The FORAGEKID Game: Hybrid-Foraging as a new way to study aspects of executive function in development

Beatriz Gil-Gómez de Liaño [a,b,*], Jeremy M. Wolfe [c]

[a] Department of Social Psychology and Methodology, Universidad Autónoma de Madrid, Spain
[b] Department of Experimental Psychology, Basic processes and Logopedic, Complutense University of Madrid, Spain
[c] Brigham & Women's Hospital-Harvard Medical School, Massachusetts, United States

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ABSTRACT

In hybrid foraging, observers search for multiple exemplars of multiple targets (e.g. look for yellow and purple perler-beads in the handicrafts box). Adults can perform hybrid searches for, literally, hundreds of different target objects. How does this ability to handle memory load develop during childhood? We compared performance under different memory loads at different ages (5–6, 11–12, and +18 years-old) in our FORAGEKID hybrid foraging video game, where observers searched for different moving real-world toys. Especially under higher memory loads, younger children show an ineffective target switching search compared to a strategy featuring longer "runs" of one type of target, implemented by older children and adults. All observers follow similar "quitting" rules for moving to the next screen. The results show that FORAGEKID could be a useful tool for understanding the development of aspects of executive function: combining memory, attentional control, and decision/strategy processes within a single enjoyable task.

Despite decades of dedicated research, there remain substantial gaps in our understanding of human cognitive development. In particular, the development of executive functions such as cognitive control, attention, working memory, cognitive flexibility or decision making processes is imperfectly understood. Knowing the development of these capabilities is crucial to improving children's learning skills and educational results. Visual search can be a useful tool to investigate many of these functions as they work together, in the service of a single goal. In typical visual search tasks, observers search for a single target among distractor items. Such tasks are vital in everyday life (Where are the keys? Where is the cat?), and they have elicited a considerable amount of research at all developmental stages (e.g. Gil-Gómez de Liaño et al., 2020; Hommel et al., 2004; Müller-Oehring et al., 2013; Wolfe & Horowitz, 2017). *Foraging* tasks are a variant of visual search in which observers search for multiple exemplars of a given target (e.g. picking berries, see Wolfe, 2013). *Hybrid Foraging* (HF), is an extension of simple foraging in which observers look for multiple instances of several targets (e.g. looking for both yellow and purple perler-beads in the handicrafts box or looking for several types of LEGO bricks in order to construct a house, see Wolfe et al., 2019). Foraging and Hybrid Foraging have received little study with humans, although there is a considerable animal foraging literature (for a review, see Bella-Fernández et al., 2021). This may be a missed opportunity, because foraging allows researchers to study search strategies using multiple targets that visual search tasks do not. In typical visual search tasks, observers end a search when they find the single target or when they decide it is not present.

* Correspondence to: Departamento de Psicología Social y Metodología, Facultad de Psicología, UAM, C/ Ivan Pavlov, 6, Ciudad Universitaria Cantoblanco, 28049 Madrid, Spain.
E-mail addresses: bgil.gomezdelianno@uam.es, bgil.gomezdelianno@gmail.com (B. Gil-Gómez de Liaño).

Foraging extends visual search tasks to include the interesting decisions about when to stop searching a "patch" because it is no longer sufficiently profitable to keep searching, even though more targets may be present. Hybrid foraging adds the complexity of choosing between different search targets. Moreover, the inclusion of several target types in hybrid foraging adds memory components (working and/or long term) to the task. Thus, foraging tasks would allow the study of aspects of executive functions that govern decision strategies and the organization of search in ways that simple visual search tasks do not.

Memory interactions both in typical search and in foraging tasks have been studied in adults and older adults, showing several interesting results relevant to the control of attention. In particular, the use of multiple target types in foraging tasks has allowed researchers to ask how often foragers switch from one target to another, as opposed to collecting targets in *runs* of the same target type. This will be further discussed below. However, the manipulation of memory load in hybrid foraging has not been tested in development. The present study aims to understand how some executive functions involved in hybrid foraging operate during development from early and middle childhood to early adulthood, paying special attention to strategies followed by children under different memory load conditions, not yet experimentally studied with children in such tasks.

Prior work contains some insights about how some executive functions develop in classic visual search tasks (e.g. Gil-Gómez de Liaño et al., 2020; Hommel et al., 2004). Gil-Gómez de Liaño et al. (2020) presents one of the most detailed analyses to date, using visual search to address how some executive functions develop in visual search from 4 to 25 years. Using a large sample of almost 300 participants from 4 to 25 years, they showed that the developmental course for different parameters in typical visual search tasks seemed to mirror several aspects of executive function development in more applied neuropsychological assessment models (Anderson, 2002). Specifically, accuracy data appeared to follow the developmental function for attentional control, search slopes followed a function similar to that of goal setting, and intercepts lay in between information processing and cognitive flexibility functions. In addition, there are recent foraging studies examining children's development, also stressing the importance of executive function development: Ólafsdóttir et al. (2016); Ólafsdóttir et al. (2019,2020) compared behavior of kindergarteners and pre-adolescents to adults. In those studies, younger children showed different patterns in search compared to those found for older children and adults. Importantly, in those studies there was a significant correlation between the performance in foraging and the performance in working memory tasks and other attentional tasks, although this relationship was not as clear in previous studies with adults (e.g. Jóhannesson et al., 2017). Also, Gil-Gómez de Liaño et al. (2022) have recently replicated those results, and incorporating the study of quitting search rules within a foraging task. They found that although younger children (4 years) might be following a "giving-up rule" when deciding when to quit the search (Krebs et al., 1974), patch leaving decisions by older children and adults (from 5 years to about 25 years) were broadly consistent with optimal quitting decisions as defined by the Marginal Value Theorem[1] (MVT, Charnov, 1976; Stephens & Krebbs, 1986), suggesting that quitting rules in search reflect quite basic aspects of the human cognition that mature relatively early in development.

The interactions of foraging search behavior with memory contents has not yet been experimentally tested with children. In previous foraging studies with children, there were two different targets to find and no manipulations of the number of targets. In adult studies, Wolfe, et al. (2016) asked observers to look for 8–64 realistic photos within an hybrid foraging paradigm using other photorealistic objects as distractors. The results showed expected increases in response times (RTs) as memory and set size increased, but more interestingly, the strategies in the search varied with memory loads. With larger memory loads, observers generated a strategy in which they prioritized the search for one target type at a time, while still holding the others in memory. This produces *runs* in which observers pick multiple exemplars of the same target type before switching to another target type. Comparable results were found by Wiegand et al. (2019) in a sample of older adults, also surprisingly showing that memory functions in older age did not essentially differ from younger ones. In the present study, we adapted hybrid foraging tasks from adults and older adults (Wolfe et al., 2016; Wiegand et al., 2019) to study memory effects in hybrid foraging in young children of 5–6 years, and older children of 11–12 years. We developed the FORAGEKID game, a hybrid foraging task in which observers must look for different toys moving around the screen within a video game-like task. FORAGEKID is intended to be a more enjoyable improvement over the simpler, basic hybrid foraging tasks featuring plain circles and squares, previously used to test children (Gil-Gómez de Liaño, et al., 2022; Ólafsdóttir et al., 2019; 2020). FORAGEKID involves a jungle filled with pictures of floating real-world toys of different colors and shapes (see it in the methods section below). Using real-world toys may be said to increase the ecological validity. More importantly, the game-like environment seems likely to increase children's motivation.

