy. This might suggest that maintenance of information, tapped by Find the Toy, may have served as an important component of success on Find Them All despite the non-systematic search.

Conclusions

This study contributes to research on working memory by investigating early spatial search strategies, showing that two- to 4.5-year-olds could proceed systematically through a line and organize their own search behaviors in an array of up to nine locations. Maximizing the outcome of search behaviors correlated with visuospatial working memory capacity. This suggests that early support of sensitivity to patterned spatial distributions may aid the development of working memory, critical to several domains of concurrent and future academic achievement.

Conflict of Interest

None of the Authors have any competing interests to declare.

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