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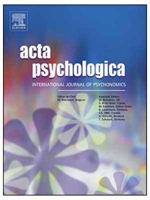

Visual foraging and executive functions: A developmental perspective

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ABSTRACT

Visual foraging tasks, where participants search for multiple targets at a time, may provide a richer picture of visual attention than traditional single-target visual search tasks. To contribute to the mapping of foraging abilities throughout childhood and to assess whether foraging ability is dependent upon EF abilities, we compared the foraging of 66 children aged 4–7 years (mean age = 5.68 years, SD = 0.97 years, 33 girls), 67 children aged 11–12 years (mean age = 11.80 years, SD = 0.30 years; 36 girls), and 31 adults aged 20–37 (mean age 30.32 years, SD 4.37 years, 18 females) in Iceland, with a task involving multiple targets of different types. We also measured three subdomains of executive functions; inhibition, attentional flexibility, and working memory. Our results show that foraging improves dramatically between the preschool and middle school years, with the older children showing similar foraging abilities as adults due to greater ease of switching between target types. The older children and adults randomly switch between target templates during feature foraging, but exhaustively forage for a single target type before switching during conjunction foraging. Younger children, conversely, tended to also stick to the same target type for long runs during feature foraging, showing that they have difficulties with feature-based tasks. Switch costs were much lower for the older children than the youngest age group, and on par with those of adults, resulting in fast and efficient foraging. Lastly, we found a connection between foraging ability and both working memory and attentional flexibility, but not inhibition. Our study shows that foraging is a promising way of studying visual attention, how it changes throughout the lifespan, and how it is connected to other cognitive functions.

1. Introduction

Traditionally, human visual attention has been studied with search tasks, where participants look for a single target among numerous distractors (Bravo & Nakayama, 1992; Kristjánsson, 2015; Treisman & Gelade, 1980; Wolfe, 1994). Recently, visual foraging, where participants look for many targets on the same trial, has received increased interest (Cain, Vul, Clark, & Mitroff, 2012; Kristjánsson, Jóhannesson, & Thornton, 2014; Wolfe, 2013). This paradigm originally comes from studies on animals (Bukovinszky, Rikken, & Evers, 2017; Dawkins, 1971; Mallott, Garber, & Malhi, 2017; Pyke, Pulliam, & Charnov, 1977, Schuppli, Forss, & Meulman, 2016), and may better capture orienting in the visual environment than single target searches, where a target is to be found, and the search then ends. One typical finding is that when food items are abundant and easily found, animals forage for multiple food types at the same time, but when they are difficult to find, they tend to forage in runs; that is, select only one type of food for an extended period of time (Bond, 1983; Dukas, 2002). This behavioral shift has been attributed to limited attentional capacities; when food is difficult to find, attentional load is high, and then the optimal strategy is to limit foraging to one food type. When the targets are easy to find, there is little effort in simultaneously foraging for different types of food and gathering more items in less time (Dukas, 2002). Studies with computerized foraging tasks have shown that human foraging behavior resembles that of animals, where they adapt their search strategy to the distribution of target items in the environment to optimize hit rate (Bond, 1982; Cain et al., 2012; Kristjánsson et al., 2014).

A foraging task developed for iPads by Kristjánsson et al. (2014; see also Jóhannesson, Thornton, Smith, Chetverikov, & Kristjánsson, 2016; Kristjánsson, Thornton, & Kristjánsson, 2016, Kristjánsson, Thornton, & Kristjánsson, 2018a, 2018b), has been used to gain insight into how humans forage for targets from different target categories. The original display consists of multiple items from four different categories, two of which are targets and two distractors. Participants are instructed to tap all targets as fast as they can, while avoiding distractors. One of the main dependent variables in this paradigm is the foraging pattern, measured in the number of runs, where a run is defined as the repeated selection of the same target type. The number of runs is inversely related to run length and is essentially a measure of how often participants switch between target types. When switches are frequent, the trial will consist of many short runs. When participants repeatedly select the same target type, the trial will consist of a few long runs. To manipulate attentional load, the foraging task can be either feature or conjunction based (Kristjánsson et al., 2014). During feature foraging, the targets are defined by only one feature; color. Participants are instructed to tap all the disks of two colors but avoid tapping the distractor items. In this condition, adult participants frequently and effortlessly switch between target categories. Task difficulty increases in the conjunction condition,

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where the items are defined by two features; color and shape. Now attentional load is higher, and participants tend to change their foraging pattern by selecting targets of the same type in long runs, most frequently tapping every single target of one category before switching to the next (Jóhannesson et al., 2016; Jóhannesson, Kristjánsson, & Thornton, 2017; Kristjánsson et al., 2014).

To our knowledge only one study has examined foraging and executive functions. Jóhannesson et al. (2017) considered the relationship between foraging and the cognitive capabilities of adults (M_{age} = 25 years). Participants were divided into two groups based on the number of runs during conjunction foraging and their performance on working memory and inhibition tasks measured. No connection was found between foraging patterns and executive functions (EF). While most studies using this paradigm have focused on the number of runs, other measures, such as foraging speed and switch costs, can also provide insight into foraging abilities and visual attention. We therefore make a distinction between foraging patterns, measured in the number of runs, and overall foraging ability, which can be measured in various ways as listed above, including foraging patterns. In Jóhannesson et al. (2017), neither foraging speed nor other indicators of foraging abilities were compared to EF performance, and it is unknown whether they are connected to other aspects of foraging, and to what extent foraging relies on cognitive capacities. Our aim was to assess different aspects of foraging abilities by measuring foraging patterns, speed, and switch costs of both children and adults, comparing them with their performance of three EF subcomponents; inhibition, attentional flexibility, and working memory.

1.1. *Foraging from a developmental perspective*

Little is known about the foraging abilities of children and how they develop into adulthood. Considering the insights into visual cognitive processes gained from foraging studies, such studies may provide valuable information on the development of visual attention. Single target visual search tasks have revealed that feature search abilities mature at a very young age (Gerhardstein & Rovee-Collier, 2002), and may even be in place in infancy (Adler & Orprecio, 2006), while processing of conjunctively defined targets is still developing during middle childhood, reaching a peak in young adulthood (Donnelly et al., 2007; Merrill & Conners, 2013; Merrill & Lookadoo, 2004; Taylor, Chevalier, & Lobaugh, 2003; Trick & Enns, 1998; Woods et al., 2013).

Children's difficulty with conjunction search has partly been attributed to underdeveloped executive functioning (Donnelly et al., 2007; Trick & Enns, 1998; Woods et al., 2013), which is a complex network of cognitive processes that underlie action planning and goal directed behaviors. Fundamental subcomponents of EF include working memory, attentional flexibility, and inhibition (Best & Miller, 2010; Hommel, Li, & Li, 2004; Miyake et al., 2000). EF is at least partly dependent on the development of the prefrontal cortex, which does not reach full maturity until young adulthood, usually around age 25 (e.g. Conklin, Luciana, Hooper, & Yarger, 2007; Diamond, 2002; Diamond & Goldman-Rakic, 1989; Moriguchi & Hiraki, 2009).