The capacity to maintain task relevant information online is under development until children are about 12 years. The peak of change falls between 6 and 10 years (Luciana & Nelson, 1998; Vuontela et al., 2013). To assess the impact of this development on foraging behavior, we loaded memory with 2–7 items. Using a hybrid foraging paradigm within a video game-like task under different memory load conditions could allow us to track the development of search within a more complex cognitive environment, including

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[1] According to MVT, an observer following an optimal quitting rule would leave the search when the instantaneous rate of target collection falls right below the average rate of collection in the task. See Charnov (1976) for details about MVT.

different memory load conditions. Importantly, we may be able to measure several executive functions like attentional control, memory, or search cognitive strategies within a single task that is enjoyable for children.

1. Method

1.1. Participants

Ninety eight observers participated in the experiment, from schools and colleges located in Madrid, Spain. From a previous similar study using simple stimuli (Gil-Gómez de Liaño et al., 2022), we could set a sample size between 21 and 33 for each age group as the minimum to guarantee reliable results. Studies with adults and older adults (Wiegand et al., 2019; Wolfe et al., 2019) have found reliable results with sample sizes of 12–15 but with children, it is better to err on the side of more observers. Since in previous developmental work on foraging the most important changes were clearly detected at ages 5–6 and 11–12 years (e.g., Gil-Gómez de Liaño et al., 2022, and Ólafsdóttir et al., 2016), we decided to use those age bins for comparisons with an adult normative sample for the present study. Thus, our 98 observers were divided into three age groups, 5–6 years (34 observers; between 5;0 - years;months - and 6;11), 11–12 years (30 observers; between 11;0 and 12;11), and an adult group, 18–38 years (34 observers, adult mean age of 26 years, with a standard deviation of 5 years). In all groups, half of the observers were men and half women to control for potential gender differences. None of the observers had any history of neurological or sensorial damage or motor impairments nor any diagnosis of schizophrenia or generalized developmental disorder, based on family's reporting for children, and self-reports for adults. We ran Conners Kiddie Continuous Performance Test 2nd Edition™ (Conners K–CPT 2™) standardized tests on the children to potentially exclude other observers for attentional problems (see materials below). In fact, none had CPT results outside the normal range.

All participants had normal or corrected-to-normal vision. Parents/guardians gave written informed consent for each minor. Each participant over age 7 gave verbal or written assent/consent after ethical committee acceptance at Universidad Autónoma de Madrid (Code of approval CEI 100–1860).

1.2. Materials

The experiment was written in Matlab 7.10 (The Mathworks, Natick, MA, USA) using the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997, Kleiner et al., 2007) version 3. Stimuli were presented on a Microsoft Surface pro i5, and observers gave responses by touching the screen. Monitor resolution was 1400×1050 pixels. The stimuli were randomly moving in order to avoid systematic strategies such as "reading" the display left-right and top-bottom, following Gil-Gómez de Liaño et al. (2022) methods. Items moved at a constant velocity of 44 pixels/sec (approximately $1.2°$ of visual angle per second), changing directions at pseudo-random intervals, again following the Gil-Gómez de Liaño, et al. (2022) methodology. The stimuli were images of well-known and familiar stuffed animals on a jungle background (see Fig. 1).

Toys were drawn from a set of 297 different "Beanie Boos" set of images. Each toy was placed in an invisible rectangle that would subtend a visual angle of 1.33º height, 1.00º width at a 60 cm viewing distance, though we did not explicitly control viewing distance. Set sizes were 40, 80 and 120. Targets constituted 20–30% of the items in each display. Observers were unaware of the number of targets in each display though. Targets were randomly selected for each observer, and all observers were tested in two memory load conditions; Low Load Memory Set Size 2 (MSS2) with 2 targets to look for, and High-Load Memory Set Size 7 (MSS7) with 7 different targets to look for, as shown in Fig. 1. The term "memory set size" (MSS) refers to the number of potential target types, held in memory. This is distinct from the visual set size, the number of items on the screen. The term "target" is somewhat ambiguous as it could refer to a target *type* held in memory or a single instance of a target, visible on the screen.

We used the Conners Kiddie Continuous Performance Test 2nd Edition™ (Conners K–CPT 2™) for assessing attention in children ages 5–6 years. The test takes 7.5 min for a performance-based assessment using pictures of objects that are familiar to young children (e.g. boat, soccer ball, train). The child must press the space bar to all objects except for the soccer ball. For the older children (11–12 years) we used the Conners Continuous Performance Tests 3 is similar but uses letters instead of pictures and takes about 15 min. Both the K-CPT and the CPT are used in clinical diagnosis of Attention Deficit/Hyperactivity Disorder (ADHD), as well as other psychological and/or neurological disorders of attention. We used it in order to control for potential attention problems in our children sample, being all of them in the normal range. The test-retest reliability reported from the Conners CPT's manual varies from 0.62 to 0.90 depending on the study and the population of interest. The median test-retest reliability reported from Conners K-CPT manual is 0.57.
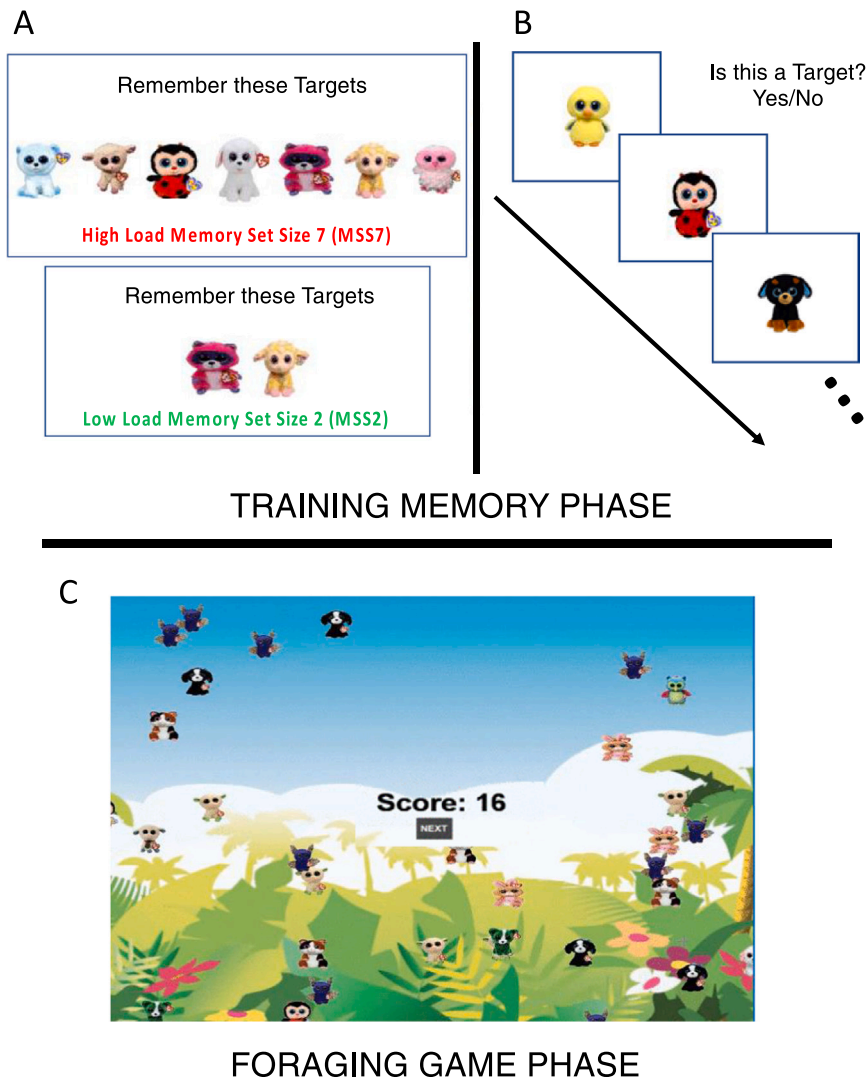
Fig. 1. Example of the experimental procedure. Note. The experimental procedure is explained in this figure. First, participants are shown one of two memory load conditions: Memory Set Size 2- with 2 targets, and Memory Set Size 7-with 7 targets (A). After exposure to the targets, participants are given a memory recognition task (B). They must reach at least 80% correct in the recognition task to play the foraging game. Then, in the FORAGEKID game (C), participants had to collect targets as quickly as possible to reach 200 points to "win" with all items in motion. Target set is not visible during the foraging task. It should be held in memory.

