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Rapid resumption of interrupted search is independent of age-related improvements in visual search

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A B S T R A C T

In this study, 7–19-year-olds performed an interrupted visual search task in two experiments. Our question was whether the tendency to respond within 500 ms after a second glimpse of a display (the *rapid resumption* effect [*Psychological Science*, 16 (2005) 684–688]) would increase with age in the same way as overall search efficiency. The results indicated no correlation of rapid resumption with search speed either across age groups (7, 9, 11, and 19 years) or at the level of individual participants. Moreover, relocating the target randomly between looks reduced the rate of rapid resumption in a very similar way at each age. These results imply that implicit perceptual prediction during search is invariant across this age range and is distinct from other critical processes such as feature integration and control over spatial attention.

Introduction

An important aspect of everyday behavior is the ability to select one object from among many and to act on it. This ability improves in child development, as all who work with young children know firsthand. For example, there is no better place to hide a pair of shoes from a kindergarten child than to place the shoes on the child's bed. A child who ordinarily expects to find his or her shoes beside or under the bed can search for a long time before finding the shoes in plain view. As this example illustrates, search success is governed by more than the magnitude of the physical contrast that distinguishes an object from its background. Expectations based on past experience are also critical.

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In this study, we explored how the implicit expectations of recent experience play a role in age-related changes in visual search.

The study of visual search has contributed much to our understanding of human attention (Wolfe, 1994, 1998) and how it differs from one end of life to the other (Plude, Enns, & Brodeur, 1994). For instance, we know that there are separable cognitive components of a successful visual search. One of these is *feature integration,* the binding of visual attributes that distinguish the target item from nontarget items. According to feature integration theory (Treisman & Gelade, 1980), to find a red square among green squares and red circles, the color red must be specifically associated with the square shape. The theory states that human vision is limited by the constraint that two or more attributes (e.g., color and shape) can be integrated (or bound) only for one item at a time. This leads to the consequence that the search time for conjunction-defined targets increases directly with the total number of items present in a scene. The slope of the search time function over the number of items, therefore, is taken to be an index of the efficiency of feature integration.

A second aspect of successful search is the ability to move the spotlight of attention from one item to the next until the target is found. According to attentional orienting theory (Posner & Peterson, 1990; Posner & Raichle, 1994), each item must be assessed with respect to its potential match to the search image, and the spatial focus of attention must be disengaged from the current item, moved to a new item, and then reengaged on that item. When age-related improvements in feature integration and spotlight movements were isolated in a study of visual search over the lifespan from 6 to 72 years of age, Trick and Enns (1998) concluded that the increased efficiency of both feature integration and spotlight movement were behind the age-related improvements in search during the school years but that only a decreased efficiency of spotlight movement was responsible for the age-related decline in search ability at the later end of life.

More recently, the importance of implicit prediction in visual search has been identified through studying searches that are momentarily interrupted and then resumed (Lleras, Rensink, & Enns, 2005). In an interrupted search task, participants search a display with brief *looks* of 100 to 500 ms that are momentarily interrupted by *waits* of 1000–3500 ms (we use *epoch* to refer to each cycle of one look followed by a wait). Adult participants are generally quite successful in these tasks, being able to identify the target on 75% of the trials within three epochs and with accuracy levels of 95% or more. But following the second and subsequent looks, two distinct phases in the response time (RT) distributions can be seen. One is an early phase of correct responding that begins at around 200 ms and peaks between 300 and 399 ms, and the second is a later phase of responding that peaks in the range of 600–799 ms. Illustrations of these two phases can be seen in the RT distributions from Experiment 1 in the current study (see Fig. 2). In contrast to the pattern of responses that occur following a single first look (<2% of responses between 0 and 499 ms), subsequent looks commonly result in 30–50% of responses occurring within 499 ms (i.e., in Epochs 2, 3, and beyond). This is the operational definition of *rapid resumption* that we use in the current study.

Lleras et al. (2005) interpreted rapid resumption within a *reentrant theory* (Di Lollo, Enns, & Rensink, 2000; Enns & Lleras, 2008), according to which all perception involves an iterative process of information, with a higher level associated with object representations and a lower level associated with precategorical sensory input. Perceptual awareness is achieved once a prediction about a candidate object is created and confirmed against the current sensory input. For example, a precondition for awareness is that the reentrant activity in the system matches the sensory input. If there is no match, then perceptual awareness of the object generating the prediction does not occur and the system generates a new prediction regarding the current sensory information, which is believed to be the basis of visual backward masking (Enns & Di Lollo, 2000). On this account, rapid resumption of an interrupted search reflects the benefit of forming implicit predictions of a target item based on an incomplete glimpse of a scene on a previous look (Enns & Lleras, 2008).

Evidence supporting the hypothesis that rapid resumption is an index of perceptual prediction comes from several findings. First, both rapid resumption and report accuracy are sharply reduced if the original display is not re-presented following a single look (Lleras et al., 2005). This suggests that participants do not have explicit awareness of the prediction. But it also indicates that rapid correct responses depend on the predicted information being confirmed in the sensory array; merely forming the prediction is not enough. Second, rapid resumption fails to occur when the first display consists entirely of distractor items and only the subsequent displays include the target (Lleras, Rensink, & Enns, 2007). This suggests that observers are making a prediction about a particular object rather than about the task context or the scene as a whole. Third, rapid resumption is sharply reduced when the location of the target is randomly relocated between looks, consistent with a prediction being made about an object in a specific location (Lleras et al., 2005). Fourth, rapid resumption still occurs when incidental features of the target item change from look to look, but it fails to occur when the changed features are relevant to the response made to the target (Lleras et al., 2007). This points to a prediction that is specifically about response-relevant features of the target. Finally, rapid resumption can occur even when the target is in a new location on each look provided that the sequence of locations follows a predictable pattern (e.g., moving around a clock face) (Mereu, Zacks, Kurby, & Lleras, 2010).

