
Children's search behaviour in large-scale space: Developmental components of exploration

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Abstract. It has been argued that visual-search tasks provide a valid model for foraging behaviour. However, Gilchrist et al (2001 *Perception* **30** 1459–1464) demonstrated that, whilst some aspects of behaviour transferred to large-scale egocentric search, there were substantially fewer revisits to previously searched locations than would be expected from the visual-search literature. This difference might be a result of the greater effort required to search in a large-scale egocentric context. Here, we present a novel, automated paradigm, for examining the effect of effort on egocentric search behaviour by manipulating the motor difficulty of the task. Children searched for a hidden target amongst a randomised display of lights by activating a switch at each potential location. The motor difficulty of the task was manipulated by requiring children to search with either their dominant or their nondominant hand. We found that when children searched with their nondominant hand, they made significantly more revisits to previously checked locations than they did when using their dominant hand. This suggests that, when the motor response was more effortful, children were less able to efficiently guide their search behaviour. Individuals with a greater visuo-spatial short-term memory span performed the task more quickly than those with a lower span. However, search latencies were unrelated to general fluid intelligence. This highlights the role of spatial working memory in the development of efficient exploration of large-scale space.

1 Introduction

The study of foraging holds a central position in behavioural ecology with the documentation and modelling of search behaviour in a wide variety of species, from non-human primates (Whiten et al 1991) to ants (Fletcher et al 1995). However, there have been virtually no systematic studies of large-scale exploration in human behaviour. This is despite the primacy of ordered search in our behavioural repertoire, whether it be hunting for food or locating lost keys.

Examinations of human search behaviour have primarily used the visual-search paradigm in which the task is to detect the presence or absence of a target item within an array of distractor items. It has been argued (eg Wolfe 1994) that the visual-search paradigm provides a constrained and well-defined context with which to study more general foraging. In addition, it has been argued that mechanisms that have been used to describe visual-search phenomena may also be central to foraging. For example, the tendency not to re-fixate a previously inspected location in search ('inhibition of return': Klein 1988; Posner and Cohen 1984) has been explicitly labelled a 'foraging facilitator' (Klein and MacInnes 1999). Despite the similarities between visual search and foraging, however, there are some significant differences between the two tasks. Not only are radically different coordinate systems used to represent search space, but also the effort required to move visual attention in search experiments is much less than that required to systematically investigate potential locations when foraging. It is, therefore, unclear whether visual search really is a suitable model for large-scale search.

Gilchrist et al (2001) addressed this question by introducing the 'human foraging paradigm' (HFP), a three-dimensional egocentric analogue of the traditional visual-search task. Participants were required to search for a target (a marble) hidden in an array of possible locations (photographic canisters) on a floor. Only by reaching down

and shaking the canisters could participants detect the presence of the target in a particular location. As in visual search, locations were randomly arranged, and display size was systematically varied. Analysis of behaviour in this task revealed some important similarities and differences in comparison to standard visual search. Consistent with serial visual search, search time increased linearly with display size, and the target-present to target-absent search slope was 1 : 2. However, whilst rechecking of locations did occur, it was relatively rare compared with that usually found in visual search (Gilchrist and Harvey 2000). Gilchrist et al (2001) argued that the increased effort of rechecking in large-scale search (walking to a location and reaching down to inspect it) compared with more conventional visual search (moving the eyes) resulted in a greater deployment of memory for previously visited locations.