Although inhibitional abilities improve rapidly over the preschool years (Klenberg, Korkman, & Lahti-Nuuttila, 2001), they continue to develop at a slower rate into middle childhood (Brocki & Bohlin, 2004; Romine & Reynolds, 2005). A few studies using computerized tasks have found that speed and accuracy in inhibitional tasks improve somewhat during adolescence (Leon-Carrion, Garcia-Orza, & Perez-Santamaria, 2004), and even early adulthood (Huizinga, Dolan, & van der Molen, 2006). These improvements during adolescence and early adulthood (age range 18–29) seem to represent greater ease with inhibiting prepotent responses, while the acquisition of inhibition during preschool years involves fundamental changes in cognition, such as a newfound ability to form rules (Best & Miller, 2010; Best, Miller, & Jones, 2009).

Attentional flexibility and working memory develop later than inhibition and continue to improve throughout adolescence (Davidson, Amso, Anderson, & Diamond, 2006; Lee, Bull, & Ho, 2013). Attentional flexibility is believed to rely on inhibition because it involves inhibiting previous activities and switching to other tasks (Best et al., 2009), and has been shown to develop at a slower rate than inhibition, with children not yet performing at adult levels by age 13 (Davidson et al., 2006). Younger children's difficulty with task switching is reflected in perseverance, or a failure to change behavior according to task demands (Anderson, 2002). As children become older, perseverance errors diminish greatly. Instead of measuring error rates, attentional flexibility can then be measured with switch costs, which involve the difference in response times between switch and no-switch trials (Huizinga et al., 2006).

Many studies have shown that working memory performance improves linearly from early childhood and throughout adolescence (Conklin et al., 2007; Gathercole, Pickering, Ambridge, & Wearing, 2004; Hale, Bronik, & Fry, 1997). When task demands are low, such as when asked to hold two items in mind, preschool aged children perform working memory tasks at adult levels. As soon as the tasks become more complex and memory load increases, their disadvantages become apparent (Luciana, Conklin, Hooper, & Yarger, 2005). Performance on many working memory tasks stabilizes between ages 11 and 15 (Conklin et al., 2007; Luciana et al., 2005), and as early as 9–10 years on recognition memory tasks (Luciana et al., 2005), but for the most complex tasks, improvements are seen until age 17 (Conklin et al., 2007).

Mental planning and flexibility, working memory, and inhibition are believed to play a large role in conjunction search, guiding spatial attention and preventing return to searched locations (Woods et al., 2013). Additionally, inhibitory control is believed to contribute to increased efficiency in conjunction search with development, by inhibiting distractors, which is arguably harder in conjunction than feature search (Hommel et al., 2004). The limitations of young children's executive processing ability can thus hamper their conjunction search performance. These limitations do not affect feature search performance, which is relies on simpler processing mechanisms (Woods et al., 2013). Ólafsdóttir, Kristjánsson, Gestsdóttir, Jóhannesson, and Kristjánsson (2016) investigated the foraging abilities of 4–7-year-old children, connecting their performance with self-regulation and working memory measures. They found that the foraging *patterns* (measured with the number of runs) of young children differ from those of adults (M_{age} = 28.3 years). The children foraged in long runs, not only during conjunction foraging, but also during feature foraging. No connection was found between foraging patterns and self-regulation and working memory, although both constructs were related to faster foraging and a higher number of completed trials during conjunction foraging. Hence, EF may affect some aspects of foraging, but more research is needed to determine the nature of this relation.

1.2. *The current study*

We had two main objectives; to continue the mapping of foraging abilities throughout childhood and to estimate whether foraging ability is dependent upon EF abilities. We compared the foraging and EF abilities of three age groups; young children aged 4–7 years, older children aged 11–12 years, and adults. We administered the foraging task developed by Kristjánsson et al. (2014), measuring foraging patterns, foraging speed, and switch costs, along with three EF tasks from the Amsterdam Neuropsychological Tasks program (ANT; de Sonneville, 1999); inhibition, attentional flexibility, and working memory.

By the age of 11 years, EF abilities have developed substantially, although they have not quite reached adult levels (Best et al., 2009; Best & Miller, 2010; Davidson et al., 2006; Lee et al., 2013). We therefore predicted that foraging patterns of 11–12-year-old children would be close to those seen for adults, with the distribution of the number of runs during feature foraging close to random, but with most trials during conjunction foraging limited to two runs (Jóhannesson et al., 2016, 2017; Kristjánsson et al., 2014; Kristjánsson et al., 2018a, 2018b). This pattern should differ from that of 4–7-year-old children who tend to also forage in long runs during feature trials (Ólafsdóttir et al., 2016). Given the developmental differences in both EF's and overall cognitive speed due to the development of general information processing (Hommel et al., 2004; Kail, 1991), we also predicted that these older children would forage significantly more quickly and efficiently than the younger children, but at a slower rate, and with higher switch costs, than adults.

Additionally, we expected a connection between foraging and all measures of EF. High working memory capacity should make it easier for participants to keep both target categories in mind (Awh & Jonides, 2001; Bundesen, 1990), diminishing both hesitations during trials and lowering switch costs, and therefore overall foraging speed. Greater attentional flexibility should both lower switch cost and facilitate switching between target categories (Huizinga et al., 2006) resulting in more runs. Finally, we believed that greater inhibitional abilities should facilitate switching between target categories by inhibiting prepotent responses; in single target search, participants seem to prefer targets of the same type as they have been attending before, and inhibition should be needed to counter that preference, again resulting in more runs (Brascamp, Blake, & Kristjánsson, 2011; Chetverikov & Kristjánsson, 2015). High levels of executive functioning should therefore result in more runs per trial and lower switch costs, as well as faster and more efficient foraging.

2. Method

2.1. Participants

Three age groups were compared. The youngest age group consisted of 42 kindergarteners and 24 first graders, aged from 4.08 to 7.17 years (mean age = 5.68 years, SD = 0.97 years, 33 girls, previously collected data from Ólafsdóttir et al., 2016). In the second age group there were 67 sixth grade students from an elementary school in Reykjavik. Their age ranged from 11.22 to 12.24 years (mean age = 11.80 years, SD = 0.30 years; 36 girls). Lastly, there were 31 adult participants aged 20–37 (mean age 30.32 years, SD = 4.37 years, 18 females). The kindergarten and school-aged participants were all recruited from the same school district. All participants had normal or corrected to normal vision. Approval from school administration was obtained, in addition to verbal consent from each participant and parental consent for underaged participants. All aspects of the experiment were reviewed and approved by the data protection authority and permission was granted by the Reykjavik Department of Education and Youth.

2.2. Equipment

The foraging task was presented on an iPad 2 with screen dimensions of 20 × 15 cm and an effective resolution of 1024 × 768 pixels, placed on a table in front of participants in landscape mode, so that viewing distance was approximately 50 cm. Stimulus presentation and response collection were carried out with a custom iPad application written in Swift using Xcode.

