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Priming of popout: III. A short-term implicit memory system beneficial for rapid target selection

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The priming of popout (PoP) (Maljkovic & Nakayama, 1994, 1996) increases the speed of attentional deployment to subsequent targets having the same feature characteristic and relative position, it lasts for approximately 5–8 trials, and is cumulative. Here we establish PoP as an example of short-term implicit memory by showing that it is qualitatively different from explicit memory. Using a post-cued recall procedure embedded in the stream of search task trials, we show that explicit memory is not selective as is PoP and is of much shorter duration. As such we argue that explicit memory is unlikely to account for the properties of PoP. In examining the decay of PoP, we find that: PoP is not evident after a 90sec delay, it does not show passive decay over much shorter intervals (1–3sec), and it gets decremented by attentional deployments to visually dissimilar stimuli, the size of the decrement being related to task difficulty. The results, taken together, suggest that PoP reflects a functionally beneficial memory system, specialized for the rapid and automatic selection of items for focal attention and saccadic eye movements.

One of the most exciting developments in memory research came about through the study of amnesic patients, when it was discovered that learning can occur without conscious awareness. For example, the famous amnesic patient HM first studied by Scoville and Milner (1957) is able to improve greatly in motor skills, yet has no recollection of ever practising them. The memory preserved in amnesic patients is not constrained to motor skills but extends to

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words and pictures (Warrington & Weiskrantz, 1968), suggesting the possibility that there exist two different neural substrates that may underlie functionally different memory systems—implicit and explicit.

While the dissociation between the two types of memory is most dramatic in amnesic patients, more recent work has documented the same kind of dichotomy in normal observers. In the latter population the signature of implicit memory is the lack of a conscious recollection of previous exposure to certain stimuli. This is typically shown by dividing a task into a study phase and a test phase. Implicit memory is indicated if observers are shown to prefer or respond faster or better to previously studied items without remembering them explicitly (Graf & Schacter, 1985; Schacter, Chiu, & Ochsner, 1993; Roediger & McDermott, 1993).

The various sorts of implicit memory revealed in this context have proven to be very durable, lasting for weeks or even years (Schacter et al., 1993). Little evidence has accumulated that there might be more transient implicit memory systems, analogous to better known short-term explicit memory systems with storage durations ranging from seconds to several minutes (Klatzky, 1975). Yet, this gap may be a simple accident of history. The rich harvest of implicit memory phenomena emerged in the context of amnesia research, where the very existence of durable memory served as a defining hallmark of implicit memory. Since amnesics are relatively unimpaired with short-term memory, there has been no opportunity to identify a deficit in short-term implicit memory within that context. Yet there remains the logical possibility that many forms of short-term implicit memory might exist, unsuspected and unforeseen, as was once the case for long-term implicit memory. More concretely, two recent candidates for this neglected category of memory have been identified.

Using a visual search task we have studied a phenomenon that we call the *priming of popout*—a speeded deployment of focal visual attention to repeated features and positions that lasts approximately 15–30sec (Maljkovic & Nakayama, 1994, 1996). With very different procedures, McKone (1995) has demonstrated a short-term memory system facilitating word recognition over a comparably short time scale. Given these two very disparate examples, we think it conceivable that many other forms of short-term implicit memory may be identified. In each case it will be of importance to review the criteria that suggest inclusion into this category of memory and see how well they are satisfied. In this paper we do this for the priming of popout (PoP), first addressing the question as to whether PoP is a case of implicit and not explicit memory and, second, determining whether it is indeed a form of short-term memory or alternatively an example of long-tem memory, perhaps under a different guise.

PoP occurs in visual search tasks where response is made to subtle shape differences in the "oddball" or popout target, tasks requiring that visual attention be spatially focused at the locus of the target site (see Bravo & Nakayama, 1992). Here repetition of the target and distractor features and repetition of the target and distractor positions influence the performance on the subsequent 5–8 trials (Maljkovic & Nakayama, 1994, 1996). The priming showed several characteristics that suggested it may be an example of implicit memory: (1) Memory is established for the feature and position which are responded to only indirectly; (2) there is no evidence of memory for the stimulus feature that one responds to directly (we find no priming for target shape, which requires the explicit response in the task); and (3) conscious effort on the part of observers does not influence their performance (for defining characteristics of implicit memory see Schacter, Bowers, & Booker, 1989).

Let us now briefly review the popout task that has revealed the phenomenon. Although popout occurs very rapidly and automatically in this task, it can be conceived of as having two separate steps—identifying the popout target by its odd feature (e.g., colour), then making a discrimination about its shape. Again, note that the subject's manual response is to the shape[1] of the target, not to the odd colour that elicits popout. Moreover, the popout colour and the shape are dissociated—from trial to trial target colour and target shape are unpredictable and vary independently. Target position is also independently chosen on each trial. It can fall on any of the twelve equidistant positions on an imaginary almost-circular ellipse (the two distractors are always equidistant from the target). Because colour and position vary randomly from trial to trial, subjects' performance cannot benefit from any form of explicit memory of past events because knowledge of preceding trials confers no predictive advantage. The possibility that explicit memory might be operative under conditions where it was specifically arranged to be advantageous was examined in two early experiments described by Maljkovic and Nakayama (1994). In Experiment 2 of that paper we varied the likelihood of a change in colour of target and distractors in each trial. If the observers' knowledge influenced the task, performance should have improved when the colours were more likely to alternate than to stay the same, because in this situation observers could have predicted, with differing degree of certainty, the upcoming trial colour. Contrary to this predictability hypothesis, the more likely was the switch in colour the more slowly observers responded. The most interesting case occurred when the colours alternated on every trial, a completely predictable situation. In this case all observers gave the slowest responses, suggesting that a passive priming of previous target colour could be responsible for the result, rather than the observers' explicit prior knowledge and expectancy of the upcoming colour.