In a number of respects, this large-scale-search paradigm differs from traditional visual-search tasks. More importantly, the target location is not visually distinguishable, and so participants must visit each location in a serial self-terminating manner. As such, this precludes the possibility of any visual guidance to the target location. However, the process of serially inspecting each item in large-scale search is equivalent to an inefficient (or 'serial') search (Treisman and Gelade 1980). In studies of rechecking behaviour in visual search (eg Klein and MacInnes 1999; Gilchrist and Harvey 2000) tasks have been used in which the target could not be detected without being fixated and so required effortful serial search. In this respect, these studies are comparable with the large-scale-search paradigm. It is also the case that foraging, in the widest sense of the word, is a highly heterogeneous activity, which may, or may not, make use of naturalistic cues and landmarks. The large-scale-search paradigm represents one such example of this activity and also retains task features that make it comparable with visual search (ie no explicit landmarks). In light of this, we henceforth restrict the use of the term 'foraging' to generic nomenclature and concentrate more on issues of large-scale-search behaviour.

The findings of Gilchrist et al (2001) suggest that the visual-search task does not adequately approximate large-scale search. Furthermore, it seems that a key component of egocentric search behaviour is the effort required to inspect a potential target location. In the present study, we aimed to further investigate the issue of effort and revisits by using a population that we reasoned should be more prone to search error in the HFP. Whilst children's spatial behaviour has been studied in a number of contexts (eg DeLoache and Brown 1983; Hermer-Vasquez et al 1999; Overman et al 1996), as yet there has been no parametric study of large-scale search in children. Investigations of children's performance on visual-search tasks suggest that whilst their general search profile is similar to that of adults (Gerhardstein and Rovee-Collier 2002), young children are less able to search for targets defined by a conjunction of features and demonstrate difficulty in voluntarily shifting attention from one item to another (Trick and Enns 1998). In line with this, MacPhearson et al (2003) report that inhibition of return is delayed in young children when they have to endogenously shift attention away from a location. It is therefore of interest to investigate how children will perform on a large-scale-search task, especially with regards to revisiting previously checked locations.

In the experiment reported here, we manipulated the cost of search in a novel automated version of the HFP. The automated HFP took the form of an isolated room, without obvious landmarks, within which children searched for targets defined by lights embedded in the floor. Participants inspected individual locations by pressing a micro-switch. Since hand proficiency is correlated with hand preference (eg Bishop 1989; Carlier et al 1993), we predicted that it would be more effortful for children to search for targets with their nondominant hand, compared to using their dominant hand.

The study required children to search with either their preferred or non-preferred hand in separate blocks, which gave a convenient within-subject manipulation of physical effort.

A number of factors may determine individual differences in overall performance between children, and identifying these factors is an important precursor to constructing a model of the development of search behaviour. An obvious factor is age, and as this novel paradigm has not been tested with children before, we deliberately selected an age range that would be able to understand the task demands but should still be sufficiently different from the adults used in the original studies. In order to explore the relationship between search behaviour and other cognitive abilities, we also administered two standardised tests to the children. Visuo-spatial short-term memory was measured with the Corsi blocks test (see Logie 1995), and generalised fluid intelligence was measured with Raven's coloured progressive matrices (Raven's CPM: Raven et al 1998).

In summary, the current study had two aims. The first was to investigate the effect of effort on rechecking in large-scale search—this is a direct test of a hypothesis put forward by Gilchrist et al (2001). The second was to begin investigating the effect of some basic cognitive abilities that support the development of exploratory behaviour.

2 Method

2.1 Participants

We selected twenty typically developing children (eight male and twelve female) aged between 69 months (5 years, 9 months) and 105 months (8 years, 9 months) from the participant database of the Bristol Cognitive Development Centre (University of Bristol). The mean age of the children was 85 months (SD = 10). Hand dominance was tested with the technique described by Coren et al (1981), which is designed for use with children and based on behavioural measures (eg drawing, pointing) rather than self-reports of hand use in various adult-orientated actions (Oldfield 1971). In our sample, seventeen children were classed as right-hand dominant and three classed as left-hand dominant. Corsi spans ranged from 3 to 5 (mean, 3.7; SD, 0.7), and Raven's CPM scores ranged from 17 to 35 out of a possible 36 (mean, 24; SD, 5.3).