1.3. Design and procedure

Observers were asked to collect 200 points as fast as possible by picking up targets in each MSS2 and MSS7 conditions. They received 2 points for every target picked, and lost 1 point for every distractor selected. When a correct target was tapped, it disappeared from the screen. If a distractor was erroneously tapped, a red cross was displayed on the distractor, but the distractor remained on the screen and the red cross disappeared. In the MSS2 they had to look for two target "beanie boos", while in the MSS7 there were seven targets (see Fig. 1). To make sure observers remembered the search targets, there was a memory test before the experimental phase. The items were shown both together and separately one by one for 3 s each in both MSS2 and MSS7 conditions in the center of the screen. Immediately afterwards, a stuffed animal was shown in the middle of the screen and the observers pressed the "A" key on the keyboard if the animal was part of the target set, or "L" if it was not a target (Fig. 1, B). Only 50% of the items shown were targets while the rest were other stuffed animal-distractors. Observers needed to get at least 80% correct in the memory test before moving to the Hybrid Foraging game. If not, they repeated the memory test until getting that 80% correct. When they reached the 80% correct score, they started the foraging game (Fig. 1, C). Target images were not available for observers to consult during the foraging game. MSS2 and MSS7 conditions were run separately and pseudo-randomly counterbalanced, with half of the participants at each age running in a MSS2/MSS7 order, and the other half running MSS7/MSS2. A score counter in the center

of the screen was updated every time they picked a target (see Fig. 1, C), and every condition ended only when they got 200 points (Thus requiring 400 total points for the whole task). Since the counter interpretation for the youngest children of 5–6 years was a bit complicated for them, those children were also updated about their score during the experimental phase to make sure they attended to the counter-points during the task. The word "next" was present in a grey square below the score, as is shown in Fig. 1. Touching the next button moved observers to a new screen, thus implementing the patch-leaving aspect of a foraging task. They could move to another patch to look for more targets whenever they chose. The "travel time" – the time from the touching of the Next button to the appearance of the next screen – was set to 2 s. The task finished when the 200 points were reached in every MSS2/MSS7 condition. It took between 15 and 25 min. All observers had a practice phase previous to the experimental phase with feedback. We checked and ensured that all of them had understood the instructions. For the youngest ones, we asked them to tell us the task objectives before starting the experimental paradigm and made sure they actually understood the task before the end of the practice phase. The practice phase required observers to get 50 points before moving to the experimental phase in both MSS2 and MSS7 blocked conditions, in order to assure that observers were trained and familiarized with the task. The whole session, consisting of the foraging game and the K-CPT and/or CPT tests, took between 30 and 45 min, including practice trials and any resting times needed by the participants.

2. Results

2.1. Runs and Switches

The Hybrid Foraging task produces a rich set of data. We will start with the study of different patterns of response: *runs* and *switches*. *Runs* are defined as the repetition of a target response (e.g., tapping on a white-puppy when the previous target tapped was also a white-puppy). *Switches* are changes in the type of target tapped (e.g., tapping on a pink-owl after tapping on a white-puppy). In foraging tasks in which observers are required to find all targets before moving to the next screen, simple feature searches (find the green and blue items among red and yellow) often produce more switches than conjunction tasks (find green squares and blue circles among blue squares and green circles; e.g. Kristjansson et al., 2014). When observers were free to move to the next screen at will, the same pattern was seen, but less dramatically (Wolfe et al., 2019). Fig. 2 shows the probability of a switch for each memory condition and age group. *Runs* plus switch trials will equal 100% of correct responses (see Table A1 in Annex A, for detailed values both for runs and switches).

There is an obvious difference between MSS2 and MSS7 results with more switches in the MSS7 condition. This is a simple by-product of the task structure. When memory set size is larger, there are more targets to switch to and less of a chance for a run, even if observers choose targets at random. The chance switch rate is shown by green lines on the graph. This chance switch rate is established by simulation. The task produces many combinations of targets. Moreover, the probabilities of each target type change as items are picked and observers do not pick all of the targets. The simulation is based on the actual displays shown to the observers and the actual numbers of items they chose from those displays. If they had chosen randomly, they would have produced switches on 40% of MSS2 selections and 70% of MSS7 selections. In fact, they produced fewer switches in both load conditions. Switches are significantly below the chance predictions for all age groups (all t > 7, all p < 0.001).
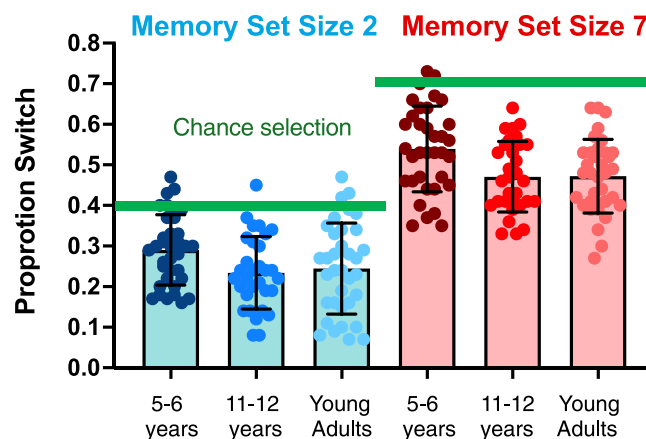