With regard to whether the predictions are implicit, Ahn and Lleras (2007, 2008) examined the role of visual–spatial working memory and executive control processes in interrupted search, both of which are considered by most theorists to be critical for conscious perception (Baars, 2002; Baddeley, 2000). Ahn and Lleras (2007) used a dual task methodology in which participants needed to first examine a visual pattern, then perform an interrupted visual search, and finally respond to a final visual pattern to indicate whether it was the same as or different from the initial pattern. They found that the memory task reduced the overall speed and accuracy of the search task, as expected (Oh & Kim, 2004). However, the rate of rapid resumption was unaffected by the difficulty of the memory task. Ahn and Lleras (2008) reported that search times were also substantially delayed when the load on an executive working memory task was high but that the proportion of rapid resumption responses was unaffected by this secondary task. These dissociations imply that the memory processes involved in rapid resumption are distinct from the processes used in visual–spatial working memory and executive control tasks, which are closely linked to the contents of conscious awareness.

It is our position that implicit predictions ordinarily help the visual system to create perceptual continuity in the face of chaotic input that occurs because of our nonuniform retinas, eye movements, blinks, and occluded views of a scene that occurs under natural viewing conditions (Enns, Lleras, & Moore, 2009). That is, the visual system constantly generates implicit predictions about information in the world to accelerate perception. Rather than passively waiting for information to accumulate and to be identified on each look, implicit predictions make preattentive contact with processes that will hasten identification and conscious perception of the world when the information becomes the focus of attention. That said, a strong commitment to a reentrant theory of vision is not required. The implicit predictions that we believe are the basis of the rapid resumption effect could be implemented through simpler models (e.g., an accumulation of evidence about a specific target over time). Yet it is still important to ask whether these predictions (be they reentrant or feed-forward) are made in the same or different ways during child development.

A developmental study of rapid resumption

The goal of the current study was to compare the rapid resumption effect among 7–19-year-olds. This is useful in at least two ways. First, it provides an opportunity to see whether implicit predictions are related to the other operations involved in visual search such as feature integration and movement of the attentional spotlight. A comparison of search in younger and older participants is a natural experiment for this question because it is already well established that mean search time improves during the school-age years (Day, 1978; Gibson & Yonas, 1966a, 1966b; Kaye & Ruskin, 1990; Thompson & Massaro, 1989; Trick & Enns, 1998; Vurpillot, 1968; for a review, see Plude et al., 1994). Yet the implicit predictions underlying rapid resumption are proposed to be critical for perceptual awareness quite generally as well as just for the completion of interrupted search tasks.

If the perceptual predictions hypothesized to underlie rapid resumption are implicit, then both data and theory suggest that the rate of rapid resumption may be very stable across the age range tested here. For example, in a recent study of *contextual cuing* in visual search, search by 5–9-year-olds children through displays they had seen previously was more efficient than searching through a display for the first time (Dixon, Zelazo, & De Rosa, 2010). More important, children's awareness of whether a given display had been seen previously or not had no bearing on the benefit children experienced from searching through it again. Studies of *implicit priming* also show similar levels across age in childhood (Billingsley, Smith, & McAndrews, 2002; Naito, 1990), whereas studies of explicit tasks (e.g., recollection, awareness of task structure) document large age-related improvements during the same period (Kail, 1990; Russo, Nichelli, Gilbertoni, & Cornia, 1995).

Several findings in the child development literature speak even more directly to the question of implicit predictions. For instance, the *revelation effect* refers to the finding that items in a perceptual recognition test are identified more accurately when they have been seen previously in a fragmentary form rather than in an intact form (Watkins & Peynircioglu, 1990). Moreover, fragmented objects are more likely to be judged as familiar, as though needing to complete the object through imagination results in a stronger trace. A study of this effect in 4- and 8-year-olds showed that it was equally evident in both age groups despite the secondary finding that the older children were better able to benefit from it when engaged in explicit recognition (Guttentag & Dunn, 2002).

A related phenomenon, the *perceptual interference effect,* refers to the finding that when participants try to identify pictures that gradually emerge into focus, they are more accurate on pictures that begin as moderately degraded rather than as highly degraded (Bruner & Potter, 1964). The incorrect predictions they form initially based on the highly degraded pictures seem to interfere with correct identification when less degraded versions are presented. Bernstein, Loftus, and Meltzoff (2005) showed that this effect was strong in both 3- and 5-year-olds, implying that perceptual predictions were occurring at these ages.

These and related findings have prompted theorists to hypothesize that there is at least a *minimal consciousness* present from birth, one that is evident in infants and young children (Zelazo, 1996, 2004). This minimal consciousness is sensory in that it is a consciousness of *what* one is seeing, hearing, or touching (the object of experience), but it is not necessarily a consciousness *that* one is seeing (a meta-consciousness of experience) and it need not involve a consciousness of a being who is doing the seeing (a consciousness of self). It is these higher levels of consciousness that change the most during child development and, therefore, are associated with the age-related changes in performance associated with explicit measures of perception and immediate memory.

On this view, there is no reason to expect change with age in the basic mechanisms of perceptual awareness. Thus, the strong prediction from this theoretical position is that we should see similar proportions of rapid resumption responses in younger and older participants even though younger children will search more slowly and make more errors. The alternative outcome – that rapid resumption occurs less often among younger participants – would be evidence that it reflects an important cognitive strategy that is acquired through further maturation or extensive experience.

A second benefit of testing individuals over a wide range of ages is that it provides an opportunity to test the fine-grained prediction that implicit perceptual predictions are made independently of other operations, such as feature integration and spotlight movement, that contribute to search time. This can be accomplished by testing the correlation between successful search time and the rate of rapid resumption in individuals who differ a great deal in overall search success. To address this question, we examined this correlation across all of our participants after statistically controlling for effects attributable to age.

Experimental design

The study included two different tests of individuals in four age groups with mean ages of 7, 9, 11, and 19 years. In Experiment 1, all of the participants performed a standard interrupted search task in which they were provided with 500-ms looks at a search display alternating with 1000-ms blanks. Each look consisted of 15 "L" shapes (nontargets) and 1 "T" shape (target). Half of the items were colored red, the other half were colored blue, and the target was randomly colored either red or blue. The participant's task was to indicate the color of the T as rapidly as possible by pressing one of two keys. As illustrated in Fig. 1A, the location of all items in the display was fixed from look to look in this experiment, providing the best opportunity for making implicit predictions from look to look and, therefore, of recording the rapid resumption effect (Lleras et al., 2005).