In Experiment 4 of the same paper we reported results of a direct test of an observer's ability to influence PoP. We gave observers double-alternating colour sequences to examine repetition and alternation effects within a single experiment. From trial to trial the shape/response and position were again unpredictable, but the colour was completely determined. It was: red, red, green, green, red, red, and so on. Observers ran in two conditions. In the passive condition they listened to the music or chatted, which is the usual way observers perfumed this very easy task. In the active condition, observers were instructed to take advantage of the knowledge of the upcoming target colour. In order to do so they subvocalized the upcoming colour. We found no diminution in the priming effect when they attended to the upcoming colour suggesting that conscious knowledge does not influence priming.

These findings indicate that PoP is an automatic process, not influenced by our prior knowledge or volition. It would seem, therefore, that the carry-over from one successive trial to another would be mediated by implicit rather than explicit memory.

The second part of our claim about PoP is that it is an example of a *short-term* implicit memory. Indeed, we suggest that it is the rare combination of the two characteristics—the implicit nature *and* the brief duration of the memory trace—that makes this phenomenon distinctive.

The major issue to be resolved regarding duration is whether the memory trace dissipates only because of the reciprocal detrimental influence of numerous highly similar stimuli over the course of an experiment. We refer here to the effects known as proactive and retroactive inhibition (Baddeley, 1986), whereby a normally long-term memory trace decays because of an unnatural, highly repetitive, stimulus sequence used in experimental procedures.

Our early results on position priming in this paradigm showed that this is not likely to be the case. Increasing the number of possible target positions from two to six to twelve, thereby decreasing repetitions of same positions, did not increase the duration of priming as the inhibition hypothesis would predict (Maljkovic & Nakayama, 1996). In the present paper we address the issue of duration more directly. In Experiments 3, 4, and 5 we demonstrate that the priming of popout is indeed of brief duration, yet its decay is not likely to be the result of processes customarily thought to explain other forms of memory decay. Although memory does decay because of interference and not passively, this interference is not obviously related to a similarity between stimuli.

EXPERIMENT 1: IMPLICIT VERSUS EXPLICIT MEMORY FOR PAST TRIALS

In the first part of this paper (Experiments 1 and 2), we examine the implicit memory aspect of PoP. To strengthen the claim that PoP is an example of implicit memory it would be desirable to show that performances on the explicit and implicit versions of the task show qualitative differences (see also Merikle & Reingold, 1991; Schacter et al., 1989) and that explicit and implicit memory have different durations. In Experiment 1 we therefore test the explicit memory of observers in the same task in which we previously demonstrated priming.

In the implicit version of the task we analyse the effects induced by each of the 15 previous trials on the current trial. To do this, we categorize a given trial as same or different as that which appeared just prior to it, or two trials back, three trials back, etc. (the method, which we dubbed *memory kernel analysis*, is described in detail in Maljkovic & Nakayama, 1994). This analysis, however, cannot be used in studying explicit recall, because there is no obvious opportunity or method to get a read-out of explicit memory of previous colours and positions in a shape-discrimination task. What is needed is an experimental procedure whereby the explicit memory of all relevant dimensions of the previous trials can be measured. We used a method modelled on the partial report technique of Sperling (1960), periodically interrupting the experiment after a random number of trials (between 15 and 25), and asking the observer to tell us the values of just one variable (colour, position, shape/response) for the 10 previous trials. Random post-cueing of either colour, position, or shape was chosen to prevent the observer from adopting a strategy of learning a single variable, e.g., colour, by verbal encoding.

In order to make explicit recall even easier, we simplified the experiment by reducing the number of target positions from the usual 12 (on an imaginary clock face) to only two—left and right.

Method

Subjects. Authors KN and VM participated in this experiment.

Stimuli. The elements were red and green diamonds, each truncated on the right or left side. The single target was of one colour and the two distractors were of the other. The colours were close to equiluminant, chosen so that reaction time for each was comparable. The luminance for red was 1.98cd/m^2 and for green 2.08cd/m^2. The CIE coordinates were .612/351 for red, and .313/.553 for green. The background had a luminance of .07cd/m^2. Diamonds were approximately 1.0° × 1.0°, with either left or right .14° cut off. They were arranged on the ellipse with the major and the minor axes of 10.0° and 8.1° respectively. The white fixation point with the luminance of 13.2cd/m^2, and of .32° × 37° of visual angle always stayed on the screen. If an equilateral triangle were superimposed on this ellipse with its tip pointing downward, then the target could be either in the left or right upper corner, one distractor always at the other corner and the second distractor always at the bottom (see Figure 1).

Procedure. The fixation point was on at all times. The stimulus would appear on the screen, and the observer's task was to find the odd-coloured target and to indicate which side was truncated. The response was executed by pressing the corresponding (left or right) button of a two-button mouse. From trial to trial the colour, position, and shape of the target were chosen randomly and independently of each other. The stimulus stayed on the screen until the observer responded. The response was followed by a blank screen with the

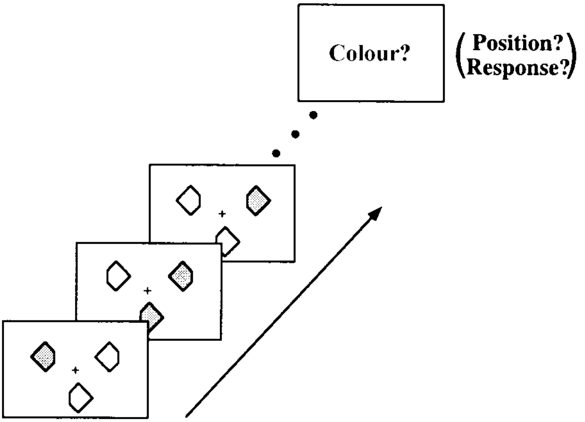

Figure 1. Schematic representation of the procedure described in Experiment 1. Task is to respond which side of the odd-coloured diamond is cut off. Target is either red or green, position left or right, and response left or right. All are chosen randomly from trial to trial. After 15–25 trials a name of a variable and question mark appear on the screen and the observer reports the value of that variable for the previous 10 trials.

fixation point presented for an interval of 2–2.5sec, after which a new stimulus was shown. Observers were instructed to fixate throughout the trial and to respond as fast as they could while trying to keep their error rate reasonably low. Every 15–25 trials the name of one variable appeared in the centre of the screen. This procedure is represented in Figure 1 (fixation frames are omitted). The observer would stop and report the value of the given variable on the trial just completed, then on the trial prior to that, etc. to the tenth trial in the past.