2.2 Apparatus

Participants were tested in the HFP apparatus; a square room (4 m × 4 m × 2.5 m) with a large raised platform floor. Embedded into the floor of the room were 49 search locations, arranged in a 7 × 7 grid. Each location contained 2 lights (1 green, 1 red) and a switch positioned between them. The lights and switches were powered and controlled by a 192-channel input/output card connected to a personal computer in an adjoining room. The PC enabled the experimenter to trigger each trial, and also recorded the location and timing (with millisecond accuracy) of each button press made by the participant. From the adjoining room, the experimenter could also monitor the participant's performance with a closed-circuit television camera that was discreetly mounted in the testing room. The HFP apparatus was within a homogeneous environment and devoid of obvious landmarks: a dark-blue curtain was mounted around the walls (also occluding the entrance), and the floor was covered with featureless grey carpeting. The room was lit by artificial means, with a dimmable lighting unit in each corner of the ceiling. This environment is illustrated in figure 1.

2.3 Design

Participants performed 2 blocks of the search experiment, using the dominant hand to activate the switches in 1 block, and the nondominant hand in the other. The order of block presentation and the hand to be used (dominant/nondominant) were fully

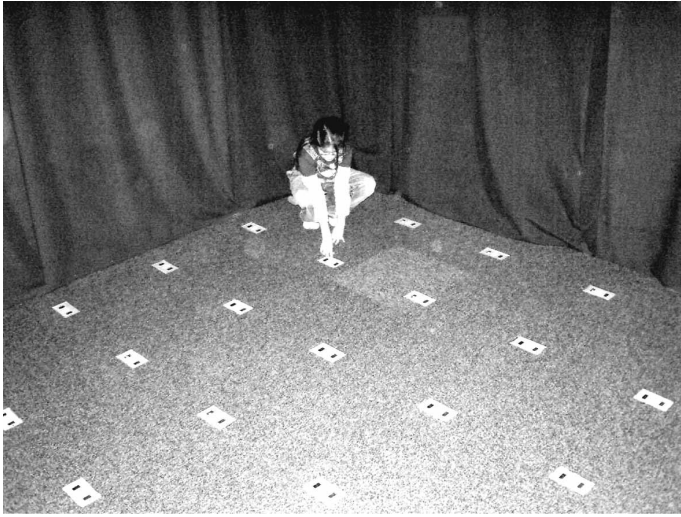


Figure 1. A child inspects a potential target location by depressing the switch.

counterbalanced across participants. Each block contained 14 individual trials, with 28 trials overall. Trial order was fully randomised for each participant. Within a trial, 16 possible target locations (green lights) were presented in a random array. Participants were required to visit locations and press the switch. When pressed, 1 of the switches turned on the red light at that location and this indicated that the target had been found. There were no visible or predictable cues as to where the target would be, although its location was constrained such that each row and column of the 7×7 grid occurred twice in a block (hence there being 14 trials). Once the target was located, all of the lights were extinguished and the next trial begun. Participants began each trial from the same fixed location: the middle point of a perimeter row, with their back to the wall.

2.4 Procedure

Before starting the first block of searching, children completed a brief battery of simple handedness measures (eg drawing a circle, pointing to their nose; see Coren et al 1981) in order to assess hand dominance and assign them to the appropriate condition. They were then taken into the foraging room by the experimenter and the task explained to them. A practice trial was triggered and children were told to visit each lit location (a green light) and press the button, because a red light was 'hiding' at one of the locations and it was the child's task to find it. The experimenter assisted the child with the first practice trial, activating a small number of switches and encouraging the child to attempt the same at other locations. The child then performed a second practice trial alone. At this point, other aspects of the task were explained. First, participants were shown the point at which they were to begin each trial and return to once having located the target. Second, they were asked to hold a tennis ball in the hand that would not be used to press the switches. This was to ensure that participants used only the required hand to make their responses. The first block was begun once it was clear that the child understood all of the instructions. Participants were monitored at all times via the television camera and each new trial was begun once the child had returned to the starting position. Following the completion of the first block, children were taken to another room and the Corsi blocks test and Raven's CPM were administered, before returning to the testing room for the second block (completed with the other hand).