The EF tasks were administered on a 17.3″ laptop computer screen with an effective resolution of 1600 × 900 pixels. Task presentation and response collection were carried out with the ANT program (de Sonneville, 1999).

2.3. Stimuli

At the start of each trial of the foraging task, there were 80 stimuli on the screen, half were targets and the other half distractors. During feature foraging the stimuli were green, red, yellow and blue disks. For half the participants, the red and green disks were targets and the yellow and blue disks distractors, and for the other half this was reversed. During conjunction foraging the stimuli were red and green disks and squares. For half the participants, the targets were red disks and green squares and the distractors were green disks and red squares, but for the other half this was reversed. The diameter was 20 pixels (approximately 0.46° visual angle). The items were randomly distributed on a non-visible 10 × 8 grid and offset from the screen edge by 100 × 150 pixels. The viewing area therefore occupied 12 × 15 cm (approximately 13.7 × 17.1°). The position of individual items within the grid was jittered by adding a random vertical and horizontal offset while gaps between columns and rows ensured that items never approached or occluded one another. The location of target and distractors, and therefore the overall spatial layout, was randomly generated from trial to trial (see Fig. 1).

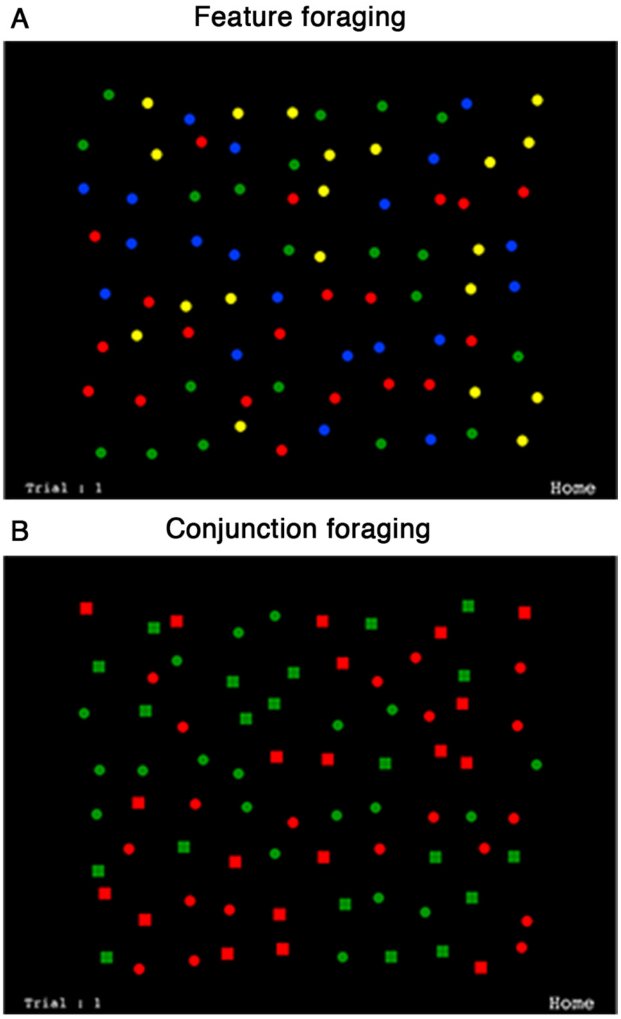

Fig. 1. Examples of the *iPad* foraging tasks. Panel A shows the feature condition, where the task is to tap all red and green disks while ignoring the blue and yellow ones (or vice versa). Panel B shows the conjunction condition where the task is to tap all the red disks and green squares (or vice versa). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Two tasks from the ANT program were used to assess executive functions. The Response organization – objects (ROO) was used to assess inhibition and attentional flexibility. The second part of Memory search 2D stimuli (MS2D) was used to assess working memory.

In ROO the stimulus is a disk that appears on the left or right-hand side of a fixation cross. In the first part, the disk is always green, in the second part always red, and in the third and final part the disk can be either red or green. In all parts, the disk location is pseudorandom, as is the disk color in the third part.

In MS2D the participant is asked to look at, and memorize, three shapes and their color; a blue triangle, a green square, and a yellow cross. On each trial, the stimuli are four shapes presented on the corners of a virtual square. The shapes are a circle, a square, a triangle, and a cross. There is always one shape of each color; red, green, blue, and yellow. Their color and location are presented in pseudorandom order, and a target is present on half of the trials.

2.4. *Procedure*

The experiment was run in a quiet room with normal illumination. Each kindergarten and school aged participant finished two 15-minute sessions on different days, with a maximum of one week between them. They completed the foraging task in one session and the EF tasks in the other. The adult participants completed all tasks in one session. The order of the foraging and EF tasks was counterbalanced, so that half of the participants started with the foraging task, and the other half with the ANT tests. During each session, the task order was also counterbalanced. In the foraging session, half of the participants started with feature foraging and the other half with conjunction foraging. The colors of the targets were also counterbalanced. In the ANT session, the order of the EF tasks was counterbalanced so that half of the participants started with the ROO and the other half with the MS2D.

2.4.1. *Foraging*

In the foraging task, the participants were asked to tap all targets as quickly and accurately as they could with the index finger of their dominant hand but avoid tapping the distractors. They were informed that the first trial of each foraging condition was a practice trial and the remaining nine trials constituted the task itself. Each trial was started by pressing an on-screen play button. The targets disappeared upon being tapped. When participants had tapped all targets, a smiley face appeared along with information about how long it had taken to tap all 40 targets. If a distractor was accidentally tapped, the trial ended, and a frowny face appeared on the screen. The 11–12-year-old and adult participants were asked to fully complete ten error free feature foraging trials and ten error free conjunction foraging trials. The 4–7-year-old participants were asked to complete five error free trials of each foraging condition. The participants were told that they could take a break between any two trials. A counter in the bottom-left corner of the screen indicated the number of completed trials, and the researcher told participants when they performed the last trial of each condition.

2.4.2. *Response organization*

The ROO task consisted of three parts. In the first part, a green disk appeared on either the left or right-hand side of a fixation cross, and participants were asked to press the left key if it was on the left-hand side of the cross and the right key if on the right. In the second part, the disk was always red, and participants were asked to press the key opposite to where the disk appears, so if it was on the left side they should press the right key, and vice versa, (inhibiting a prepotent response). In the third part, the disk could be either red or green. If the disk was green, participants should press the key on the same side as the disk appears. If it was red, they should press the key on the opposite side. This part assessed attentional flexibility, since participants must switch between response sets. Participants were asked to keep their index fingers on the response keys throughout each trial and respond as quickly and accurately as possible. The disk remained on the screen until participants pressed a response button, or for a maximum of 7000 ms if no response was made. Responses were valid if they occurred between 200 and 6000 ms after stimulus appearance. The time between response and stimulus appearance was fixed at 1200 ms. If participants missed a trial, a trial was added at the end of the session so that the response number was the same for all participants. Before each part, participants were shown how the stimuli appeared on the screen, given instructions on how to respond and performed eight practice trials before the task itself started. Parts one and two consisted of thirty trials each and part three of sixty trials, thirty for each color.