KN ran 14 blocks of 200 trials in three sessions, and VM ran 25 blocks of 200 trials in five sessions. (Note that only about half of the trials could be analysed because of the recall procedure used.)

Results and discussion

Whereas in previous experiments we measured reaction times to discriminate the shape of the odd target, here we examined the error rates for recall of attributes for previous trials in the past. Thus, we show the percentage error for the colour, position, and response on the first previous trial, second previous trial, and so on for ten trials in the past. Although reaction times from the implicit- and error rates from the explicit-memory task are not directly comparable, qualitative differences in the shapes of the curves are instructive (see Figure 2). On the X-axis is the past trial for which we are assessing explicit memory, and on the Y-axis is the percentage error. As observers could only have guessed a variable or missed it, the chance performance is 50%. This value is marked by the dotted line.

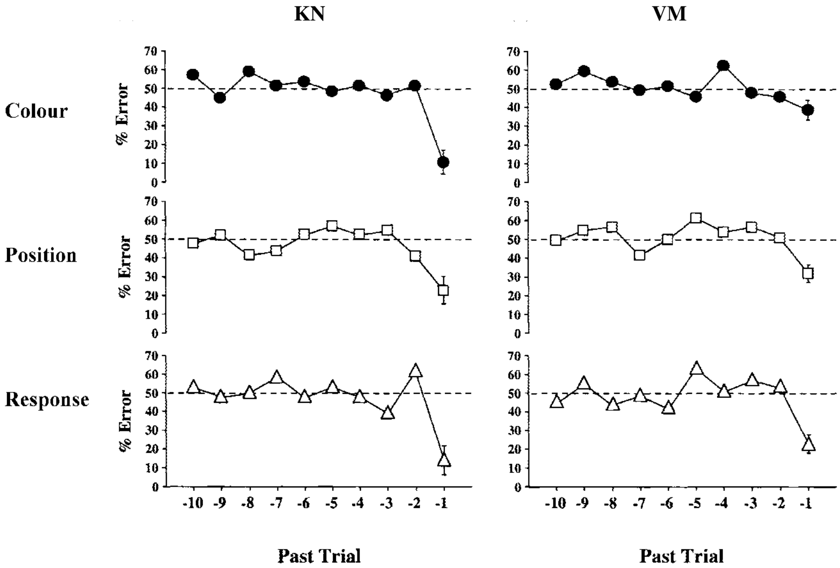

Figure 2. Experiment 1. Explicit memory for colour, position, and response for 10 trials in the past. Dotted line shows the chance performance level of 50%. Both observers show explicit memory for the first previous trial, but neither remembers what was presented on the second and earlier trials in the past.

In comparison to the hypothesized short-term implicit memory responsible for PoP, explicit memory for previous trials shows two very different characteristics: (1) Its duration is much shorter, evident only for one trial in this testing situation, and (2) it is indiscriminate. There is a comparable amount of explicit memory for *all* possible attributes of the previous trial, i.e., colour, position, and shape response.

For observer KN it was possible to make a direct comparison between explicit and implicit memory from the same set of data.[2] The results are shown in Figure 3. To obtain results for the implicit memory (right panel) we used the same memory kernel analysis described earlier (Maljkovic & Nakayama, 1994). On the present trial (trial *n*) the colour of target and distractors could be the same or switched as that on trial *i* in the past. We calculated reaction times for the same and switched cases for each of the 10 trials prior to the current trial.[3] We then subtracted reaction times of the "switched" trials from those of the "same" trials. The resulting curve shows the amount of priming, that is, how much faster the observer is when the colour of the current trial was the same (as opposed to different) as it was *i* trials in the past. In the left panel explicit memory data are shown as percentage correct. Note the two crucial differences between these sets of data, one regarding the duration of these two types of memory, the other regarding the variables that are remembered. The priming effect is replicated—strongest facilitation is exerted by the immediately

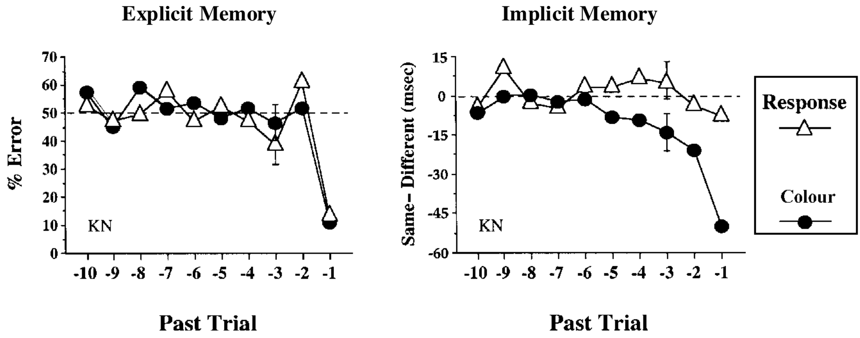

Figure 3. Experiment 1: Explicit and implicit memory results obtained from the same set of data of observer KN. Note the difference in patterns of data between the two panels. Explicit memory, expressed as percentage correct, is identical for colour and shape, present only for the first trial in the past, and non-existent for any prior. Implicit memory, measured as the reduction of RT to same colour in the past, shows a qualitatively different pattern. For shape it is non-existent, whereas for colour it is clearly evident and decays over approximately five trials.

preceding trial, then decays *gradually*, still evident for the fifth trial in the past. Explicit memory, in contrast, is evident only for the first previous trial. Also confirming our previous priming results, we see no evidence of implicit memory when the shape is repeated. Previous trial shape, however, is recalled explicitly just as accurately as the colour on the previous trial.