3 Results

For the dominant-hand condition, the mean overall search time (to find the target) was 24.0 s (SD = 4.22 s). For the nondominant-hand condition, the mean search time was 26.2 s (SD = 4.99 s). Participants were significantly faster in the dominant-hand condition, compared to the nondominant-hand condition ($t_{19} = 2.20$, $p < 0.05$). This difference was in part due to the number of inspections carried out in each condition. In each trial of the dominant-hand condition, a mean of 9.24 (SD = 1.51) button presses were made (this measure includes the target location and revisits to previously inspected locations). In the nondominant-hand condition, there was a mean of 10.7 (SD = 2.02) button presses. Although small, this difference was statistically reliable ($t_{19} = 2.59$, $p < 0.02$).

3.1 Revisit data

Gilchrist et al (2001) related revisit rates in foraging to the cost of search. In the present experiment, search cost was investigated by manipulating the hand with which participants searched. The number of times that a location was inspected more than once in a trial was calculated for each participant. These frequencies were categorised according to the number of revisits per location (ie no revisits, 1 revisit, 2 revisits, etc). Data were transformed into a percentage of the total number of button presses in the respective block. When participants searched with their dominant hand, a mean of 88.8% (SD = 9.2%) of button presses did not involve any revisits. For the remaining responses, 8.7% (SD = 6.5%) were single revisits, 2.2% (SD = 2.9%) were double revisits, and 0.2% (SD = 0.4%) were triple revisits. No locations were visited more than three times in a trial. In contrast, when participants searched with their nondominant hand, a mean of 83.4% (SD = 10%) of button presses did not involve any revisits. For the remaining responses, 13.2% (SD = 7.2%) were single revisits, 3.1% (SD = 3%) were double revisits, and 0.4% (SD = 0.7%) were triple revisits. On only one trial was a location visited more than three times in a trial (one child made 4 visits to a location). Revisit data are illustrated in figure 2. There was no reliable difference between blocks for the percentage of button presses that were not revisits (although the test does approach significance; $t_{19} = -1.86$; $p = 0.078$). However, there were significantly more single revisits when children searched with their nondominant hand, compared to searching with their dominant hand ($t_{19} = 2.32$, $p < 0.05$). There was no difference between blocks for double revisits ($t_{19} = 0.85$, $p > 0.05$) or for triple revisits ($t_{19} = 0.901$, $p > 0.05$).

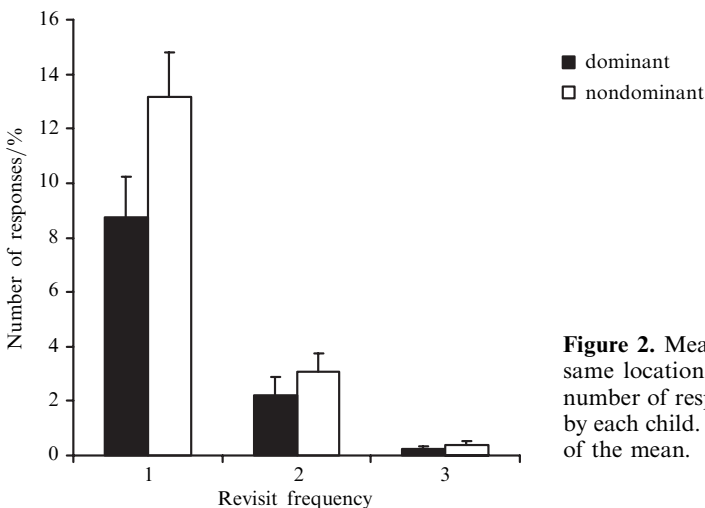


Figure 2. Mean frequency of revisits to the same location as a percentage of the total number of responses (button presses) made by each child. Bars illustrate standard error of the mean.