Fig. 2. Proportions of *switch responses* by Age-Group and Memory Condition. Note. In this figure, data show Low Load (Memory Set Size - MSS 2) in blue and High Load (Memory Set Size - MSS 7) in red. Each dot is one observer. Bars are means. Error bars are + /- 1 sd. Horizontal green lines show simulated switch rates if observers were choosing at random.
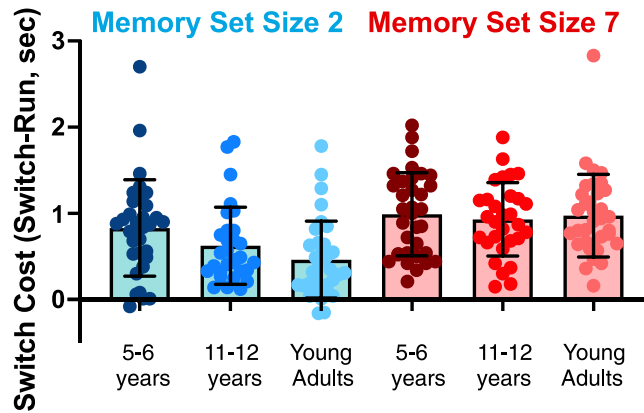
Fig. 3. Difference between Switch and Run Response Times (RTs) by Age-Group and Memory Condition. Note. Individual dots are individual observers. Bars show means. Error bars show + /- 1 sd.
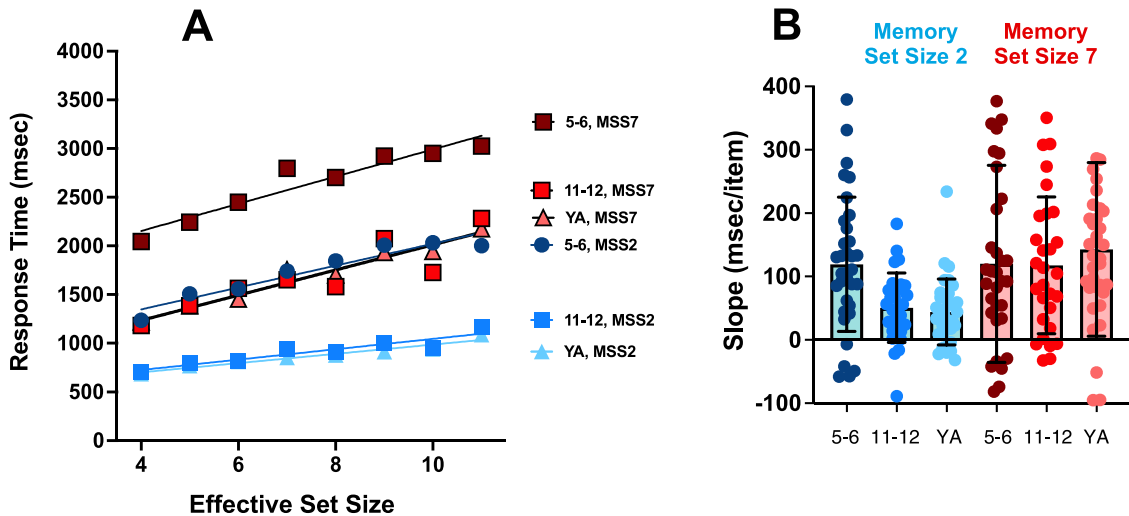

Fig. 4. A) Average RT x Effective set size (EffSS) for each Age Group and Memory Set Size. B) Slope of RT x Effective Set Size (EffSS). Note. Each dot is one observer. Bars are average data. Error bars are + /- 1 sd.

The younger children make more switches than the older children and young adults (YA). For MSS2, the younger compared to older children show significant differences [t(62) = 3.01, p = 0.004; d= 0.754], while they are marginally significant when comparing younger children (5–6 years) with YA [t(66) = 1.85, p = 0.068; d= 0.448]. For MSS7, the effect is clear in both comparisons, younger compared to older children [t(62) = 3.25, p = 0.002; d= 0.756] and younger compared to YA [t(62) = 3.17, p = 0.002; d= 0.769]. The older children and YA groups do not differ from each other, for MSS2 [t(62) = 0.78, p = 0.439; d= 0.195] or for MSS7 [t(62) = 0.24, p = 0.814; d= 0.060].

Why are runs over-represented? One reason may be that switches are comparatively expensive. Fig. 3 shows the average Switch RT minus the average Run RT. Obviously, the values are greater than zero in all conditions (all t > 8, all p < 0.001). For the direct values both for RT runs and switches, see Table A2 in Annex A.

A mixed effects analysis with age group and memory set size as factors reveals a clear effect of memory set size [F(1,96) = 34.4, p < 0.001, η^2 = 0.264], showing higher costs for the MSS7 condition (see Fig. 3). The effect of age group is marginal [F(2,100) = 2.9, p < 0.057, η^2 = 0.055] as is the interaction [F(2,96) = 3.1, p < 0.051, η^2 = 0.061]. Looking at Fig. 3 again, it seems that the cost for the MSS2 conditions is higher for the youngest children, while for MSS7 it is high for all observers regardless their age.

Fig. 4 shows the effect of the "effective set size" (EffSS) on RT as a function of age and condition. In this experiment, set size could be 40, 80, or 120 items at the start of a trial. The number decreased as targets were collected. The relevant set size measure, in this case, is not the absolute set size, but the EffSS, defined as Total Set Size / number of targets. Thus, if 20% of 40 items are targets, EffSS is 40/ 8 = 5. Fig. 4A shows average RT x EffSS functions for EffSS from 4 to 11. Larger EffSS values occur in the data, but they are relatively rare.

It is clear in Fig. 4A that young children 5–6 years are markedly slower than older children and that older children 11–12 years

perform like the young adult (YA) group. It is also clear that MSS7 is slower than MSS2 for all groups, as would be expected. The efficiency of search can be measured by the slope of the RT x EffSS function. These slopes are shown for each observer in each memory condition in Fig. 4B. Slopes can be highly variable, especially if small number of trials are involved. Nevertheless, an ANOVA on the slopes with Age and Memory Load as factors shows a clear effect of Memory Load [$F(1, 94) = 14.33$, $p = 0.001$, $\eta^2 = 0.132$]. The effect of Age is not significant [$F(2, 94) = 1.57$, $p = 0.213$, $\eta^2 = 0.032$]. Probably this reflects the wide variability in this measure. The interaction of Age and Memory Load is significant [$F(2, 94) = 4.09$, $p = 0.019$, $\eta^2 = 0.080$], showing that slopes at MSS2 are clearly higher for the younger children (5–6 years), while they do not differ among ages at high load MSS7 conditions, where it seems difficult enough for all observers. The most interesting aspect of these data is the clear indication that performance has reached adult levels by age 11–12.

### 2.2. False Alarm-Error Rates and Misses (or items left behind)

As a critical manipulation in our non-exhaustive hybrid foraging game, observers can move from one screen to the next whenever they choose. The targets that are left on the screen when the observer leaves for the next screen could be labelled as "misses" but these misses can also be thought of as a matter of choice in this task. When distractor items are selected, these can be considered as False Alarm (FA) errors.