2.4.3. *Memory search*

In the MS2D task, participants saw three shapes and were asked to memorize them and their color. They were then informed that each trial consisted of four shapes, presented on the corners of a virtual square. If one of the shapes was a memorized shape, participants were asked to press the yes-key, while if not they should press the no-key. Participants were asked to keep their index finger on the response keys throughout the session and respond as quickly and accurately as possible. The response key was always on the same side as the participants dominant hand. The shapes remained onscreen for 7000 ms or until response. A mask subsequently appeared until the next trial started after 1200 ms. Responses were valid if they occurred between 200 and 6000 ms after the stimuli appeared. Each session started with 12 practice trials, after which participants were asked if they still remembered the shapes and were then shown the memory set again if they were unsure of the target items. The session lasted 48 trials but if a participant missed a trial, the same shapes reappeared but at different locations, so the number of responses for every participant was held constant.

2.5. *Dependent variables and data analysis*

The first trial of both foraging conditions was considered a practice trial and erased from further analysis. Taps on the areas between targets were also excluded from analysis, as well as the errors and the first tap of each trial. Results from error trials was analyzed like other trials, up to the point a distractor was tapped, and the trial ended, excluding the analyses on the number of runs. Since not completing a trial would result in fewer runs and skew the results, the number of runs was only calculated based on fully completed trials. Foraging speed was measured in inter-target times (ITTs, the time between taps on two targets). Other dependent variables were switch costs and the number of runs. A run is defined as repeated selection of the same target category. The number of runs is inversely proportional to run length; the longer the runs in each trial, the fewer they will be. Since each trial consists of 40 targets divided into two categories, the minimum run number on each trial is two (participants exhaustively forage for one target category before turning to the other). The maximum run number is 40 (participants switch between target categories after each tap on a target). In the former case, the length of the two runs is 20, 1 in the latter.

The mean run number and mean ITTs were calculated for each participant in each foraging condition and used to compare foraging with EF measurements. Additionally, switch costs in both foraging conditions were calculated for each participant by subtracting the mean ITTs of every tap in a run except from the first one from the mean ITTs of the first tap in a run, where the participant switches from the other target category. Note that during conjunction foraging the switch rate is much lower than during feature foraging, so any between-condition comparison of switch costs must carry this caveat.

In line with previous research using the ANT (see e.g. Brunnekreef et al., 2007; Mesotten et al., 2012; Schuitema et al., 2013), two new variables were created by subtracting the RTs from the first part of ROO from the RTs from the second and third parts for each participant, to obtain measures of inhibition and attentional flexibility, respectively. By subtracting the RTs of the task measuring baseline response speed from the RTs of the tasks measuring inhibition and attentional flexibility, we get a purer measure of those effects since we do not measure overall differences in response speed between participants, but only how the added tasks of inhibiting prepotent responses and switching of task demands affects RTs.

The dependent variable in the working memory task was the mean RT for hits (i.e. correctly identified targets). A multiple regression

Table 1
Foraging speed, the number of runs, and error rates, during feature and conjunction foraging.

	Feature foraging		Conjunction foraging	
	Mean	Sd	Mean	Sd
4–7-year-old				
ITTs (ms)	1143.30	653.04	1287.70[**]	588.64
Number of runs	10.94	8.23	4.98[**]	5.39
Errors	2,06	1,96	2.78	2.93
Errors per trial	0.79	1.04	1.46[**]	1.42
11-12-year-old				
ITTs (ms)	434.97	64.85	525.53[**]	88.51
Number of runs	13.38	2.85	4.56[**]	2.53
Errors	1.52	1.78	2.28[*]	2.21
Errors per trial	0.17	0.20	0.25[*]	0.25
Adult				
ITTs (ms)	348.34	50.25	451.44[**]	85.20
Number of runs	14.25	4.70	3.80[**]	2.12
Errors	0.58	0.85	1.45[*]	1.39
Errors per trial	0.06	0.09	0.16[*]	0.15

[*] The differences between feature and conjunction foraging within age-groups were statistically significant at 0.01 (paired samples *t*-tests).

[**] The differences between feature and conjunction foraging within age groups were statistically significant at 0.001 (paired samples *t*-tests).

analysis run in blocks was used to assess the relationship between foraging and executive functions. Repeated measures ANOVAs were run to assess differences between foraging conditions. Analyses were performed with SPSS.

3. Results

Table 1 shows descriptive statistics for performance on the foraging task. The differences in error rates, runs, and foraging speed reveal that conjunction foraging condition is far more difficult than feature foraging for all age groups. Participants are slower, more prone to error, and refrain from switching between target categories during conjunction foraging. Foraging also improves with age. ITTs decrease with age (feature foraging: F(2, 158) = 61,18, $p < 0.001$, $\eta_p^2 = 0.438$, conjunction foraging: F(2,148) = 84,24, $p < 0.001$, $\eta_p^2 = 0.532$), the number of runs during feature foraging increases slightly (F(2, 158) = 4.37, $p = 0.014$, $\eta_p^2 = 0.052$, for conjunction foraging, $p = 0.380$, $\eta_p^2 = 0.013$), and error rates decrease. Note that the youngest participants (from Ólafsdóttir et al., 2016) only had to complete four trials per condition, but the older participants were asked to complete nine trials. Many of the youngest participants were not able to complete all trials, so the number of trials per participant varied from one to four during feature foraging and zero to four during conjunction foraging.

The mean number of errors per trial was calculated as well as the mean number of errors per participant, to enable comparison of error rates across age groups. Two 2 × 3 ANOVAs on errors and age group show that error rates decrease as participants get older during both feature, F(2, 158) = 18,79, $p < 0.001$, $\eta_p^2 = 0.192$, and conjunction foraging, F(2, 147) = 35.45, $p < 0.001$, $\eta_p^2 = 0.325$.

3.1. Foraging pattern

Fig. 2 shows the distribution of the number of runs of all three age groups by foraging condition. The foraging patterns of the 11–12-year-olds are much more similar to those of adults than the young children. During feature foraging, there is a clear peak at two runs for the younger children, showing that mostly they tapped all targets of one category before moving on to the next; a strategy seen for the conjunction foraging condition in older participants, but rarely during feature foraging. The run distribution for both the 11–12-year-olds and adults is bell-shaped, peaking between 14 and 18 runs, indicating that switches between target categories are frequent and close to random. Note, however, that a small peak can be seen at two runs for the adults, which reflects the foraging patterns of three participants who completed most trials in only two runs. The remaining 28 adults completed most trials by randomly switching between target categories, resulting in more runs per trial. Conversely, during conjunction foraging, the number of runs was highly positively skewed in all age groups, peaking at two runs, indicating that most participants foraged exhaustively for one target category before switching to the other. A repeated measures ANOVA on run number for feature vs conjunction foraging was run with age as a between subject factor. There was a main effect of both foraging condition, F(1, 123) = 354.88, $p < 0.001$, $\eta_p^2 = 0.743$, and age group, F(1, 123) = 19.76, $p < 0.001$, $\eta_p^2 = 0.243$, and a significant interaction between age group and condition, F(2, 123) = 19,88, $p < 0.001$, $\eta_p^2 = 0.244$. The interaction reflects that there are differences in the number of runs during feature but not conjunction foraging (Table 1).