As such, these results show a clear dissociation between implicit and explicit memory in this visual search task. Implicit memory exists only for colour and position and not for the shape/response aspect of the target. Explicit memory exists for all three aspects—colour, position, and shape. Furthermore, implicit memory shows the greatest effect on the first subsequent trial and then decays gradually over the following 5–8 trials. Explicit memory is evident for only the immediately preceding trial.

EXPERIMENT 2: FURTHER EVIDENCE FOR A DISSOCIATION OF IMPLICIT AND EXPLICIT MEMORY

The dissociation between patterns of implicit and explicit memory across the same trials makes it improbable that priming results are due to intentional retrieval on the part of the observer. It is, however, possible that observers actually remember more than just three values at any one time (the immediately preceding colour, position, and response) but with verbal or written reporting of a long sequence the memory of anything prior to the first response may suffer from interference. In addition, although we have previously shown that one's knowledge or expectations do not influence the task, it may be of concern to some readers that the two authors participated in the first experiment. So in Experiment 2 we dealt with these two possible criticisms by: (1) Using a more restricted partial report procedure, and (2) testing three new subjects with no prior experience with the task. We required the explicit reporting of stimuli values for just the first or just the second trial prior to the current trial. At any given time, the observer was asked to recall a single value—either the colour, the position, or the shape/response of the target that appeared on the trial −1, *or* on the trial –2.

Method

Subjects. Observers AES, JJ, and NR, who had no prior experience with the task, participated in this experiment. They ran 1700–1800 trials, in sessions of 200 trials each, on three separate days over a period of three weeks.

Stimuli. The stimuli used were the same as in Experiment 1.

Procedure. The procedure was similar to that described in Experiment 1 with two exceptions: (1) The number of trials before the observer was asked for a report was 4–10 instead of the longer runs used in Experiment 1, and (2) in addition to asking for a report of a particular variable (colour, response, or position), the observer was also asked whether to report the immediately preceding trial (trial −1, *or* the second previous trial final –2, while ignoring trial −1).

Results and discussion

We report both the explicit memory error rates, and the implicit memory reaction times. Reaction times were analysed using the memory kernel analysis as in Experiment 1, but only for the two previous trials. Explicit memory data were analysed in the same way as in Experiment 1. In Figure 4 we present the results averaged across all three subjects.

In the left panel are the explicit memory data. The Y-axis shows percentage correct for each condition. Note that the percentage correct values decrease from the bottom to the top of the Y-axis. When plotted this way deviation below the chance baseline shows the amount of memory, and can be compared to the pattern of priming in implicit memory. Explicit memory is essentially identical for all three variables—colour, position, and shape/response. All are remembered with high accuracy if they came from the immediately preceding trial, and much worse, though still somewhat better than chance, from the second trial in the past. In the right panel are the reaction time data for implicit memory, plotted as the amount of facilitation for the repeated variable. The pattern is different. Same-colour and same-position responses show significant priming for both trials, with the usually observed, diminution of priming for the second

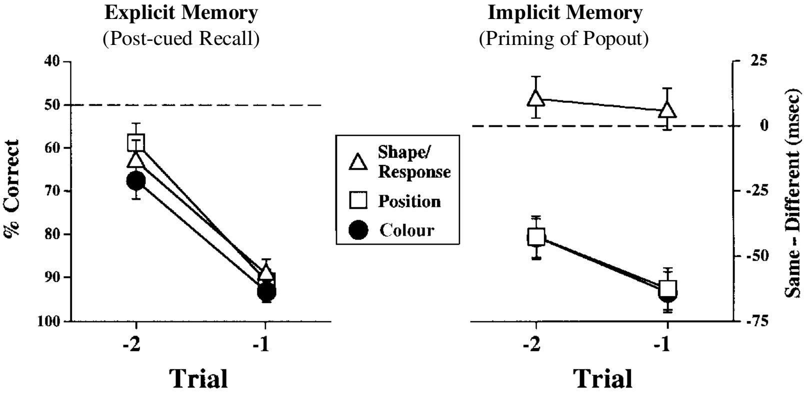

Figure 4. Experiment 2. Data from the post-cued recall of a single trial in the past (trial –1 or trial –2) are plotted in the left panel, and priming data for the same two trials in the right panel. Note the same trend as that seen in Figure 3. Explicit memory, excellent for all three variables from the immediately preceding trial, is almost gone for the second previous trial. In contrast, priming exists for both trials for colour and position, but, importantly, not for response.

trial. However, note a complete lack of priming for shape/response (open triangles), again as previously reported.

Thus, results from this experiment replicate the radically different implicit and explicit memory patterns obtained in Experiment 1. Although this experiment shows that there is some explicit memory for the second trial in the past, the shape/response data indicate that it is unlikely to be a source of PoP. If explicit memory had made a contribution, one would expect to see priming for shape/response and this did not happen. We suggest, therefore, that the PoP results are not accounted for by explicit memory contamination, and that the priming of popout is truly an example of implicit memory.

In sum, the results show a qualitative difference between PoP, our candidate for implicit memory, and explicit recall of previous events in a visual search task. As such, they provide new and independent evidence for a distinct implicit memory process.