Average proportions of False Alarm errors are shown in Table 1. Rates are generally low, with more FA errors committed by younger children and at the higher memory load replicating previous findings (Gil-Gómez de Liaño et al., 2022). We performed repeated measures ANOVAs with Memory Load as a within-subjects factor and Age-Group as a between subjects factor. There were significant main effects for condition and Age-Group, [$F(1,95) = 42.01$; $p < 0.001$; $\eta^2\ 0.310$] and [$F(2,95) = 4.33$; $p = 0.020$; $\eta^2 = 0.080$], respectively. The interaction was not significant ($F<1$).

Fig. 5 shows the percent of targets left behind when the observer moves to the next patch/screen as a function of age group and memory load. An ANOVA shows a clear effect of Memory Load [$F(1, 95) = 78.19$, $p < 0.001$, $\eta^2 = 0.451$]. More targets are left behind when the memory load is higher. Interesting, there is very little evidence for a developmental progression here. The effect of Age is not significant [$F(2, 95) = 0.24$, $p = 0.790$, $\eta^2 = 0.005$] nor is the interaction of Age and Memory Load [$F(2, 95) = 1.17$, $p = 0.310$, η^2

Table 1
Proportion of False Alarms Memory Load and Age Group. Standard Errors are in brackets.

	Memory Set Size 2 (MSS2)	Memory Set Size 7 (MSS7)
5–6 years	0.028 (0.003)	0.049 (0.006)
11–12 years	0.015 (0.003)	0.036 (0.007)
Young Adults	0.008 (0.003)	0.039 (0.006)
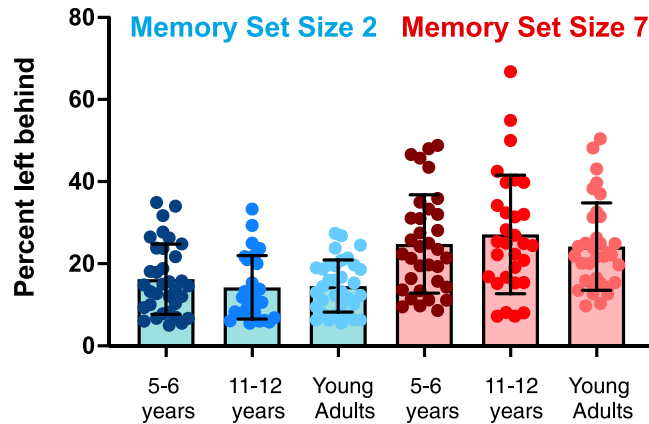
Fig. 5. Percent of targets left on the screen when observers move to the next screen by Age-Group and Memory Condition. Note. Individual dots are individual observers. Bars show means. Error bars show + /- 1 sd.

Table 2
Proportion of target *types* that are not collected, averaged across participants, as a function of Memory Load and Age Group. Parenthetical values are the s.e.m.

	Memory Set Size 2 (MSS2)	Memory Set Size 7 (MSS7)
5–6 years	0.10 (0.02)	0.45 (0.05)
11–12 years	0.08 (0.02)	0.52 (0.05)
young adults	0.05 (0.02)	0.51 (0.06)

= 0.024].

There are three reasons why target items might be left behind. First, observers might simply not have properly encoded a target type. In this case, that target would never be collected by that observer. This is very rare in these data. No one completely forgot a target type at memory set size 2. For memory set size 7, in young children of 5–6 years, five observers forgot one item, and just two forgot more than one. For older children of 11–12 years, five observers forgot just one item. In young adults group (YA), eight observers forgot one item. As seen, again, that performance is similar in each age group.

A second way to miss targets is to fail to collect any instance of a target type from that screen. That is, even if you know that the owl is a target, you might not search for owls in a particular screen. Table 2 shows the proportion of target *types* that are not collected as a function of Memory Load and Age Group. Clearly, there is a very large effect of Memory Load [$F_{(1, 95)} = 190.2$, $p < 0.001$, $\eta^2 = 0.667$]. Again, the effect of Age Group is not significant [$F_{(2, 95)} = 0.23$, $p = 0.800$, $\eta^2 = 0.005$], and the interaction is not significant either [$F_{(2, 95)} = 1.3$, $p = 0.270$, $\eta^2 = 0.027$].

It might seem odd that the percentage of target types left behind (Table 2) is higher than the percentage of individual targets left behind (Fig. 5). However, this is not mysterious or unreasonable behavior. There are different numbers of instances of target types in each display. Observers tend to find and pick the more common targets. They are more likely to overlook a target type if only one or two of that type appear in the display. The ~50% of target types that are not collected at Memory Set Size 7 are those with fewer instances in the display. Again, it is interesting that the rules that produce these left behind percentages appears to be essentially mature at the age of 5–6 years. The basis for this behavior lies in the rules for patch leaving, discussed in the next section.

2.3. Search Quitting Rules: MVT Predictions

Targets get left on the screen when the observer chooses to leave one screen for the next. This is a version of the patch-leaving problem that has been studied in the animal behavior literature (DeVries et al., 1989; Stephens & Dunlap, 2009; Stephens & Krebs, 1986). One approach to modeling the patch leaving decision is to employ Charnov's (1976) Marginal Value Theorem (MVT). According to MVT, an observer who was following an optimal quitting rule would opt to move to the next screen/patch when the instantaneous rate of target collection (the inverse of the response time between successive target collections) meets or falls below the average rate of collection in the task. In our previous work with children performing foraging tasks (Gil-Gómez de Liaño et al., 2022), we found that from 5 years old, observers seem to behave in a near MVT optimal manner. Observers from 5 to young adulthood followed a similar pattern of patch leaving.

To assess this behavior in the present study under different memory load conditions, we calculated the average and instantaneous rates. The *average rate* is calculated as the total number of points collected divided by the time spent in the whole task (including the 2 s travel time between screens). To compute the *instantaneous rates*, we calculate average RTs for each one of the last 10 items tapped,
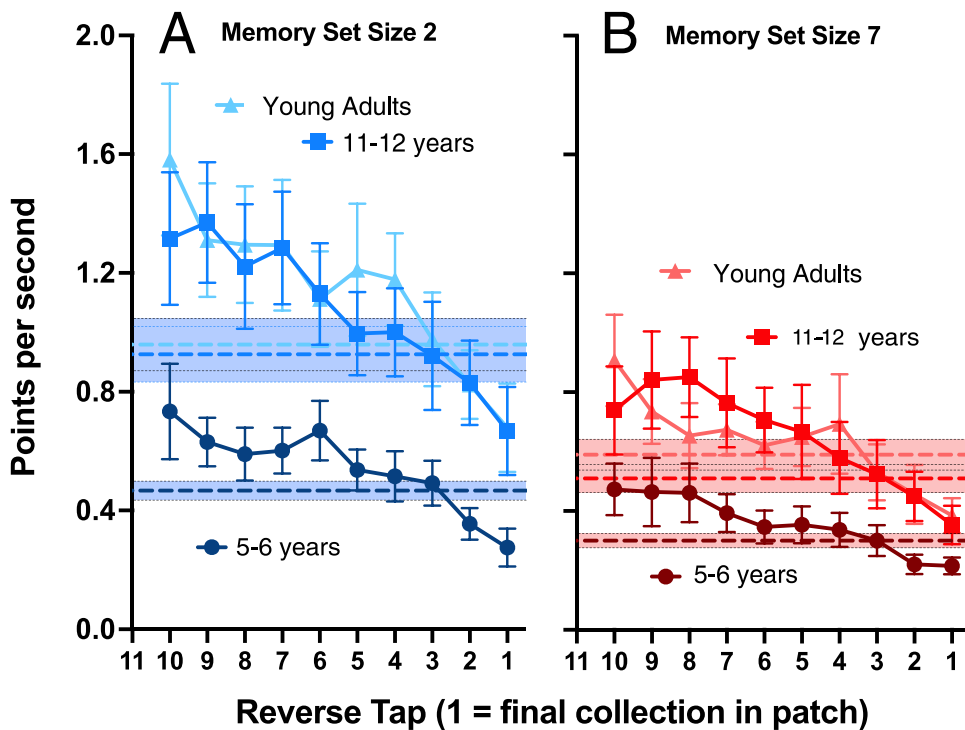