3.2 Individual differences

In order to see whether individual participant factors were related to general performance in the task, we entered them into correlational analyses. Mean search times, collapsed across blocks, were entered into a Pearson's correlation with participant age (in months): there was no relationship between these two variables ($r = -0.224$, $p > 0.05$). To confirm the lack of an age effect, search time was compared with other participant variables (test scores) in a partial correlation, controlling for age. There was a significant negative correlation between foraging time and Corsi span ($r = -0.643$, $p < 0.05$). Those children with a longer span performed the task in a shorter time than those with a shorter span. There was no relationship between scores on Raven's CPM and search time ($r = 0.113$, $p > 0.05$). A quotient was calculated from scores on the Coren et al (1981) handedness inventory so that children with left-hand responses on all items scored 0 and those that used their right hand on all items scored 100 [see Schachter (2000) for a similar transformation of scores on the Oldfield (1971) handedness inventory]. This was found to correlate with search time ($r = 0.496$, $p < 0.05$) and points towards a tendency for children with a lower quotient (ie those who were more left-handed) to perform the search task more quickly than children with a higher quotient (ie those who were more right-handed).

The same analyses were applied to the number of button presses made by participants. Mean inspection frequencies, collapsed across blocks, were entered into a partial correlation, controlling for age. This showed a negative correlation between inspection frequency and Corsi span that approaches significance ($r = -0.399$, $p = 0.09$). The data suggest that those children with a longer span performed the task with fewer inspections than those with a shorter span. As with the analysis of search time, inspection frequency was unrelated to scores on Raven's CPM ($r = -0.213$, $p > 0.05$), and it was also unrelated to the handedness quotient ($r = -0.290$, $p > 0.05$).

4 Discussion

Human search behaviour has primarily been studied with the visual-search paradigm. One of the many justifications for this focus is that it provides a constrained and well-defined context within which to study foraging (eg Klein and MacInnes 1999). However, research conducted by Gilchrist et al (2001) suggests that the visual-search task may not necessarily be such a good model: in their human foraging paradigm (HFP) participants were found to make fewer revisits to previously inspected locations, compared to those usually found in visual search. They argued that this was because the effort required to inspect each location is greater in large-scale search than in visual search, and hence memory is more likely to be deployed to save on costly rechecking. Here, a novel automated apparatus was used to extend the HFP and further examine the issues of effort and cost in large-scale search. The current study made use of a developmental population, not only to demonstrate the applicability of the paradigm to groups other than typical adults, but also to begin to address the cognitive mechanisms that might lead to the development of efficient search behaviour in children.

There were 2 conditions: in 1 block children searched using only their dominant hand, and in the other block they searched using only their nondominant hand. Search was more effortful, and therefore costly, when children were confined to using their non-preferred hand (see Bishop 1989; Carlier et al 1993). In trials where the nondominant hand was used, children made significantly more revisits to locations that they had already inspected, compared to the dominant-hand condition. Overall, individual differences in children's performance were related to their spatial working-memory ability: children with a longer Corsi span completed trials in less time and with fewer visits than children with a shorter span (although the latter observation approaches significance). However, their search performance was unrelated to their score on Raven's

CPM, and there was no effect of the child's age (although a larger sample size of specified age groups would be necessary to fully explore this point). Search time was also correlated with handedness, with left-handed children, and those with no hand preference, searching in less time than strongly right-handed children.