PREVIEW OF EXPERIMENTS 3–5: SHORT-TERM NATURE AND DECAY OF PRIMING

The three experiments that follow address the second main issue of this paper: Is PoP a short-term memory phenomenon or is it perhaps a longer-term process, only seeming to decay quickly because of the specific methods used?

In Experiment 3 we provide an estimate of the duration of priming showing that PoP is evident after 30 but not after 90sec. In Experiment 4, we show that despite the short-tem nature of PoP, the decay is not passive. Over varying short inter-trial intervals (1, 2, 3sec), no difference in decrement is evident. This finding suggests that events in the form of further trials are needed to decrement PoP. In Experiment 5 we examine this interference hypothesis and show that there is a surprising lack of specificity regarding the events needed to decrement the memory. While the amount of decay is correlated with the difficulty of the interfering task, the stimuli need not be visually similar.

EXPERIMENT 3: TESTING LONGER INTERVALS REVEALS THE BRIEF DURATION OF IMPLICIT MEMORY

In the present and in previous papers, we have shown that the duration of PoP is short, lasting no more that 20–30sec (or about 8 trials spaced at approximately 3sec intervals). As such, PoP is very different from forms of implicit memory so far reported. Other researchers have found implicit memory effects that last weeks and even months (Mitchell & Brown, 1988; Parkin & Streete, 1988). The continuous sequence of trials which we have used cannot indicate how long the memory lasts without the potential effects of interference from subsequent trials. Clearly a more systematic examination of the duration of PoP would be useful to better support the notion of a distinctive short-term implicit memory phenomenon. For this purpose we looked for the possibility of a longer duration of PoP by taking advantage of the cumulative nature of the priming to maximize its strength. The basic experimental logic was as follows.

Observers were given two sequences of 14 same-colour trials, then the colour of target and distractors switched and the observer ran another two sequences of 14 same colour trials. In between each sequence a delay of either 30sec or 90sec was inserted. If the memory persists over this interval then the second sequence should start with much faster responses than the first; if the memory dissipates, responses in the second sequence should slow down to response times comparable to those of the first sequence.

Method

Subjects. Observers were the author KN, and two subjects with no experience with the task, SH and AG.

Stimuli. The elements were red and green diamonds (as described earlier) for observers SH and AG, and yellow-ochre and orange-ochre diamonds for observer KN (see Note 2). Orange yellow had a luminance of 8.17cd/m^2 and CIE coordinates .541/.411, and ochre-yellow had a luminance of 8.62cd/m^2 and CIE coordinates .484/453. In this experiment the target occupied one of the 12 positions on the ellipse (described in Experiment 1); the position of the target was chosen randomly from one trial to the next. The distractors were equidistant from each other and from the target.

Procedure. Observers were given a 14-trial sequence of e.g., red-target trials. As they finished, the timer was set for 30, or (in a separate session) for 90sec. When this interval was over the observer started another sequence of 14 red-target trials. After the delay the target was changed to green, and observers ran the first green-target sequence of 14 trials, and, again after the delay, the second green-target sequence (see Figure 5a). A single session consisted of eight pairs of sequences, 4 red and 4 green. Each sequence was preceded by two practice trials (not shown), for a total of 16 trials per sequence. All observers ran two sessions for each delay, giving us 48 trials for each data point.

Results and discussion

Mean reaction times were calculated for each trial of the first sequence and for each trial of the second sequence, and then combined over all observers. These data are shown in Figure 5b. Error rates are not shown, as they were below 5% for all conditions. Short sequences that we have used here are considerably noisier than sequences extracted from long runs of data. For this reason the data presented in Figure 5b have been smoothed with a 3-bin binomial function (the current point is weighted twice as much as the two surrounding points; the first and last points we weighted three times as much as the one adjacent point).

The two same-colour sequences are shown following each other; the X-axis shows the order of the trial within both sequences (1 through 28), and the grey area indicates the point at which a break of either 30 or 90sec was introduced.

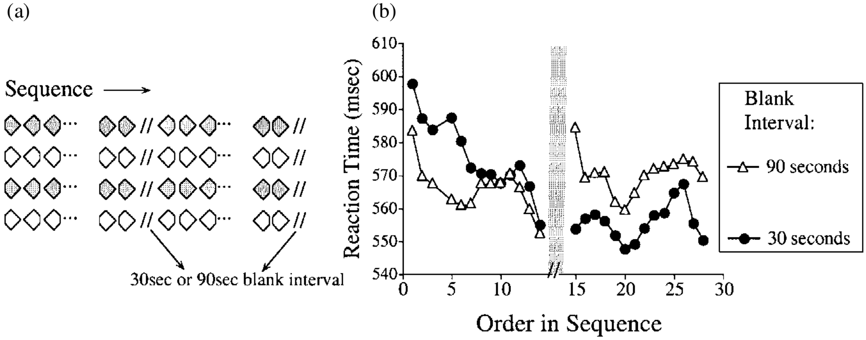

Figure 5. Experiment 3: Design of the experiment is shown in (a). Between each two same-colour trial runs either a 30 or a 90sec delay (marked "//") is inserted. Following another delay the colour is switched and the following two same-colour runs are presented. In (b) the data from two sequences are shown as following each other, the gray area marking the point of interpolated delay. After a 30sec break (filled circles) responding continues at the same fast rate, suggesting memory is present after this time. After a 90sec delay (open triangles), however, responding slows down, showing that the priming has decayed.

First, consider the case where the trial sequences were separated by 90sec (open triangles). The main result is that after a 90sec break, latencies rise to the initial level of the first sequence, indicating that the priming accumulated at the end of the first 14 trials has decayed completely. In contrast, if we look at the data with the 30sec break (filled circles), the break does not disrupt priming—responding continues with the same low reaction times reached by the end of the first sequence.