Fig. 6. Mean Instantaneous Rate for the last 10 reverse taps for each Memory Set Size condition and Age Group. Note. Dashed lines represent the average rate for each condition. (A) Memory Set Size 2. (B) Memory Set Size 7. Shaded areas and error bars show 95% C.I.
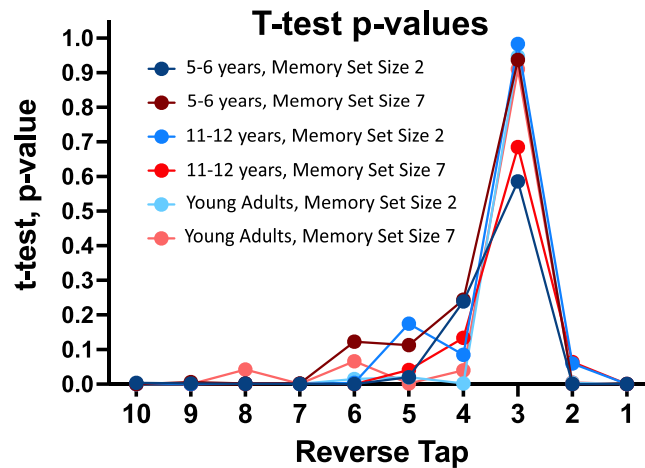
Fig. 7. P-values of T-tests comparing individual observers instantaneous rates with their average rates for each Age Group and Memory Load. Note. Values are not corrected for multiple comparison.

counting in *reverse* order from the item tapped just before the "Next" button. As in Gil-Gómez de Liaño et al. (2022), we will refer to the position in the order as the "reverse tap". Thus, reverse tap 1 is the last item tapped before leaving the patch, reverse tap 2 is the previous one, and so forth. Again, following previous works with a similar task (Gil-Gómez de Liaño et al., 2022; Wolfe et al., 2019 & Wiegand et al., 2019), we plotted the rate of picking by the reverse tap from 1 to 10 for each age group and memory load, as shown in Fig. 6.

As shown in Fig. 4, younger children are slower foragers than older children whose rates of collection are virtually identical to those of young adults. What is interesting in this analysis is how similar all the patch leaving rules appear to be. Every instantaneous rate function drops to the average rate at Reverse Tap 3 (Fig. 6), regardless of their picking rate (being slower for younger children, as also seen before). The rate continues to decline for two more taps and then the observer moves to the next screen.

Fig. 7 shows the p-values of T-tests comparing individual observers' instantaneous rates with their average rates for each Age Group and Memory Load shown in Fig. 6 (we can see the direct T-tests and p-values in Annex A, Table A3). The figure is one way to illustrate the very similar behavior across conditions.

The spike at Reverse Tap 3 shows the point where the *instantaneous rate* crosses the average rate for all conditions. The next tap, Reverse Tap 2, produces significant p-values for the 5–6-years-old group and young adults (all p < 0.005; see Table A3, Annex A). The 11–12 years are not significantly below the average rate at Reverse Tap 2 (both p's = 0.060, see Table A3, Annex A). At Reverse Tap 1, all conditions are well below the Average rate (all p < 0.001, see Table A3, Annex A). In MVT terms, observers are being slightly conservative, tapping twice after the instantaneous rate falls to the average rate. Conservative or not, observers are obviously doing something very similar at all ages and at both memory loads. The patch leaving rule appears to be essentially adult at least as early as 5–6 years.

2.4. Foraging Variables and CPT measures

Since we have the CPT measures for our children sample (5–6 and 11–12 years), it is interesting to investigate the connection between hybrid foraging and CPT measures in the present study. Although it may be debatable, the CPT has shown to be a helpful index to test children's executive function difficulties (e.g., Barnard et al., 2015). Thus, looking for connections between our measures and those found in the CPT might be a useful way to determine if our task could also serve as an measure of aspects of executive function. Table 3 shows the correlations between our main foraging variables and the most relevant CPT indexes.

As can be seen in Table 3, interesting results arise from the correlations analysis. First, most variables in our foraging game significantly correlate with most variables in the CPT test. Only slopes in foraging and commissions in the CPT did not show significant correlations. The rest of the variables correlate at some point for both memory load conditions in the foraging. Moreover, the correlations follow plausible patterns: For instance, response times in the CPT are aligned and correlate with response times in the foraging game. That is, observers who are faster in one task are faster in the other too. On the other hand, omissions in the CPT do not correlate with the proportion of "targets left behind" in foraging. As we have seen before, targets left behind in foraging should not be understood as simple omissions since they are left behind at will as part of the observer's foraging game. Thus, the proportion of hits in foraging negatively correlates with omissions and detectability in the CPT: The higher the tendency to show omissions and the lower the ability to detect the target in the CPT, the less capacity to generate hits in the foraging game.

Interestingly, the "average rate" measure in foraging correlates with "response time at block change responses" in the CPT. As we mentioned before, the "average rate" is calculated by dividing performance (hits, total points collected in a patch) by the time spent (in that patch). It can be considered to be a measure of efficiency and might also be related to the capacity to effectively regulate attentional processes, which could explain its relation with changing the task/block in the CPT. Finally, foraging slopes do not correlate with any CPT measures. Slopes might be related to another type of cognitive function not directly tested in the CPT task, or simply, as we pointed out before, the high variability found for those measures (especially for young children) could explain the lack of relations with the CPT measures.

Table 3
Pearson linear correlations with p-values between CPT main indexes (T-scores) and the main FORAGEKID game variables. Shaded cells show significant results.