3.2. Foraging speed and switch costs

The mean ITT per tap number was calculated for each age group. As panels a) and b) of Fig. 3 show, the 11–12-year-olds and adults have similar ITTs, but the young children were much slower during both foraging conditions. For each age group, the ITTs were similar throughout trials, except for distinct mid- and end peaks. End peaks occurred in both foraging conditions for all age groups, but are larger during conjunction than feature foraging, and much larger for the 4–7-year-old children than the other age groups. This may indicate a difficulty in finding the last target among many distractors. The mid peaks only occur during conjunction foraging for the 11–12-year-olds and adults but also appear during feature foraging for the 4–7-year-olds. Since most trials during conjunction foraging are completed in only two runs in all age groups, these mid peaks represent switch costs. This could also explain why there are mid-peaks during feature foraging for the 4–7-year-olds, because they completed the majority of the feature foraging trials in two runs, and they are the only age group that shows switch costs during feature foraging. In fact, when looking at switch costs (panels c) and d) of Fig. 3), there is a clear correspondence between the size of the switch costs and the mid peaks for each age group.

It is worth noting that the difference in mean ITTs between the feature and conjunction foraging trials mainly stem from the mid and end peaks. The remaining ITTs seem to be similar during feature and conjunction foraging (compare the ITTs of panels a) and b) in Fig. 3). The trials were split up in peaks vs. other taps and a three-way ANOVA with foraging condition, peaks, and age group as between-subjects factors was conducted. All main effects were significant (all $ps < 0.001$), meaning that there was an overall difference in ITTs between the feature and conjunction foraging conditions, the peaks and other ITTs within a trial, and age groups (η_p^2s = 0.224, 0.461, and 0.536, respectively). Bonferroni post-hoc test revealed that the ITTs of the 4–7-year-olds differed from both other age groups ($ps < 0.001$), but no difference was found between the 11–12-year-olds and the adults. The interaction between peaks and age group was significant, F(2, 149) = 40.07, $p < 0.001$, η_p^2s = 0.350, meaning that when foraging condition is ignored, there is a greater difference between peaks and other ITTs within a trial for the youngest age group than the other two. There was also an interaction between foraging condition and peaks, F(1, 149) = 38.84, $p < 0.001$, η_p^2s = 0.207, meaning that regardless of age, the peaks are higher during conjunction than feature foraging. An interaction was also found between foraging condition and age, F(2, 149) = 6.65, $p = 0.002$, $\eta_p^2 = 0.082$, indicating that when the distinction between peaks and no peaks is ignored, there is a greater difference between the ITTs of feature and conjunction foraging for the youngest participants than the older age groups. Finally, there was a three-way interaction between condition, peaks and age, F(2,

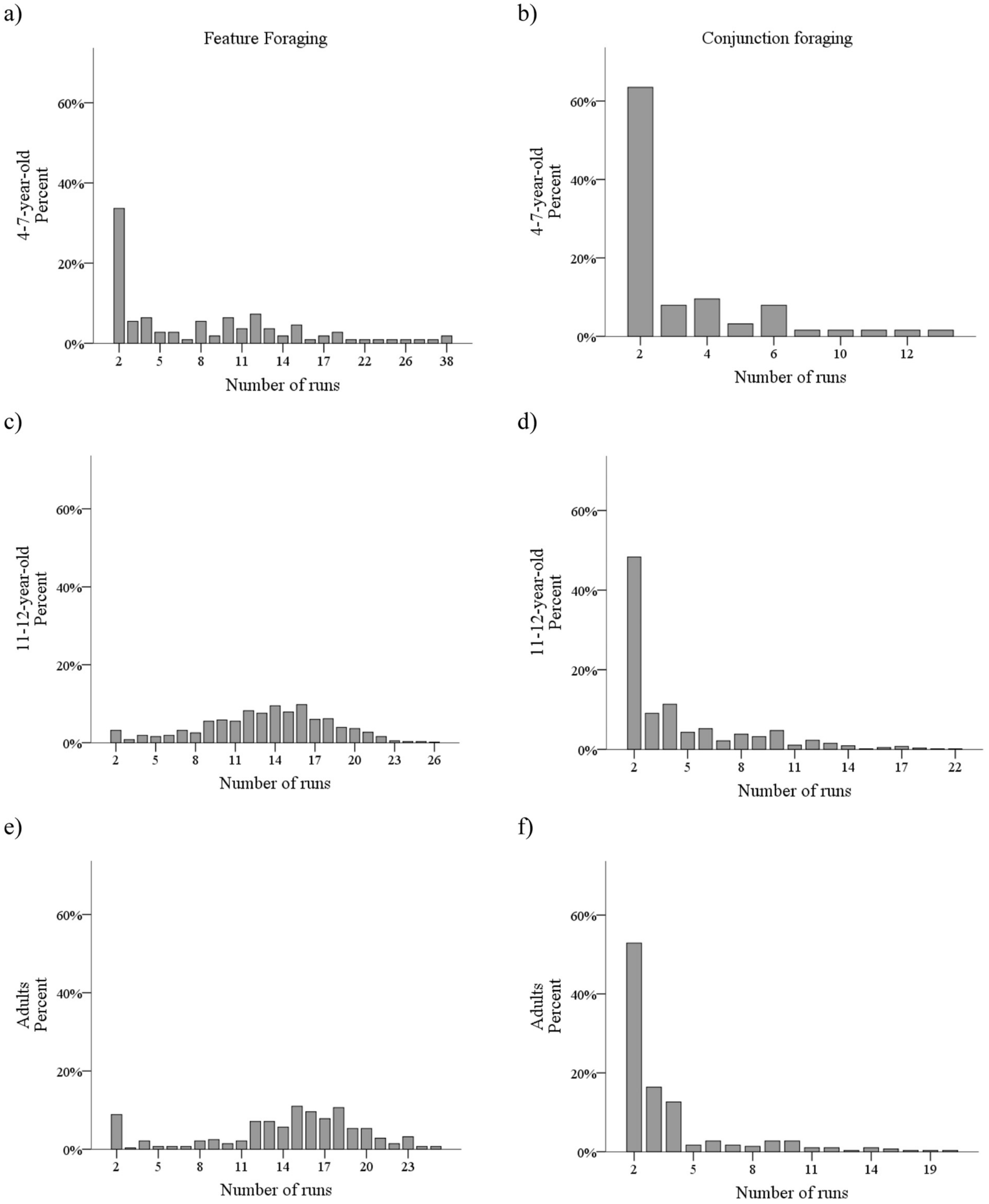

Fig. 2. The distribution of the number of runs during feature (left) and conjunction foraging (right), collapsed over participants of each age group. Panels a) and b) show foraging for the 4–7-year-olds, panels c) and d) for the 11–12-year-olds, and the foraging of adults is shown in panels e) and f).