The data also show that initial responding is slower during the 30sec than during the 90sec sequence. This finding is again predicted by the preserved priming over the shorter and its loss over the longer break. When the interval between sequences is only 30sec, the first sequence (trials 1–14) occurs just 30sec after the second run of opposite colour targets and distractors. The residual effects from the previous opposite colour sequence act to slow down responding after the shorter, but not after the longer break.

These results show that the implicit memory we have described is indeed short-term. Even the maximally saturated colour memory, accumulated over 14 trials, does, not affect the sequence that follows only 90sec later.

EXPERIMENT 4: DECAY IS NOT LIKELY TO BE PASSIVE

In the previous experiment we have shown that there is essentially no sign of priming after a 90sec blank interval but strong evidence for it after a delay of 30sec. The presence of memory after a 30sec interval is to be contrasted with many of our previous studies where in a normal sequence of trials (approximately one every 3sec) priming has disappeared by 30sec. A major difference is that during the 30sec delay in Experiment 3 the observer was not required to perform any task; there were no intervening trials as there were in previous experiments. These two sets of results therefore argue against a passive time-dependent memory decay, and instead suggest that there might be a component of the memory that decays as a result of the occurrence of trials.

We test this suggestion by examining the amount of cumulative priming with different intertrial intervals (ITIs). In the case of shorter ITIs the same mount of priming would be added to a less decayed memory trace, leading rapidly to a substantially greater overall priming over the same number of trials. Longer intertrial intervals should therefore show less overall accumulated priming than shorter ones (see Figure 6a). Figure 6a schematically shows the theoretical amount of priming expected with a three-fold change in ITIs if priming decay were rapid, passive, and simply time dependent. It assumes that each trial produces the same amount of facilitation (plotted on the Y-axis) and decays with the same steep exponential function we have reported earlier (Maljkovic & Nakayama, 1994).

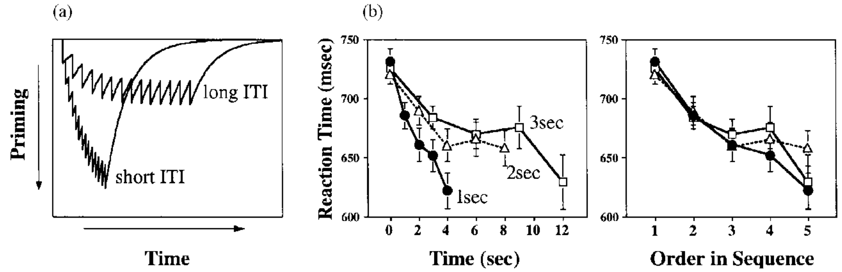

Figure 6. Experiment 4. Given that a single trial memory decays exponentially, (a) schematically represents the amount of accumulated priming in two conditions where the only difference is that their ITIs differ by a factor of three. With frequent trials (short ITIs), each subsequent priming "pulse" is added to a less decayed trace, resulting in a considerably larger priming effect after the same number of trials. In (b), we plot the data for chance repetitions of up to five same-colour trials for different ITIs. First, priming (reduction of RTs) is shown as a function of time; it clearly does not decay with time, as the overall amount of priming is similar. Plotting the same data as the function of trial repetitions shows that curves overlay one another. Thus, the decay of memory depends on the number of trials, not on time alone.

Moreover, with an exponential time-dependent decay, the greatest diminution of memory should take place immediately following a trial. Thus, the small changes in short ITIs should be much more revealing than the equivalent changes in long ITIs. We therefore used three brief ITIs in the current experiment: 1, 2, and 3sec. If decay is time-dependent these ITIs should lead to different amounts of accumulated printing. Conversely, if there is no difference between these conditions, we must seek an interference effect.

Method

Subjects. Author KN and the naive observer JC (a practised psychophysical observer who has never previously ran in this task) participated in the experiment.

Stimuli. The elements were red and green diamonds for observer JC, and orange-yellow and ochre-yellow diamonds for observer KN, all as described in Experiments 1 and 3. The target could appear in any of the 12 equidistant positions around the ellipse, as described in Experiment 3.

Procedure. The procedure was similar to that described in Experiment 1 (target colour, position, and shape varied unpredictably from one trial to the next), with two exceptions: (1) There were no interruptions in a trial sequence (explicit memory was not tested), and (2) intertrial interval was fixed at 1, 2, or 3sec per block of 100 trials. Both observers ran 200 trials in each condition in a counter balanced order.

Results and discussion

We again analysed the data, taking advantage of the cumulative nature of PoP. If the memory diminishes with time the overall cumulative effect should be greater for shorter than for longer ITIs, as shown in Figure 6a. That is, if we plotted responses by the order in which they occurred within a sequence, the curve for 1sec ITI should be the steepest, the one for 2sec less steep, and the one for the 3sec ITI should be the most shallow.

The averaged data are shown in Figure 6b. In both panels we plot reaction time means to same-colour repetitions. When the target colour of each upcoming trial is unpredictable, as in this experiment, same-colour sequences will occur by chance. Every time the target colour switches within a 100-trial block it is designated the first trial in sequence. If this trial is followed by the same-colour trial, this is the second trial in the sequence. The subsequent same-colour trial is the third trial in the sequence, and so on. The switch to the other colour brings us back to the first position. Since longer sequences are increasingly improbable and standard deviations consequently increasingly large, here we chose to present the means for the first five trials within a same-colour sequence. The first data panel plots reaction times as a function of the time elapsed since the beginning of the sequence. Contrary to the passive decay hypothesis, all three conditions show comparable amounts of accumulated printing at the end of the sequence. There is no evidence for less priming for the 3sec than for the 1sec interval. Thus, we cannot understand the maintenance of priming in terms of time alone. The right-hand panel shows the same data replotted as a function of the order in sequence of same-colour trials. The curves for all three ITIs overlap, showing that each repeated presentation reduces reaction times by a similar amount regardless of the time elapsed between trials.