Revisit frequency was affected by the manipulation of cost in this task. However, the current experiment shows an increase in revisit frequency associated with an increase in cost. Gilchrist et al (2001) proposed that there are fewer revisits in foraging, compared to visual search, because it is more effortful to inspect potential target locations in large-scale search. Here, we find that increased effort is associated with poorer memory: search with the nondominant hand led to more revisits. A possible explanation for this finding is that when the motor response required to search the environment is more effortful, then fewer resources are available to efficiently organise their search. For example, recent developmental research on large-scale Piagetian search tasks indicates that infants can inhibit a prepotent motor response under low task demands (walking to target) but make perseverative errors when the required response is more complex (descending stairs towards target) (Berger 2004). It may be that making the children use their nondominant hand required that they actively inhibit making a response with the preferred hand, even when it was holding a ball (cf Goldin-Meadow et al 2001). Functional imaging studies show that response inhibition activates a fronto-striatal network that includes the prefrontal cortex (eg Booth et al 2003). Dorsolateral prefrontal cortex has been deemed critical to working memory and controlled attention abilities (see Engle et al 1999a), and its utilisation in the inhibition of a preferred response may therefore compromise efficient search. Booth et al (2003) found that frontal activation was greater in children, compared to adults, when inhibiting a prepotent response, and argued that immature prefrontal networks require more effort in maintaining a no-go response. This might tally with the findings of Gilchrist et al (2001), who noted the comparative lack of revisits in adult search (although physical effort was not directly manipulated in their experiment).

In the current study, there were large individual differences in performance. These differences were significantly related to Corsi span, but not to scores on Raven's CPM. In addition, the association between performance and Corsi span remained when age was partialled out of the analysis. This suggests that spatial memory (as measured by the Corsi) is a more important aspect of organising foraging behaviour than general fluid intelligence (as measured by Raven's CPM): those children with a greater short-term spatial span proved to be more efficient searchers, regardless of their general intelligence. Support for this functional separation comes from a study by Engle et al (1999b), who used structural equation modelling to compare multiple measures of working-memory capacity, short-term memory, and general intelligence. In the resulting model, working memory span measures were found to tap general processes and abilities, and were highly related to general intelligence. Short-term memory measures, however, were found to be domain-specific and unrelated to general aspects of ability. Corsi span, while not used in the Engle et al (1999b) study, is an example of a spatial short-term memory task, and is therefore a measure of domain-specific spatial memory. It is this specificity that is associated with the efficiency of children's search behaviour, rather than more general abilities.

Spatial working memory appears to be an important factor in the efficient search of large-scale space. Presumably this is because those children with longer spatial working-memory spans were better able to organise their search. Future studies specifically addressing this relationship will help to identify the relevant mechanisms. It is also interesting that search time was associated with handedness, such that left-handed children, and those without a strong hand preference, were faster than children with a strong right-hand preference. As the current study was not designed to explore this issue,

we do not intend to devote much discussion to the finding. However, it does tally with recent evidence suggesting that left-handedness is associated with spatial abilities. Reio et al (2004) tested a large corpus of individuals on various spatial tasks, such as visual exploration and spatial visualisation, and found them to be reliably associated with left-handedness. These findings support the argument that spatial abilities are lateralised to the right cerebral hemisphere, which is likely to be the dominant hemisphere for left-handed individuals (Annett 2002).

These findings point to the importance of egocentric search behaviour in our larger understanding of spatial cognition and working memory. There are few developmental studies of searching behaviour in large-scale space, and those that do exist have primarily addressed children's use of landmarks in the environment (eg Anooshian et al 1982; DeLoache and Brown 1983; Keating et al 1986; Overman et al 1996; Plester et al 2002). In the current study, however, participants searched in an environment that was devoid of major landmarks, other than the structure provided by the stimulus array. Efficient search required effective tagging of inspected locations with some form of memory. As such, it shares many features with the visual-search paradigm, and enables controlled parametric measurement of spatial behaviour. However, large-scale search behaviour (as measured by the HFP) is not the same as visual search. Although this paradigm is clearly not equivalent to naturalistic foraging (eg searching for food in woodland), it nevertheless represents a fruitful means with which to systematically study large-scale search behaviour in both adults and young children, and also enables the analysis of other processes that enable an active goal-driven exploration of our environment.

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