149) = 5.80, $p = 0.004$, $\eta_p{}^2$s = 0.072, indicating that the peak x condition interaction described above differed between the age groups. These differences can be seen in panels a) and b) in Fig. 3. In both foraging conditions, the peaks are much larger for the 4–7-year-olds than the others, as are the differences in the sizes of the peaks.

Panels c) and d) in Fig. 3, show that switch costs are much higher during conjunction foraging for all age groups, highlighting the effort involved in switching between target categories during difficult tasks. This increased effort can, in turn, explain the long runs seen during conjunction foraging.

The switch costs of 11–12-year-old children are on par with those of adult participants, whereas the 4–7-year-old children show considerably larger switch costs during both feature and conjunction foraging. A three-way repeated measures ANOVA on condition and switch costs, with age as a between subjects factor, revealed significant main effects (all $ps < 0.0001$, $\eta_p{}^2 = 0.500$, 0.430, and 0.579, respectively). Bonferroni post-hoc comparisons revealed that the ITTs of the 4–7-year-olds differed from the other two age groups ($ps < 0.001$), but

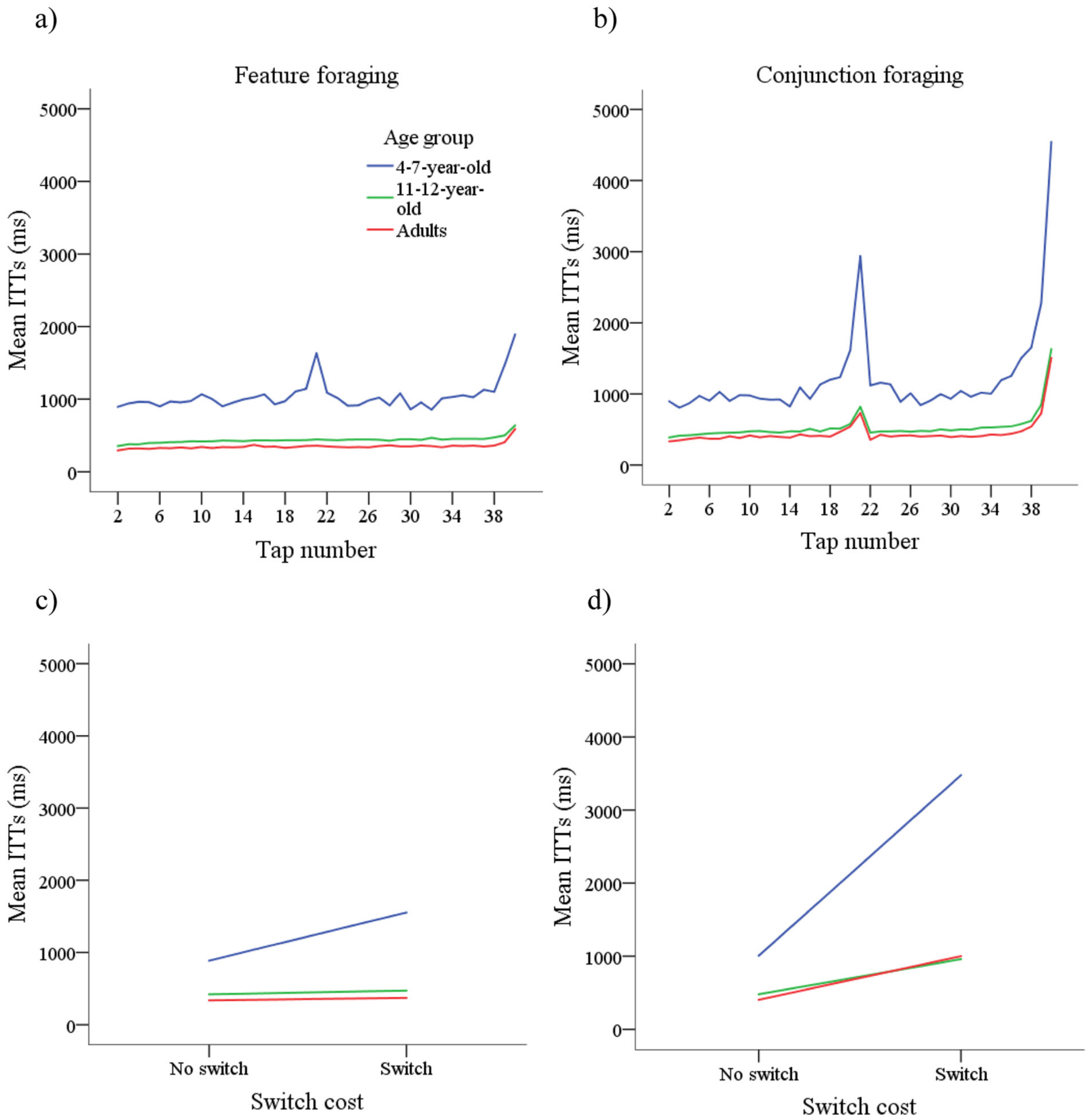

Fig. 3. Comparison of the ITTs of 4–7-year-olds (blue lines), 11–12-year-olds (green lines), and adults (red line) for the feature (left) and conjunction (right) foraging conditions. Panels a) and b) show the ITTs for every tap in a trial, and panels c) and d) show the switch costs for each age group. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

no difference was found between the 11–12-year-olds and the adults. All two-way interactions were also highly significant (all $ps < 0.0001$, condition × age $\eta_p{}^2 = 0.354$, switch cost × age $\eta_p{}^2 = 0.398$, and condition × switch cost $\eta_p{}^2 = 0.405$). Finally, the three-way interaction between condition, switch cost, and age was significant, $F(2, 149) = 30.36$, $p < 0.001$, $\eta_p{}^2 = 0.289$.

3.3. Foraging ability and executive functions

We explored the connection of executive functions and foraging with a series of multiple regression analyses. We predicted that greater EF abilities would be connected to faster ITTs, lower switch costs, and larger run numbers. Table 2 shows response times, error rates and standard deviations for the EF tasks, divided by age group. The youngest age group completed different EF tasks from the other two groups, so the comparison is restricted to 11–12-year-olds and adults. Independent samples *t*-tests revealed significant differences between the response times (RT) and error rates of the older children and the adults (Table 2).

A linear regression of the connection between EF and ITTs during feature and conjunction foraging revealed that different aspects of EF are connected to the foraging speed of 11–12-year-old children and adults (see Table 3). While attentional flexibility is the only EF that affects children's foraging speed, the speed of the adult participants depends partly on working memory. Inhibition did not affect the foraging speed of either age group.