			Response Style: Accuracy/RT	Detectbility (d')	Omissions	Commissions	Perseverations	Hit Response Time	Block Change Response Time	Inter-stimulus Response Time
Memory Set Size 2	Proportion of Hits	Pearson Correlation	-0.067	**-0.352**	**-0.318**	-0.239	-0.227	-0.070	0.071	0.101
		p-value	0.638	**0.011**	**0.023**	0.091	0.110	0.628	0.622	0.480
	Proportion of False Alarms	Pearson Correlation	0.067	**0.352**	**0.318**	0.239	0.227	0.070	-0.071	-0.101
		p-value	0.638	**0.011**	**0.023**	0.091	0.110	0.628	0.622	0.480
	Proportion of Items Left Behind	Pearson Correlation	0.138	0.175	0.239	0.082	-0.044	0.174	-0.029	-0.052
		p-value	0.334	0.219	0.091	0.566	0.762	0.222	0.841	0.717
	Average Rate	Pearson Correlation	-0.071	-0.190	-0.185	-0.098	-0.087	**-0.348**	**0.310**	0.110
		p-value	0.622	0.182	0.194	0.495	0.545	**0.012**	**0.027**	0.441
	Slope	Pearson Correlation	-0.024	-0.194	-0.104	-0.148	-0.218	-0.145	0.234	-0.049
		p-value	0.867	0.173	0.470	0.300	0.124	0.308	0.098	0.734
	Patches Visited	Pearson Correlation	**0.391**	0.247	**0.353**	-0.019	0.072	**0.282**	-0.198	-0.142
		p-value	**0.005**	0.081	**0.011**	0.893	0.615	**0.045**	0.164	0.319
	Total Response Time	Pearson Correlation	0.121	**0.292**	**0.324**	0.181	0.263	**0.353**	**-0.333**	0.008
		p-value	0.397	**0.038**	**0.020**	0.203	0.062	**0.011**	**0.017**	0.956
Memory Set Size 7	Proportion of Hits	Pearson Correlation	-0.239	**-0.330**	**-0.307**	-0.143	-0.204	-0.241	0.253	-0.124
		p-value	0.091	**0.018**	**0.029**	0.318	0.151	0.088	0.073	0.385
	Proportion of False Alarms	Pearson Correlation	0.239	**0.330**	**0.307**	0.143	0.204	0.241	-0.253	0.124
		p-value	0.091	**0.018**	**0.029**	0.318	0.151	0.088	0.073	0.385
	Proportion of Items Left Behind	Pearson Correlation	0.118	0.264	0.234	0.203	0.259	0.124	-0.122	**0.326**
		p-value	0.409	0.061	0.098	0.154	0.067	0.387	0.393	**0.020**
	Average Rate	Pearson Correlation	-0.049	-0.246	-0.195	-0.174	-0.191	**-0.282**	**0.384**	0.044
		p-value	0.733	0.081	0.170	0.222	0.180	**0.045**	**0.005**	0.761
	Slope	Pearson Correlation	-0.056	-0.101	-0.154	-0.047	-0.056	-0.148	0.236	-0.111
		p-value	0.699	0.480	0.280	0.745	0.698	0.302	0.095	0.438
	Patches Visited	Pearson Correlation	0.197	0.175	0.236	0.081	0.166	**0.354**	-0.108	0.223
		p-value	0.166	0.218	0.096	0.570	0.245	**0.011**	0.450	0.115
	Total Response Time	Pearson Correlation	0.134	**0.339**	**0.322**	0.220	**0.309**	**0.347**	**-0.412**	0.093
		p-value	0.347	**0.015**	**0.021**	0.122	**0.027**	**0.013**	**0.003**	0.518

* For all correlations, sample size was set to 51 observers. That counts all children from 5 to 12 years old with some missing values due to technical problems with the CPT program (losing 4 from the 11–12 years sample, and 9 from the 5–6 years group, from the original sample sizes shown in the methods).

3. Discussion

The present study uses a foraging game to investigate how some aspects of executive function operate in early and middle childhood, with special emphasis on the effects of different memory load conditions, not yet experimentally studied with children in foraging tasks. The new FORAGEKID game, a hybrid foraging task in which observers must look for different toys moving around the screen within a video game-like task, simulates a complex real-world setting in which multiple components interact within environment that is richer and more-ecologically valid than the more basic tasks, typically used in the lab (as, for example, in our own prior work: Gil-Gómez de Liaño et al., 2022; as well as Ólafsdóttir et al., 2019). Using an enjoyable video game for scientific research purposes makes it easier to collect extended quantities of data. The use of images of well-known toys makes it easier to manipulate memory load and see how this interacts with executive processes related to attentional control and planning processes during search. The results show that FORAGEKID is responsive to developmental changes in attentional control, memory maturation, and planning strategies, revealing critical differences between 5 and 6-year-old children and 11–12-year-old and young adults.

We manipulated memory load by asking observers to look for two (Low Load – MSS2 condition) or seven (High Load – MSS7 condition) targets in separate blocks. Memory for distinctive objects is very large for adults and not limited to the ~4 items that can be held in working memory (Cowan, 2001). Younger and older adults can perform foraging tasks of the sort used here with memory loads of 64 items (Wiegand et al., 2019; Wolfe et al., 2016). However, the capacity to maintain information online in children is under development until about 12 years (Luciana & Nelson, 1998; Vuontela et al., 2013), so the seven item memory load, used here, represents a substantial memory load for younger children. Indeed, as seen in the results, loading with seven targets is sufficient to generate significant differences between the two load conditions (MSS2 and MSS7) for all age groups. As shown in the methods, the 2 or 7 target types are not visible during the foraging game. Thus, in general, MSS7 is harder than MSS2, showing that the observers need more cognitive resources to maintain and update target information in memory to guide attention in the foraging task when playing with seven targets compared to when playing with two. All observers, regardless of age, show increased RTs, False Alarms-FA, and misses (or, more accurately here, items left behind). Thus, the load manipulation is generating the expected effects (Wolfe et al., 2016). Interestingly, the 11–12-years-old observers essentially behave just like young adult observers in all measures tested. As shown by Anderson (2002) and replicated by Gil-Gómez de Liaño et al. (2020), different aspects of executive functions mature at different developmental stages. More complex properties, like cognitive flexibility or working memory have shown to be not fully mature until even young adulthood. Thus, the cognitive functions here tested seem to be those that mature earlier in development. Alternatively, some of them may not be fully developed even in our oldest, young adult participants, aged in their early 20′s. More research with middle-age and older adults would be needed to assess this possibility. For now, our results show that 11–12 years-old observer behave like the young adults sample in our task. Performance of the 5–6-year-old group differed from the other groups (see Fig. 4). These younger children were slower and less accurate than older children and young adults (YA) (see Fig. 4). Younger children were more likely to switch from one target type to another than the older groups, though all groups continued collecting the same item (in "runs") at a higher rate than predicted by chance selection among targets (see Fig. 2).

Why would younger children switch to a new target a bit more often than older children? As noted above, switches are relatively expensive in RT and those switch costs are somewhat greater for younger children (see Fig. 3). An answer may lie in the *relative* costs of switching. The younger children have markedly slower average RTs so the ratio of switch cost to mean RT is smaller for young children. This is significant for Memory Set Size 7 (both t-tests < 0.05) though not for Memory Set Size 2. Younger children may be inclined to switch a bit more often because the relative cost of the switch is less noticeable than for the older observers.