It is therefore the sheer occurrence of the trial that determines the strength of the implicit memory, not the time elapsed between trials, at least for the intervals tested here.

EXPERIMENT 5: LACK OF STIMULUS SPECIFICITY IN CAUSING MEMORY DECAY

At first glance it may seem that the results of Experiments 3 and 4 are contradictory. In Experiment 3 we showed that priming decays with time, so that after a blank interval of 90sec it is largely gone. Yet Experiment 4 indicates that decay depends on the number of events, not on time. Over a three-fold range of short intervals (1 to 3sec) there is no appreciable decay. How can we explain this discrepancy? One obvious point is that the range of short intervals (1–3sec) used in Experiment 4 might be too short a time over which to see decay. Yet this explanation alone is not entirely satisfactory given the steep exponential decay of the priming function we have seen for colour (Maljkovic & Nakayama, 1994).

Perhaps a more likely explanation, and the one we will supply partial evidence for, rests on the possibility that during the longer intervals used in Experiment 3 (up to 90sec), the subject would be more prone to deploy attention inadvertently, say directing attention or making eye fixations to different parts of the screen during this period. If the deployment of attention by itself is sufficient to decrement the priming, then it is conceivable that this would be more likely to occur over a longer 90sec period than over a shorter 30sec period.

Although there is no way to chronicle such hypothesized intentional allocations over the longer time intervals of Experiment 3, we can begin to address this question by asking whether unrelated allocations of attention over the short intervals we usually employed might result in the decay of priming. To examine the effect of a distracting stimulus on the decay of colour priming, observers ran sequences of same-colour trials interleaved with trials comprising a visually different stimulus (see Figure 7a).

The distracting stimulus was a Gabor patch, a spatially localized black and white sine-wave grating of a particular spatial frequency. The task to be performed on this new stimulus was identical to the colour task in its attentional requirements. Observers detected the Gabor patch with the odd spatial frequency (the target), then responded to its shape—whether its top was shifted to the left or to the right (vernier acuity task). PoP is observed with these stimuli for repetition of both target feature (in this case spatial frequency) and position (Maljkovic & Nakayama, 1994, 1996).

If this distracting, visually different, stimulus causes colour memory to decay, then the cumulative priming of same-colour trials should be smaller than when no trials are inserted. If the distracting stimulus does not interfere with priming then we should see a cumulative effect very similar to that of a no-interference condition.

Method

Subjects. Author KN and a practised psychophysical observer FV, with no prior experience with the task, participated in the experiment.

Stimuli. Both observers saw two types of stimuli—Gabor patches and colour diamonds. The Gabor patches were of two spatial frequencies, 3.15 and 1.66 cycles per degree, with the target being always of one, and distractors, when present, of the other spatial frequency. The top half of each Gabor patch was offset by 0.09°. Red and green diamonds were used for both observers (as previously described). The target occupied one of 12 positions on the ellipse, as described in Experiment 3.

Procedure. Observers were given sequences of same-colour trials over which we measured cumulative priming. In all but the baseline condition, we

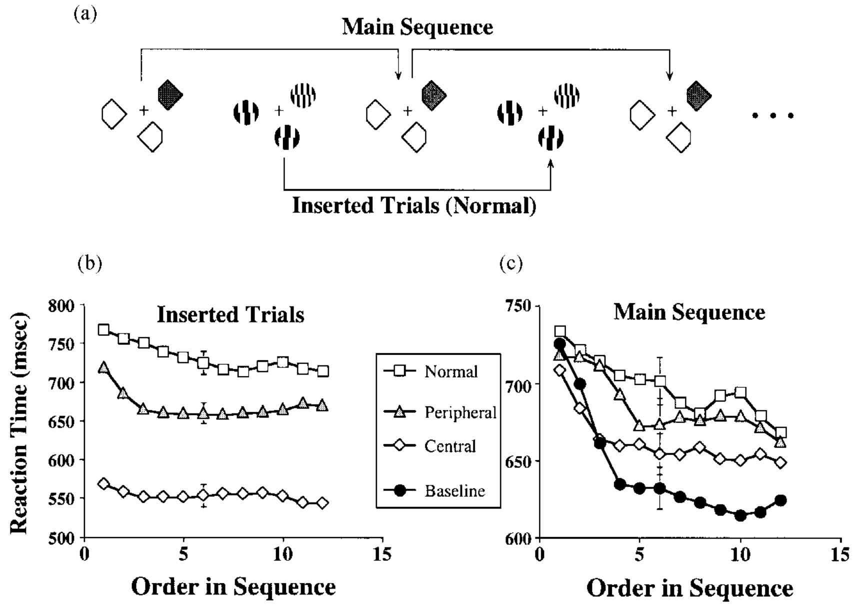

Figure 7. Experiment 5: (a) illustrates the design of the experiment. We always measured cumulative priming of the "main" (colour diamonds) sequence; different types of visually unrelated stimuli (comprising Gabor patches) were then inserted between each two trials of that sequence. In (c) filled circles ("baseline") show the amount of colour priming observed without any inserted elements. Open symbols represent the amount of colour priming ("main sequence" in the earlier schematic) when different configurations of Gabor-consisting trials where inserted. A "normal" inserted trials (open squares) had a target and two distractors, as shown in (a); a "peripheral" trial (grey triangles) contained only target but no distractors, and a "centre" trial (open diamonds) was only a target at fixation. (b) shows reaction times to the inserted elements themselves, the three types of stimuli clearly being very different in difficulty. Note that all types of inserted elements reduced colour priming, and that they do so depending on task difficulty.