No connection was found between error rates during foraging and EF measures (all $ps > 0.05$). Similarly, no connection was found between error rates of either EF task and foraging (all $ps > 0.05$). Therefore, error analyses will be excluded from the subsequent discussion.

Attentional flexibility is defined as the ability to switch between two

Table 2

Means, error rates, and standard deviations of the executive functioning tasks.

	Mean (ms)	Standard deviation	Mean error rates	Standard deviation
11–12-year-olds				
Inhibition	125.21	63.55	1.07	1.45
Attentional flexibility	332.82	140.38	3.37	2.71
Working memory	2214.13	578.84	7.12	4.26
Adults				
Inhibition	51.19[**]	39.07	0.61[*]	0.80
Attentional flexibility	233.24[**]	87.24	2.35[*]	1.92
Working memory	1811.77[**]	459.98	4.00[**]	3.58

Note 1. The means reported for inhibition and attentional flexibility are the differences between response times during the baseline task and the tasks relying on inhibition and flexibility, thus reflecting the size of each effect regardless of the differences of overall speed for each individual. Note 2. The mean reported for working memory is the response times of correctly identifying a target (hits). Error rates in the working memory task reflect the number of misses.

[*] The differences between children and adults were statistically significant at 0.05.

[**] The differences between children and adults were statistically significant at 0.001.

Table 3

Linear regression of the effects of EF measures on ITTs of children and adults during feature and conjunction foraging.

	B	SE B	B	*P*
Feature foraging				
Children (11–12-year-old)				
Working memory	0.020	0.014	0.179	0.154
Inhibition	−0.127	0.146	−0.125	0.378
Attentional flexibility	0.165	0.069	0.358	**0.020**
Adults				
Working memory	0.049	0.019	0.444	**0.018**
Inhibition	−0.330	0.250	−0.256	0.199
Attentional flexibility	0.127	0.121	0.220	0.305
Conjunction foraging				
Children (11–12-year-old)				
Working memory	0.022	0.019	0.143	0.254
Inhibition	−0.141	0.200	−0.102	0.484
Attentional flexibility	0.226	0.095	0.360	**0.021**
Adults				
Working memory	0.111	0.032	0.600	**0.002**
Inhibition	−0.248	0.409	−0.114	0.549
Attentional flexibility	−0.018	0.198	−0.018	0.929

Note 1-feature foraging. $R^2 = 0.160$ for children ($p = 0.012$); $R^2 = 0.309$ for adults ($p = 0.017$).

Note 2-conjunction foraging. $R^2 = 0.148$ for children ($p = 0.019$); $R^2 = 0.357$ for adults ($p = 0.007$).

Values in bold are statistically significant at 0.05.

Values in italics are marginally significant.

Table 4

Linear regression of the EF's influence on switch costs of children and adults during feature and conjunction foraging.

	B	SE B	β	*P*
Feature foraging				
Children (11–12-year-old)				
Working memory	0.015	0.007	0.249	**0.048**
Inhibition	−0.104	0.078	−0.191	0.187
Attentional flexibility	0.077	0.037	0.311	**0.042**
Adults				
Working memory	0.007	0.018	0.080	0.706
Inhibition	−0.153	0.232	−0.153	0.514
Attentional flexibility	0.042	0.112	0.093	0.714
Conjunction foraging				
Children (11–12-year-old)				
Working memory	−0.027	0.063	−0.051	0.670
Inhibition	−1.157	0.663	−0.242	0.086
Attentional flexibility	1.226	0.315	0.567	**0.000**
Adults				
Working memory	0.251	0.220	0.236	0.264
Inhibition	1.622	2.851	0.130	0.574
Attentional flexibility	−0.677	1.382	−0.121	0.628

Note 1-feature foraging. $R^2 = 0.405$ for children ($p = 0.011$); $R^2 = 0.027$ for adults ($p = 0.863$).

Note 2-conjunction foraging. $R^2 = 0.456$ for children ($p = 0.002$); $R^2 = 0.052$ for adults ($p = 0.687$).

Values in bold are statistically significant at 0.05.

Values in italics are marginally significant.

Table 5

Linear regression of the influence of EF's on the number of runs of children and adults during feature and conjunction foraging.

	B	SE B	β	*P*
Feature foraging				
Children (11–12-year-old)				
Working memory	−0.001	0.001	−0.127	0.336
Inhibition	0.007	0.007	0.154	0.316
Attentional flexibility	−0.004	0.003	−0.196	0.232
Adults				
Working memory	−0.001	0.002	−0.144	0.489
Inhibition	0.014	0.027	0.114	0.616
Attentional flexibility	−0.011	0.013	−0.199	0.422
Conjunction foraging				
Children (11–12-year-old)				
Working memory	0.001	0.001	0.269	**0.044**
Inhibition	−0.001	0.006	−0.024	0.873
Attentional flexibility	−0.001	0.003	−0.054	0.735
Adults				
Working memory	0.001	0.001	0.287	0.128
Inhibition	−0.008	0.011	−0.141	0.489
Attentional flexibility	−0.011	0.005	−0.442	*0.052*

Note 1-feature foraging. $R^2 = 0.053$ for children; $R^2 = 0.068$ for adults ($ps > 0.05$).

Note 2-conjunction foraging. $R^2 = 0.066$ for children ($p = 0.236$); $R^2 = 0.261$ for adults ($p = 0.040$).

Values in bold are statistically significant at 0.05.

Values in italics are marginally significant.

tasks and we believed that this measure would have the strongest connection to switch costs during foraging. Participants with the greatest attentional flexibility should, in other words, find it easiest to switch between target categories. As Table 4 shows, both working memory and attentional flexibility are connected to the time it takes children to switch between target types during feature foraging, but during conjunction foraging, attentional flexibility was the only EF measure that was related to switch costs. Inhibition does not seem to be related to children's switch costs in either foraging condition. No connection was found between EF and the switch costs of adult participants.

Table 5 displays the connection between the EF measures and run number. We expected run number during feature foraging to be close to random, as participants would switch between target categories effortlessly and not surprisingly EF has no effect on either the children's or adults' run number during feature foraging. During conjunction foraging, however, we expected run number to be higher for participants with more developed EF abilities. There is no effect of either attentional flexibility or inhibition for the children, and working memory has a very small, but significant, effect on run number, but in the wrong direction. This means that the longer the RTs are in the working memory task, the more often the participants switch between target categories. But a b of 0.001 is essentially a flat line and taking into account that the standard error is the same size, the significant *p*-value does not amount to much. For the adults, there is no effect of working memory or inhibition on the number of runs, but the effect of attentional flexibility approaches significance.

To summarize; attentional flexibility and working memory, but not inhibition, seem to affect ITTs and switch costs in both foraging conditions, but any effects of EF's on the number of runs seem at best to be small.