In Experiment 2, four different groups of participants with age characteristics similar to those in Experiment 1 performed the same task with one critical exception. This time, the location of the target

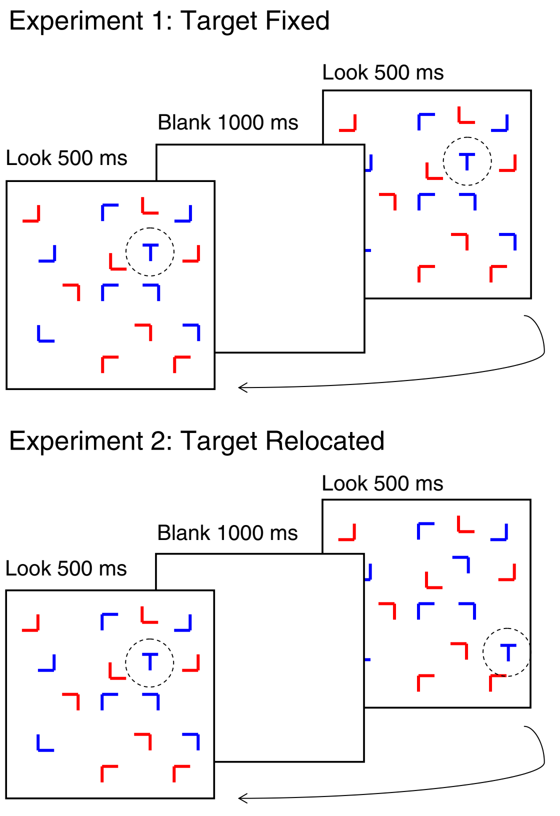

Fig. 1. Illustration of the interrupted search task in Experiment 1 (target fixed) and Experiment 2 (target relocated). Brief looks at a search display (500 ms) were interrupted by longer blanks (1000 ms) until the target color was identified (a blue T in these examples). The dashed circle around the target is shown here only for illustration purposes. (For interpretation of the reference to color in this figure legend, the reader is referred to the Web version of this article.)

moved randomly from look to look among the locations occupied by the same-color nontargets. Relocating the target from look to look sharply reduces the value of making implicit predictions from look to look and, therefore, is expected to reduce the degree of rapid resumption (Lleras et al., 2005, 2007). However, the primary question was whether this decrease would be the same for all participant groups, as is predicted if the implicit predictions generated during search are independent of feature integration and movement of the spotlight (Lleras & Enns, 2009), or whether it would be greater for the youngest participants who search least efficiently, as predicted by the view that rapid resumption does not index a separate operation of visual search ability.

The participants in both experiments were 18 second-graders (7–8 years of age, 11 boys and 7 girls, mean age [year;months] = 7;6, *SD* = 3.3 months), 20 fourth-graders (9–10 years of age, 16 boys and 4 girls, mean age = 9;7, *SD* = 3.7 months), 20 sixth-graders (11–12 years of age, 6 boys and 14 girls, mean age = 11;8, *SD* = 4.3 months), and 20 adults (8 men and 12 women, mean age = 19;8, *SD* = 5.4 months). Half of the participants in each age group were randomly assigned to Experiment 1, and the other half were assigned to Experiment 2. The children were recruited from public elementary schools in the Montreal area, and the adults were college students who participated for extra credit in a psychology course at the University of British Columbia. All of the participants were treated in accordance with American Psychological Association (APA) standards, with all children's parents providing prior written informed consent and children providing verbal assent. The adult participants provided written informed consent and debriefing in accordance with the behavioral research ethics board at the University of British Columbia.

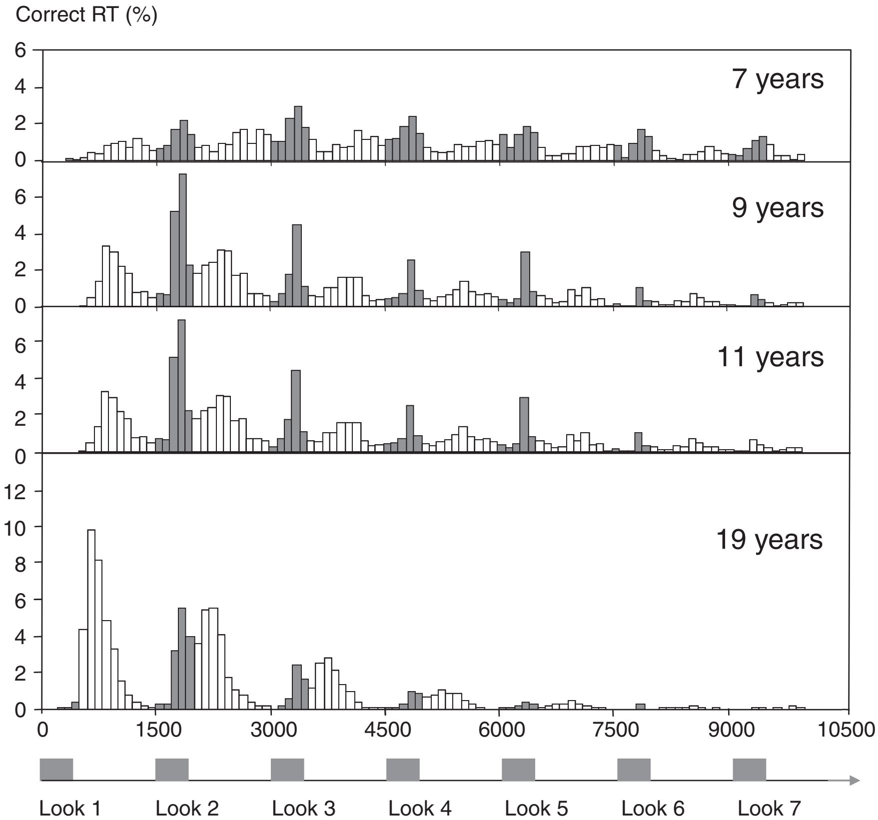

Fig. 2. Correct mean RT distributions in Experiment 1 (target fixed). The search display was alternately visible for 500 ms (looks) and blank for 1000 ms. Histograms shown in gray are all responses occurring between 0 and 500 ms following the onset of each look.