If correct, this account would be part of a broader argument that, while younger children are slower and more error-prone, their decision-making, at least for quitting rules in search looks quite adult-like, even at age 5–6. This adult behavior is more clearly illustrated in the patch leaving behavior, illustrated in Fig. 6 and 7. On average, the instantaneous rate of picking reaches the average rate on Reverse Tap 3. Observers collect two more items and then leave for the next screen/patch. This behavior seems remarkably stable across Memory Load and Age Group. One might or might not want to consider these results as evidence that observers are following Charnov's (1976) Marginal Value Theorem (MVT). Regardless, whatever the account of this behavior, it appears that the same rules are operating across the age range. Replicating previous findings (Gil-Gómez de Liaño et al., 2022), the decision-making process behind quitting rules in search seems to be a basic piece of cognition. Unlike other aspects of foraging behavior studied here, the patch leaving/quitting rules to be present in approximately adult form, at least from about 5 years old.

In sum, FORAGEKID is a single enjoyable task for children that may allow us to measure attentional control, memory processes, cognitive strategies, and decision-making processes. The correlations of the CPT measures and the foraging outcome variables for children between 5 and 12 years show a clear relationship between the tasks. This suggests that our FORAGEKID game could be used to measure a subset of executive functions shared by our task and the CPT. This could be of practical value since the CPT has shown to be a helpful index to test children's executive function difficulties (e.g., Barnard et al., 2015). However, more research is needed to directly test the relationship of the FORAGEKID results to established measures of different executive functions. One approach might be to look for neural correlates of executive functioning networks in participants playing the game. Other complementary approaches would be including new manipulations within our game. For instance, according to our results, search strategies and quitting rules are tapping into fundamental cognitive functions. Adding a more complex decision-making processes, such as a task-switching demand, could make the game a more powerful test of executive functions. For the present, this paper has focused on the basic foraging behavior of children as a function of their age group. Looking at any of the figures showing individuals observer's performance, it is clear that there is significance variance in these measures between observers. In future work, we will also investigate whether this variance is attributable to mere noise or if it is correlated with clinical measures (e.g. the CPT measures for clinical samples or any other neuropsychological test). If variation in FORAGEKID performance is meaningful then it could be used in interventions with atypically

developing children with executive functions problems such as attention deficit with hyperactivity disorders, dyslexia, learning disabilities, or autism spectrum disorders. It could also be useful as a clinical training tool or in educational contexts as part of everyday classroom activities intended to help young children to develop appropriate strategies to improve search and, potentially, executive functions. Although more research is needed, altogether, the present results highlight the rich potential of hybrid foraging search used in our FORAGEKID game to help us understand and evaluate basic cognitive processes across the lifespan in typical and atypical development.

4. Conclusions

The FORAGEKID game is a hybrid foraging task in which cognitive psychologists can study several aspects of executive functions, attention, memory, planning and decision-making processes within a single task that children enjoy. FORAGEKID has children collecting well-known toys within a complex interactive environment. In the present study, we manipulated memory load in the form of the number of target types in a hybrid foraging task. This has not yet been studied as a function of age. The results show differences between younger (5–6 yrs) and older (11–12) children with older children showing more efficient searches that are comparable to adults performance. Younger children are slower, less efficient foragers. However, the rules governing their foraging (e.g. when to move to the next screen) appear to be essentially adult. Although more research is needed, FORAGEKID may be a useful tool for assessing and training essential cognitive functions in educational and clinical contexts.

Context Paragraph

The present study is part of a long-lasting research collaboration between Beatriz Gil-Gomez de Liaño lab (UAM) and Jeremy Wolfe's lab (BWH-Harvard Medical) studying foraging tasks in development to understand attention, memory and other executive functions in development. It is framed within the EU (Marie Sklodowska-Curie Actions: FORAGEKID 793268) as a new way to understanding aspects of executive function development during childhood using the new FORAGEKID video game developed by the authors.

ANNEX A

See.in Table A1,Table A2,Table A3.

Table A1
Mean Proportion of Correct Responses by Type of Response (Run/Switch) for each condition (MSS2/MSS7) by Age Group. Standard Errors in Brackets.

	Memory Set Size 2 (MSS2)		Memory Set Size 7 (MSS7)	
	Run	Switch	Run	Switch
5–6 years	0.67 (0.016)	0.33 (0.016)	0.42 (0.015)	0.58 (0.015)
11–12 years	0.73(0.017)	0.27 (0.017)	0.50 (0.016)	0.50 (0.016)
young adults	0.71(0.016)	0.29 (0.016)	0.49 (0.015)	0.51 (0.015)

Table A2
Mean Response Time (seconds) for Correct Responses by Type of Response (Run/Switch) for each condition (MSS2/MSS7) by Age Group. Standard Errors in Brackets.

	Memory Set Size 2 (MSS2)		Memory Set Size 7 (MSS7)	
	Run	Switch	Run	Switch
5–6 years	1.69 (0.06)	2.47 (0.08)	2.31 (0.09)	3.62 (0.14)
11–12 years	0.86 (0.06)	1.49 (0.09)	1.27 (0.09)	2.31 (0.15)
young adults	0.85 (0.06)	1.35 (0.08)	1.24 (0.09)	2.27 (0.14)

Table A3

T-tests with their corresponding p-values and degrees of freedom (df) shown in Fig. 7.

| | Memory Set Size 2 MsS2 | | | | | | | | | Memory Set Size 7 MsS7 | | | | | | | | |
| | 5–6 years | | | 11–12 year | | | Young Adults | | | 5–6 years | | | 11–12 year | | | Young Adults | | |
Reverse Tap	t	df	p-value	t	df	p-value	t	df	p-value	t	df	p-value	t	df	p-value	t	df	p-value
1	5.69	33	< 0.001	4.70	29	< 0.001	5.14	33	< 0.001	6.36	33	< 0.001	7.48	29	< 0.001	6.90	33	< 0.001
2	4.03	33	< 0.001	1.96	29	0.060	3.13	33	0.004	4.62	33	< 0.001	1.93	29	0.064	3.02	33	0.005
3	0.55	33	0.586	0.02	29	0.983	0.07	33	0.947	0.08	33	0.937	0.41	29	0.685	0.11	33	0.910
4	1.20	33	0.239	1.78	29	0.085	3.33	33	0.002	1.19	33	0.244	1.54	29	0.134	2.14	33	0.040
5	2.46	33	0.020	1.39	29	0.175	2.45	33	0.020	1.63	33	0.113	2.14	29	0.041	3.31	33	0.002
6	4.16	33	< 0.001	3.08	29	0.004	2.57	33	0.015	1.58	33	0.123	4.16	29	< 0.001	1.90	33	0.066
7	3.56	33	0.001	4.67	29	< 0.001	3.79	33	0.001	3.39	33	0.002	3.90	29	0.001	3.75	33	0.001
8	3.49	33	0.001	3.45	29	0.002	3.79	33	0.001	3.31	33	0.002	5.79	29	< 0.001	2.12	33	0.042
9	3.38	33	0.002	5.40	29	< 0.001	4.35	33	< 0.001	2.97	33	0.006	4.19	29	< 0.001	4.21	33	< 0.001
10	3.09	33	0.004	4.03	29	< 0.001	5.35	33	< 0.001	4.25	33	< 0.001	3.61	29	0.001	5.42	33	< 0.001

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