4. Discussion

Although interest in human foraging has increased in recent years, little is known about children's foraging and how it develops into adulthood. We had two main objectives; to continue the mapping of foraging abilities throughout childhood and to assess the relation of foraging and EF abilities. Previous research on human foraging shows that for adult participants, foraging patterns are determined by task demands. When attentional load is high, most people tend to forage in long runs, but switch effortlessly between target categories when targets are easily distinguished (Jóhannesson et al., 2017; Kristjánsson et al., 2014). Here, the foraging patterns of 11–12-year-old children were similar to those of adults. The number of runs was close to random during feature foraging, but conjunction foraging trials mostly consisted of two runs. This pattern differs markedly from what was observed for the younger children, who tended to also forage in only two runs during feature foraging. As well as showing different foraging patterns, the younger children are also less effective foragers than the older children and adults with significantly higher switch costs, and slower overall foraging.

The general consensus is that when it comes to feature search, young children and infants perform similarly to older children and adults (Adler & Orprecio, 2006; Bhatt, Bertin, & Gilbert, 1999; Gerhardstein & Rovee-Collier, 2002; Thompson & Massaro, 1989; Trick & Enns, 1998). One study measured saccade latencies in three-month-old infants and adults during feature and conjunction search tasks, to find out whether single features pop out for infants as they do for older children and adults'. They found that like adults, infants do exhibit pop-out over the span of milliseconds, regardless of distractor set sizes (Adler & Orprecio, 2006). Similarly, when a visual search task with game-like features was administered to 12 to 36-month-old children to assess their performance in feature and conjunction search, their search slopes in the feature search task were relatively flat, suggesting that the same process is involved in feature search from infancy to adulthood (Gerhardstein & Rovee-Collier, 2002). By studying visual attention with a foraging task, we have found that young children do in fact have more difficulty with feature-based tasks than older children and adults, that are not only seen in higher ITTs, but also significantly increased switch costs and fewer runs per trial.

The foraging task also reveals that throughout most of the foraging trials (for all age groups) search times are very similar between the feature and conjunction tasks. The mid and end peaks mostly produce the differences in mean ITTs. In fact, Kristjánsson et al. (2018a, 2018b) have found that by varying the set sizes of the foraging trials, the difference in the size of the end peaks closely resemble search slopes during feature and conjunction searches; end peaks during feature foraging remain the same size, but for conjunction foraging, the end peaks increase with set size. They speculate that these end peaks reflect performance in single-target visual search, since they appear as participants search for a single target (the last target) among distractors. Thus, single target visual search paradigms may only provide a narrow window onto attentional orienting while foraging yields richer and more dynamic information.

By comparing the mid peaks of the three age groups, we found that they reflect the size of the switch costs, which are, in turn, connected to the number of runs. Larger switch costs highlight the effort involved in switching between target categories during difficult tasks. This increased effort can explain the long runs seen during conjunction foraging for all age groups and feature foraging of the 4–7-year-olds.

When children have turned 11 years old, their foraging patterns, ITTs, and switch costs are similar to adults. However, the relationship between foraging ability and EF, may reflect that children and adults using different mechanisms while completing the foraging tasks. The children with the greatest attentional flexibility were the fastest foragers (lowest ITTs), but no connection was found between attentional flexibility and ITTs in adults. Conversely, a connection was found between working memory and ITTs for the adult participants and not the children. This may be due to different developmental trajectories of different aspects of EF. Previous research has found that different subcomponents of EF are used in problem solving throughout development. Young children rely primarily on inhibition, and that focus gradually changes to attentional flexibility and then working memory over the course of development (Best et al., 2009; Huizinga & van der Molen, 2007; Senn, Espy, & Kaufmann, 2004). Huizinga and van der Molen (2007) compared performance on various EF tasks and the Wisconsin Card Sorting Test (WCST) for four age groups. They found that 7-year-old children relied heavily on inhibition and attentional flexibility while completing the WCST task, the performance of 11 and 15-year-olds was best predicted by attentional flexibility, but the 21-year-olds relied on working memory. The same thing may occur during foraging, where 11–12-year-old children rely on attentional flexibility, and adults on working memory, to successfully complete the same task.

No connection was found between EF and the switch costs of adults. For the children, both attentional flexibility and working memory affected switch costs during feature foraging, but during conjunction foraging the effect of working memory disappeared, while the connection with attentional flexibility grew stronger. This most likely reflects that the children keep both target items in mind during feature foraging but switch between target templates during conjunction foraging. Working memory load during conjunction foraging is presumably much higher than during feature foraging (see Awh & Jonides, 2001; Kristjánsson et al., 2014). We speculate that during the easier foraging task, the children with the greatest working memory capacity have an advantage because they can more easily maintain the target categories in working memory, allowing faster switches between the categories. During conjunction foraging, working memory is no longer connected to switch costs, which may indicate that the children find it difficult to hold two conjunction targets in mind.

Note that in a recent study, Jóhannesson et al. (2017) investigated the effects of inhibition and working memory on foraging patterns, finding no connection. They divided their participants, based on the number of runs, into "super-foragers" and "normal-foragers" (Kristjánsson et al., 2014) and tried to find differences in EF abilities between those groups. But the group comparison may not have been sensitive enough to assess the connection between EF and foraging, since foraging patterns may not have differed by enough between the groups. We believed that a regression analysis would be better suited to find any existing connection. We predicted that attentional flexibility would facilitate switching between target types, and greater inhibition would counter the preference for tapping the targets of the same type as previously attended (Brascamp et al., 2011; Chetverikov & Kristjánsson, 2015), affecting the number of runs during conjunction foraging. There was no connection between children's number of runs and EF, but attentional flexibility seems to have some effect on the number of runs of adults during conjunction foraging.

No connection was found between inhibition and foraging (in line with Jóhannesson et al., 2017). Note that the task in neither study involved a pure measure of inhibition, but a complex conflict task, which requires the participants to inhibit a prepotent response and produce an alternative one that conflicts with it, as well as remembering an arbitrary rule, which requires working memory (Best & Miller, 2010). In fact, previous research has revealed that tasks that simply require withholding a prepotent response, load on a different factor from tasks requiring conflicted responding (Carlson & Moses, 2001). Inhibition should therefore be assessed in a simple task involving withholding a prepotent response, ensuring no confounding of inhibition with other functions, such as working memory for definite conclusions. Likewise, inhibition seems to play a large role in the EF of young children (Senn et al., 2004) so it would be interesting to assess the connection between inhibition and foraging in younger populations.

5. Conclusions

Foraging patterns, foraging speed, and switch costs of 11–12-year-old children differ from those found for 4–7-year-old children and are much more similar to those seen for adult participants. By using a foraging task instead of a single target visual search task, we have found that young children do have more difficulty than their older counterparts completing feature-based tasks, not only reflected in slower foraging, but also with higher switch costs and different foraging patterns. Additionally, a connection was established between foraging and EF, where all aspects of foraging ability measured in the current study show a connection to either working memory, attentional flexibility, or both, but inhibition was not found to affect foraging. Lastly, the connection between foraging and EF showed different patterns in children and adults, likely reflecting different developmental trajectories of EF subcomponents. More foraging research is needed to fully grasp the complex relationship between these factors.

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