Experiment 1: searching for targets in a fixed location

Method

Displays and apparatus

A schematic of the display sequence is shown in Fig. 1. All of the experiments were generated using MATLAB and the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997). The experiments were controlled by 3.4-GHz Pentium IV PCs and were viewed on 17-inch NEC monitors (square viewing area $20.36 \times 20.36°$ of visual angle). The programs recorded and timed observers' key presses. The displays consisted of colored items (1 T and 15 Ls), which were either red or blue (presented as RGB color value [255 0 0] or [0 0 255], respectively) and were displayed on a white background. The items subtended $0.71 \times 0.71°$ at a viewing distance of 57 cm and were presented in one of four possible orientations (rotated 0, 90, 180, or 270°), with an equal number of red and blue items on every display. The colored items were assigned randomly to 36 locations within an invisible 6×6 grid, with each cell subtending $1.07 \times 1.07°$ and each item randomly jittered within a cell.

Task and design

Participants' task was to report the color of the T as rapidly and accurately as possible. Participants used the keyboard to report target color – the "z" key to indicate blue targets and the "/" key to indicate red targets. They were encouraged to respond as quickly as possible while maintaining a level of accuracy greater than 90%. Participants completed five blocks of 45 trials each for a total of 225 trials per participant per condition.

Procedure

The children were taken from their classrooms one at a time to a quiet room in the school where the task was administered. The adults were tested individually in a quiet office that was part of a laboratory suite. All of the participants were told that they were going to play a computer game involving shapes. The task was to search for the target T shape and to press the "z" key if it was blue or the "/" key if it was red. Each participant completed 15 practice trials that were not recorded prior to the first block of test trials and the instructions were repeated if necessary. Following completion, the children chose one of many small prizes (e.g., pencils, erasers, stickers) as a token of appreciation. The adults were given extra credit in a university psychology course.

Each trial began with a small fixation cross at the center of the screen. After 500 ms, the fixation cross disappeared and was replaced by the first search display for 500 ms (Look 1). A blank screen was then shown for 1000 ms before the search display reappeared (Look 2). We refer to the sequence of one look and one blank as an epoch with total duration of 1500 ms. Epochs were repeated 15 times or until a response was recorded, with no response being recorded as an error.

Results and discussion

The frequency of correct responses for seven epochs (each epoch includes a 500-ms look followed by a 1000-ms blank) can be seen in Fig. 2. The combined results of all the participants in a given age group are shown in a single panel. The few correct responses that were made after 10.5 s (<10%) are not shown. As in previous studies of interrupted search, very few correct responses were made in fewer than 500 ms following a first look. However, on the second and subsequent looks, there was a sizable proportion of rapid resumption responses (shaded in gray).

Two age-related findings are immediately apparent in Fig. 2. First, older participants correctly identified the target sooner than younger participants. Second, rapid resumption of search following an interruption is clearly evident in all age groups (responses shaded in gray). The correct mean RT and mean percentage error (PE) for each age group (closed symbols for Experiment 1) are displayed in Fig. 3. An analysis of variance (ANOVA) indicated a significant decrease in RT with age, $F(3, 35) = 21.08$, $p < .001$, $MSe = 853{,}060$, partial $\eta^2 = .644$, with each step between groups significant by a Fisher's LSD (least significant difference) test ($p < .05$). The same analysis of PE indicated no significant age differences, $F(3, 35) = 1.09$, $MSe = .003$, although there was a tendency for larger RT values to be associated with higher error rates, consistent with improved search ability in older participants, $r(2) = .372$. As such, these data suggest that the less efficient visual search abilities of younger participants are as much in evidence in an interrupted search task as they are in a standard search task where the displays remain on view until the target is found.

The second finding – a large proportion of rapid resumption responses following Look 2 in all age groups – is summarized in the left panel of Fig. 4 (black bars for Experiment 1). In this figure, the correct responses made in Epoch 2 and beyond were separated into three equal-length phases of 500 ms. Responses made during the first 500 ms are rapid resumption responses according to the operational definition we use. These can be compared directly in their frequency with the frequency of responses made during the second and third 500-ms phases of the epochs.

These three proportions were tabulated for each participant and submitted to an ANOVA examining the between-participant factor of age (7-, 9-, 11-, or 19-year-olds) and the repeated measures factor of phase (first, second, or third 500-ms period). There was a significant interaction of Age $\times$ Phase, $F(6, 70) = 7.36$, $p < .001$, $MSe = .030$, partial $\eta^2 = .387$, which was explored in greater detail for simple effects of age during each phase. These analyses indicated no significant difference with age during the first phase (Fig. 4, left panel), $F(3, 35) = 2.23$, $p < .11$, although if anything there was a tendency for the relative frequency of responses during this phase to *decrease* with age. Responses during the

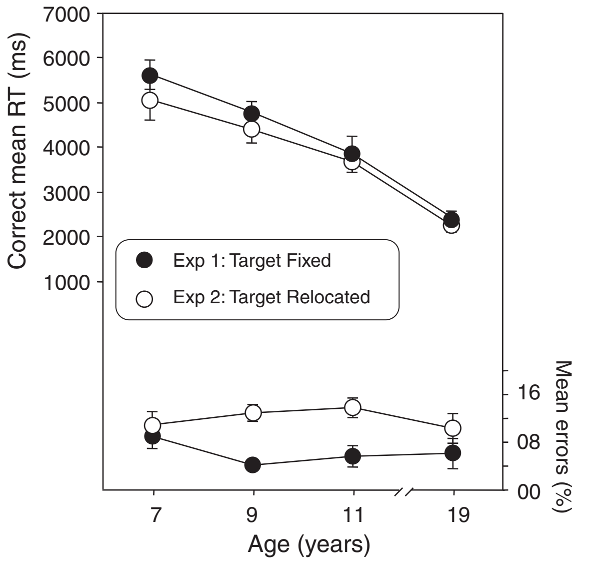

Fig. 3. Upper panel: Correct mean RTs and standard errors (in milliseconds). Lower panel: Mean PEs. Bars = 1 standard error. Closed black disks represent Experiment 1 (target fixed). Open circles represent Experiment 2 (target relocated).

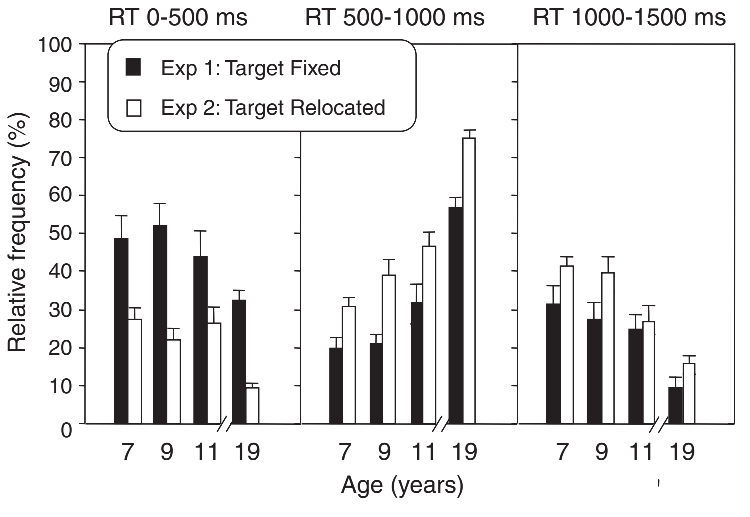

Fig. 4. Relative frequency of correct responses during three 500-ms phases following the second and subsequent looks at the search display. Rapid resumption is defined as a correct response occurring within the first 500 ms (left panel).

second phase (Fig. 4, middle panel) increased sharply with age, $F(3, 35) = 23.92$, $p < .001$, partial $\eta^2 = .672$, and responses during the third phase (Fig. 4, right panel) decreased with age, $F(3, 35) = 5.02$, $p < .01$, partial $\eta^2 = .301$. These data indicate that younger participants showed at least as much evidence of rapid resumption as older participants. However, beyond the first 500-ms period, older participants were generally able to respond earlier in the epoch than younger participants, as indicated by their greater proportion of responses during the second phase (Fig. 4, middle panel) than during the third phase (Fig. 4, right panel).

To examine the rapid resumption effect over a large range of individual differences in overall search time, we examined the correlation between mean successful search time and the proportion of rapid resumption responses over all 40 participants. This simple correlation was positive and significant, $r(37) = .51$, $p < .01$, implying that less efficient search (longer mean RT) is associated with a greater frequency of rapid resumption responses. However, this simple correlation does not take into account the ages of the participants, which also correlates strongly with search time, $r(37) = -.78$, $p < .01$ (older participants have a lower mean RT). When the partial correlation between rapid resumption and search time was examined with the variable of age held constant, any sign of a link between these two measures disappeared, partial $r(37) = -.01$, $p > .80$. In contrast, the partial correlation between age and search time (controlling for rapid resumption) remained strong, $r(37) = -.71$, $p < .001$, and the partial correlation between age and rapid resumption (controlling for search time) was slightly (but not significantly) negative, $r = -.16$, $p > .20$ (younger participants showed a trend toward *more* rapid resumption). Taken together, these results show rapid resumption to be independent of overall search time.

We believe that the tendency for younger participants to show a *larger* rapid resumption effect than older participants may be a measurement artifact. Specifically, younger participants generally responded to the target more slowly than older participants. As such, on a given trial, they generally recorded a greater number of looks before correctly identifying the target. Also, because they responded more slowly, younger participants were more likely than older participants to respond during the last 500-ms phase of any epoch, as indicated in Fig. 4 (right panel). Thus, if on this last epoch younger participants did not have sufficient time to complete their planned response, then it also follows that some of their responses would be made during the first 500 ms of the next look and be incorrectly counted as a rapid resumption response when in fact it was really a delayed response to the previous look. In sum, all of this may conspire to give younger participants greater opportunity than older participants for their responses to be incorrectly tabulated during the rapid resumption phase. An alternative to this possibility is that the 500-ms look period combined with the 1000-ms wait period may have been quite sufficient for even the youngest children to report any target-related information they discovered.

The next experiment was expected to be helpful in clarifying this issue because we expected the possibility of rapid resumption to decrease when the target was relocated from look to look, although the tendency for younger observers to have longer search times (and therefore to obtain a greater number of looks) would still exist as in Experiment 1. In other words, if participants had the opportunity to partially process a target at a specific location on look n yet failed to fully process it and respond to it, then this prediction about the target would likely be less helpful to them on look $n + 1$ given that on look $n + 1$ the target would now be in a new location. Thus, we anticipated a reduction in rapid resumption for all of the participants. If the hypothesis of age-invariant rapid resumption is correct, then we expected the reduction in the proportion of rapid resumption responses to be constant across age despite possible measurement error in the absolute number of responses that are assigned to the rapid resumption phase as opposed to the other phases.

Experiment 2: search for targets that are randomly relocated

Method

This experiment was identical to the previous one with two exceptions. First, a different set of 39 participants was tested after being selected at random from the same pool as in Experiment 1. Second, the location of the target moved randomly from look to look among the locations occupied by the same-color nontargets. Participants were told that the target would randomly appear in different locations from look to look.

Results

The frequency of correct responses for the first seven epochs is shown in Fig. 5. Again, the few correct responses that were made after 10.5 s (<10%) are not shown. Large age differences in correct mean

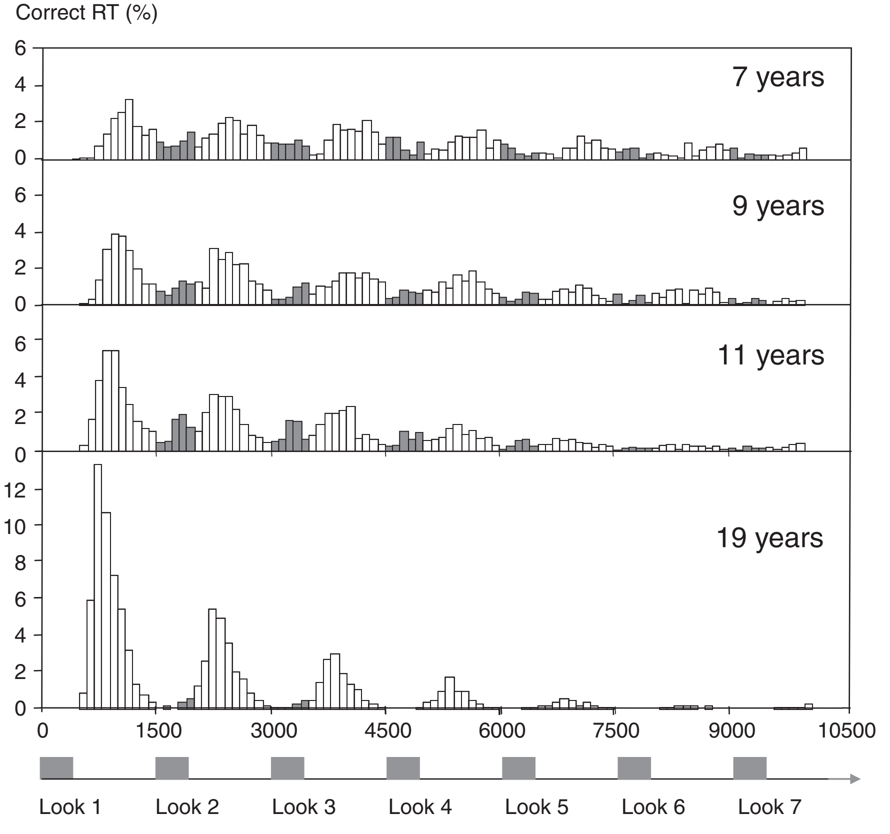

Fig. 5. Correct mean RT distributions in Experiment 2 (target relocated). Histograms shown in gray are all responses between 0 and 500 ms following the onset of each look.

RT are apparent, and these are summarized in Fig. 3 (open symbols). The main findings were that the participants in all of the age groups found the task to be somewhat more difficult, as indicated by a higher rate of errors, but that otherwise the older participants correctly identified the target sooner than the younger participants, consistent with Experiment 1.

These conclusions were supported by the following analyses. An ANOVA indicated a significant decrease in RT with age, $F(3, 35) = 16.20$, $p < .001$, $MSe = 852{,}056$, partial $\eta^2 = .581$, with each step between groups being significant by a Fisher's protected t test ($p < .05$). A comparison between experiments did not reveal any interaction, $F(3, 70) = 0.21$. The analysis of PE indicated no significant age differences, $F(3, 35) = 0.70$, $MSe = .004$, $MSe = 852{,}558$, although the comparison between experiments revealed significantly more errors overall when the target was relocated (Experiment 2) than when it was fixed (Experiment 1), $F(1, 70) = 18.31$, $p < .001$, $MSe = .004$, partial $\eta^2 = .206$.

A notable feature of this experiment (see Fig. 5) as compared with Experiment 1 (Fig. 2) is the reduced number of rapid resumption responses. This was an intended consequence of relocating the target from look to look in this experiment, and the effect for each age group can be seen in Fig. 4 (open symbols). The most important finding, in this context, is that the reduction in rapid resumption responses caused by target relocation (shown in Fig. 4, left panel) is roughly constant for all age groups (a reduction of ~20%). This means that even if aspects of this study's design led to inaccurate *absolute* estimates of the rapid resumption rate for a given age, the *relative* differences between the two experiments can be taken as an index of the influence of the one factor that differs between them, namely, whether the target had a fixed or uncertain location. Because all other aspects of the experiments were identical, this difference is not susceptible to errors in the absolute measurement of an effect.

This interpretation was supported by the following analyses. An ANOVA comparing the two experiments and four age groups during the first phase showed a significant decrease in responses in Experiment 2, $F(1, 70) = 50.84$, $p < .001$, $MSe = .019$, partial $\eta^2 = .421$, a decrease in response with age, $F(3, 70) = 6.55$, $p < .01$, $MSe = .190$, partial $\eta^2 = .219$, and (most important) no hint of an interaction of Age × Experiment, $F(3, 70) = 0.63$, $MSe = .190$.

The ANOVAs on the responses in the other two phases showed a similar independence between the factors of experiment and age. For example, target relocation resulted in a *greater* frequency of responding during the second phase (500–1000 ms), $F(1, 70) = 34.48$, $p < .001$, $MSe = .012$, partial $\eta^2 = .330$, an *increase* in these responses with age, $F(3, 70) = 52.07$, $p < .01$, $MSe = .120$, partial $\eta^2 = .691$, and no hint of an interaction, $F(3, 70) = 0.38$, $MSe = .120$. For the third phase (1000–1500 ms), the target relocation resulted in an *increased* frequency of responding, $F(1, 70) = 8.09$, $p < .001$, $MSe = .014$, partial $\eta^2 = .104$, a *decrease* in these responses with age, $F(3, 70) = 15.27$, $p < .01$, $MSe = .140$, partial $\eta^2 = .415$, and no hint of an interaction, $F(3, 70) = 0.73$, $MSe = .140$.

A final notable feature of the RT distributions from the two experiments (Figs. 2 and 5) is that a greater proportion of correct responses was made in Epoch 1 when the target was relocated on every look. On average, across all age groups, 18% of correct responses occurred in Epoch 1 when the target was fixed (Experiment 1), but 29% of the responses occurred in Epoch 1 when the target was relocated (Experiment 2), $F(1, 70) = 12.71$, $p < .001$, $MSe = .018$, partial $\eta^2 = .154$. Of course, the older participants also generally had more correct responses in Epoch 1 than the younger participants, ranging from a low of 13% for 9-year-olds to a high of 42% for 19-year-olds, $F(3, 70) = 18.68$, $p < .001$, $MSe = .018$, partial $\eta^2 = .444$. However, these two main effects did not interact significantly, $F(3, 70) = 0.95$, $MSe = .018$, indicating that this too was a feature of the target relocation experiment that was independent of overall search time. We interpret this to reflect a strategic decision on the part of all the participants to be more vigilant on the first look when targets are randomly relocated on subsequent looks because the random relocation of targets from look to look contributes to a frustrating search experience.

In contrast to the relationship between mean successful search time and the relative frequency of rapid resumption responses that was found in Experiment 1, only a small and nonsignificant positive simple correlation was found between search RT and rapid resumption, $r(37) = .18$, $p > .20$. The smaller correlation in this experiment likely reflects the reduced frequency of rapid resumption overall. The simple correlation between age and search RT was still strong, $r(37) = -.75$, $p < .001$. The partial correlation between search RT and rapid resumption (with age controlled) was near zero, $r(37) = -.04$, $p > .80$, although the partial correlation between age and search RT (with rapid resumption controlled) was still strong, $r(37) = -.74$, $p < .001$, and that between age and rapid resumption was again slightly negative, $r(37) = -.21$, $p > .20$, indicating that the younger participants again showed somewhat *more* rapid resumption.

In an attempt to address whether this nonsignificant trend was anything more than a measurement artifact, we reran the correlation analyses in Experiment 1 after controlling for the baseline levels of rapid resumption that were measured in Experiment 2, where the target was relocated on each look. Specifically, we computed an *adjusted rapid resumption* rate for each participant in Experiment 1, by subtracting from each participant's original measure an age-appropriate constant, defined as the group's average measure of rapid resumption in Experiment 2, where implicit predictions were unlikely by design. The partial correlation between age and rapid resumption was now $r(37) = .096$ (rather than $r(37) = -.16$). This confirms that there was no change with age in the rate of rapid resumption once baseline age differences in this measure were taken into account.

General discussion

The participants in this study, 7–19 years of age, performed an interrupted visual search task in which brief looks at the display (500 ms) were separated by longer waits (1000 ms). This type of search is not especially difficult, usually leading to successful target identification in three or four looks, but under these conditions it was characterized by a unique pattern of responding. Specifically, following the second, and subsequent, looks at the display, there was a volley of correct responses that occurred less than 500 ms following the reappearance of the display. This is striking because such rapid responses almost never occurred on seeing the display for the first time. Therefore, these rapid responses are (a) evidence of some form of memory being used to connect the information gained in separate glances, because they occurred only after the display had been seen at least once, and (b) evidence of a rapid interaction between memory and sensorimotor processes, because they occurred with such short latency on redisplay and were absent when an expected display failed to appear (Enns & Lleras, 2008). We refer to these rapid memory-guided sensorimotor interactions as *implicit perceptual predictions* because participants seem to be unaware of their existence (i.e., implicit) and because they involve an anticipatory use of the remembered information (i.e., predictive).

The question of interest in this study was whether young school-age children would show evidence of these implicit predictive processes. Perhaps rapid resumption reflects a sophisticated cognitive strategy that is acquired only with extensive experience. However, these processes were very much in evidence for all age groups tested; rapid resumption responses accounted for more than 40% of all responses for all three groups of children in Experiment 1, and they accounted for more than 20% of all responses for all three groups of children in Experiment 2.

Another primary question in this study was whether rapid resumption responses would increase with age. One reason to expect an increase is because school-aged children search less efficiently than young adults (i.e., are slower and less accurate). Thus, if rapid resumption reflects processes that are improving with age during the school years, we would expect increases here as well. Yet we hypothesized that rapid resumption would be present to the same degree in younger and older participants because we interpret rapid resumption to reflect implicit processes that are critical for perceptual awareness in general, not to the task of visual search in particular. Accordingly, rapid resumption should be unrelated to the processes of search that are known to change with age such as feature integration and control over the spatial spotlight of attention (Trick & Enns, 1998). This was confirmed given that we found no hint of rapid resumption increasing with age. This implies that children engage in implicit perceptual prediction to identify the target in an interrupted search task in essentially the same way as adults.

This interpretation was also supported by finer-grained analyses. The large range of individual differences in search time in this study allowed us to test whether participants who were skilled at search in general (i.e., those who were generally the fastest and most accurate) were also those with the largest number of rapid resumption responses. Correlational analyses confirmed that there was no hint of relationship between mean search time and rapid resumption after the effects of age were controlled (i.e., held statistically constant through an analysis of partial correlation). To be sure, age correlated positively with mean search time, and there was even a small tendency for age to correlate negatively with rapid resumption, but once age was controlled the partial correlation between search time and rapid resumption was effectively zero.

We interpret the small tendency for children to show an even *larger* rapid resumption effect than young adults in this study as a measurement artifact. Because the younger participants generally took longer to find and respond to the target, they also ended up viewing a greater number of displays on each trial. Furthermore, their increased response latencies may have caused a larger proportion of spillover responses than in older groups – responses based on information gathered on look n but that were not recorded until the beginning of look $n + 1$. Such delayed responses would end up being classified in our paradigm as rapid resumption, and more so for the relatively slower participants (i.e., the youngest ones) than for the faster participants (i.e., the older ones). Crucially, this bias is removed in a comparison of the two experiments, which differed only in whether the target remained in the same location (Experiment 1) or whether it was relocated from look to look (Experiment 2). This comparison indicated that target relocation resulted in an age-invariant reduction in the frequency of rapid resumption of approximately 20%. Given that the tendency to respond slower and have spillover responses miscoded was likely the same for the younger children across both experiments, the 20% reduction in rapid resumption responses in Experiment 2 is most likely related to a reduction in the use of predictions when targets moved from look to look compared with when they remained stationary (as in Experiment 1).

Relation to other developmental studies

As reviewed in the Introduction, there is an extensive literature documenting relative invariance during the school years in measures of implicit perception and cognition. Thus, the current results, showing similar levels of rapid resumption in children ranging over the elementary school years, are in keeping with previous findings of contextual cuing (Dixon et al., 2010), priming in object identification (Billingsley et al., 2002; Naito, 1990), the revelation effect (Guttentag & Dunn, 2002), and the perceptual interference effect (Bernstein et al., 2005), all showing that implicit perceptual processes are relatively intact in young children.

Moreover, these results help to narrow down the question of "what develops?" with regard to the large age changes seen in visual search over the lifespan. In particular, they suggest that the basic mechanisms of visual object identification (i.e., registering an object and associating it with a preexisting response in memory) do not change during the school-age period. This is in sharp contrast to two other critical aspects of successful visual search – feature integration and movement of the attentional spotlight – that do show large age changes over the same period (Trick & Enns, 1998).

Both of these components of a successful search are very likely tightly coupled to the control processes usually associated with conscious perception. Consider first feature integration. As measured in a typical visual search study, finding a target defined by both shape and color (e.g., the red square) involves forming a mental search template of the target and then moving the spotlight of attention around the items in the display until a match is found. Finding the match itself likely involves only confirming a perceptual hypothesis, something that searchers of all ages are very capable of doing. However, maintaining the correct template in mind and avoiding finding spurious matches among distractors that share only one feature (e.g., red circles or green squares) likely involves the conscious control of the contents of working memory (Baddeley, 2000). Similarly, controlling the movement of the attentional spotlight from one item to the next likely involves executive processes under conscious control (Baars, 2002) both to move from one item to another and to disengage from one distractor to test for a match in another. In support of this conjecture, dual task search studies with adults have reported that both the immediate contents of working memory (Downing, 2000) and task similarity (Oh & Kim, 2004) have a strong influence on the overall speed and accuracy of visual search.

It is also worth noting that the current findings inadvertently address a long-standing issue in the measurement of response time in children. Speeded responses of school-age children, in both simple detection and choice decision tasks, are invariably slower than adult responses by several hundred milliseconds (Plude et al., 1994). This is usually interpreted as reflecting slower decision and response processes rather than slower perceptual processing, but the evidence for this is circumstantial and indirect. Here children were able to make rapid resumption responses, which are correct responses in less than 500 ms from the onset of new information, at the same rate as adults. At face value, it implies that generally slower decision and response processes in children are not the whole story because even though a rapid response following a second or third look requires the same decision and motor processes as a response following a first look, our data show that young children can make these as rapidly as young adults.

The rapid responses of children, then, imply that the general slowness of their responses in other tasks may arise from the *initiation* of decision and response processes but not from their execution. In the current study, the slower initiation time of children was still in evidence on the many responses that were made 500 ms after any given look. As shown in Figs. 3 and 4, large age-related improvements in response speed were evident during this period, with the youngest participants making more responses during the 1000–1500-ms period than during the 500–1000-ms period and the older participants making most of their responses during the earlier 1000–1500-ms period. These are all responses that are likely initiated by the sensory evidence from a single look with no carryover from a previous look. As such, they provide the opportunity to observe the usual age-related speed-up in decision and response processes. In contrast to this, the relative proportion of responses during the 0–500-ms period is constant with age because the initiation of the correct decision and response is prepared during the 1000-ms blank period (wait) that occurs before the display reappears. This provides the opportunity for the next look to trigger the already-prepared response when the implicit perceptual prediction prepared from the previous look matches the sensory evidence in the current look (see Lleras et al., 2007, for additional evidence of response preparation based on implicit predictions in young adults). On this interpretation, the artificial delays imposed while performing an interrupted search provide an opportunity to measure response latencies that are very similar in the age range of 7–19 years.

Relation to other studies of rapid resumption

The current finding of age invariance in the rapid resumption effect contributes to the growing body of evidence that rapid resumption is reflective of a subset of perceptual processes that are implicit (i.e., largely encapsulated from conscious awareness) and dissociable from other processes crucial for visual search such as control over the spatial spotlight of attention and the difficulty of visual feature integration.

The uniqueness of the processes reflected in rapid resumption is evident in several ways. One sign in the original report of Lleras et al. (2005) was the finding that the rate of rapid resumption was unaffected by display size. Although a larger number of items in the display slowed search, it did not affect the relative proportion of early versus late responses (i.e., before or after 500 ms following a look). Lleras and colleagues commented that "when rapid resumption occurs, it is as if the target were the only item on the display" (p. 686). This is consistent with the independence of rapid resumption from the feature integration processes that are required to differentiate a target from the other non-target items. In a follow-up, Lleras and Enns (2009) found that both involuntary shifts of attention (manipulated by nonpredictive and sudden appearances of an object in the visual periphery) and voluntary shifts of attention (induced by making peripheral cues highly predictive of the target) were completely independent of the rapid resumption effect, although both of these cues had the expected effects of reducing the mean search time.

The current finding of age invariance in rapid resumption is, therefore, entirely consistent with these previous studies. One way in which the current findings contribute uniquely is that the comparison between the younger and older participants can be viewed as a natural experiment involving individual differences in the capacity of visual–spatial working memory, the capacity of executive control processes, the efficiency of feature integration, and the control over the spatial spotlight of attention. All of these abilities are well known for their substantial improvements in capacity and efficiency over the school-age years. As such, the current study is one of the strongest possible tests of the dissociation of rapid resumption from these other abilities.

At the same time, we note that there *are* important factors that influence the rate of rapid resumption, including a reduction in it when targets are relocated from look to look (Lleras et al., 2005; this study), a reduction when targets undergo a task-relevant feature change, but not a task-irrelevant change, from look to look (Lleras et al., 2007), a reduction when no implicit predictions are formed even though the target is presented to the center of gaze (van Zoest, Lleras, Kingstone, & Enns, 2007), and a reduction when the display is unlikely to reappear (Lleras et al., 2005). These boundary conditions, involving both environmental and strategic factors, highlight that rapid resumption is consequential in perceptual performance. Therefore, the current developmental evidence, together with the past evidence, is consistent in its support for the hypothesis that rapid resumption reflects the confirmation of an implicit perceptual prediction, a prediction formed on the basis of partial information obtained about a target in one look but awaiting sensory confirmation in the next. The crucial finding that rapid resumption can be observed in full force in young children confirms the primacy of this type of perceptual processing, which we believe is used in linking information from one glance of the world to the next.

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