inserted a stimulus from the spatial frequency variant of the task (always the same spatial frequency over a given sequence) between each two colour trials. The types of inserted stimuli can be divided into four categories: (1) *Baseline*—nothing was inserted between trials; (2) *normal stimulus*—target and two distractors were used; this condition is represented in Figure 7a, (3) *peripheral target*—a target but no distractors (a single Gabor patch in periphery), and (4) *central target*— a single Gabor patch, which replaced the fixation point during the trial. Each sequence began with two warm-up trials, which showed both stimuli that would be seen, followed by 12 trials over which we measured printing. Thus the duration of sequences was 14 trials for the baseline, and 26 trials for all other conditions. The four different conditions were interleaved, with the only restriction that the features switch from one sequence to the next in order to prevent floor effects with repeated exposure to same-feature trials. All combinations of spatial frequency and colour were used with both observers. We always used the same ITI in order to obtain comparable starting reaction times over the different conditions. We believe this did not affect our data—as we have shown earlier, there is no difference in memory decay with either a 1sec or a 3sec ITI. Both observers ran three sessions each, for a total of 24 trials per data point per observer.

Results and discussion

The goal of this experiment was to see whether unrelated allocations of attention to a distracting stimulus would lead to a decay of feature priming. All three manipulations interfered significantly with feature priming, as evidenced by less cumulative priming than that observed in the baseline condition.

Data for both observers showed the same pattern of results, and their average is shown in the graphs (statistical tests performed on each observer confirmed the aggregate findings). 3-bin binomial function was used for smoothing the data, and the results are shown in Figure 7.

In Figure 7b are reaction times for the three types of inserted trials. The interfering tasks might be considered as representing different levels of difficulty, as reflected in large differences in reaction times. A single element in periphery took more time to respond to than when it was in the centre and less than when it also had to be distinguished from distractors ("normal" condition). In addition, the "peripheral" and "normal" conditions show cumulative priming. The lack of priming in the "central" target condition might be the result of a floor effect.

Having noted these large differences in types of inserted tasks, now examine Figure 7c. Here the priming for colour is shown both for a sequence with no interference (filled circles), and for those in which interference was produced by each of the three previously described distracting stimuli (open symbols). Also remember that the inserted stimuli were always visually different from the colour stimuli (black-and-white spatial frequency patches versus colour diamonds). All three types of intervening trials produced a reduction of priming. Without interference (the baseline sequence) we observed typical cumulative priming over the first six trials, and a subsequent asymptotic performance. The interfering trials reduced this priming and they did so incrementally, according to task difficulty as reflected by the RTs for the interfering trials themselves (shown in Figure 7b). The "central" condition interfered the least, the "peripheral" somewhat more, and the "normal" stimulus interfered with the priming the most, as evidenced by the smallest accumulated priming in this condition.

It is therefore apparently not necessary that the interfering task be visually similar, but it is necessary that it be difficult, in order for it to interfere with the priming. We need to add a cautionary note here. All three interfering tasks required determination of the high-acuity aspect of the target, which in turn required focal attention. Had high-acuity not been necessary for response we may not have observed a decay. Although this is a possibility, we would suggest that priming might still taper off with a similar time course in normal viewing. First, while the range of interference tasks we used was not exhaustive, we believe the difference in difficulty between them is sufficient to suggest a range of difficulty in visual tasks encountered by viewers in daily life. Second, eye movements themselves require that focal attention be shifted to the goal of the next saccade (McPeek, Maljkovic, & Nakayama, 1999), which would also cause a reduction in priming. Thus, we suggest that priming of popout is indeed a memory lasting on the order of not more than minutes and propose that PoP is unlikely to be a long-tem learning effect as it is likely to be weakened with each new allocation of attention.

GENERAL DISCUSSION

PoP as short-term implicit memory

The principal goal of this paper was to more firmly establish that the priming of popout (PoP) is indeed an example of a new class of memory phenomena, short-tem implicit memory. The results were presented in two section: One to show that the memory is implicit; the other to more clearly establish its short-term nature.

The question regarding the implicit nature of PoP was addressed by comparing the specificity and time course of implicit and explicit memory in the same task, to deal specifically with the possibility that PoP might be mediated by some form of explicit memory. We had had reason to doubt this possibility because our previous work showed that neither increasing predictability nor complete explicit knowledge of upcoming trials had any effect on the strength of priming (Maljkovic & Nakayama, 1994). In the present paper we sought to show that the patterns of data for explicit and implicit memory are very different in two respects, thus fulfilling one of the major criteria for dissociating the two (Merikle & Reingold, 1991). We showed that: (1) Explicit memory was much shorter lasting than PoP; and (2) explicit memory was equally evident for all three aspects of a previous trial, position, shape, and feature (colour), whereas PoP occurs only for the colour and position but not the shape of the target. Both these findings reinforce the implicit nature of PoP established earlier and indicate that any explanation based on the contaminating effects of explicit memory is unlikely.

In the second section of the paper, we further considered the short-term aspect of the PoP. Specifically, we wanted to discover the upper limit of the duration of PoP, and also to explore the mechanisms of its decay. In Experiment 3 we established that after a blank interval of 90sec, PoP was not measurable, thereby providing additional, independent, support for our earlier conclusion that PoP was indeed a short-term memory phenomenon. Varying the intertrial interval produced no effect in the mount of priming accumulated over five trials (Experiment 4), suggesting that passive decay could not, by itself, explain the loss of priming seen in Experiment 3. We therefore subsequently examined the effects of interference on PoP (Experiment 5), and found that indeed, this is the likely cause of the decay of priming. Two facts seem particularly relevant for understanding the decay of priming. First, visually unrelated stimuli will cause interference (in our experiment responding to black and white Gabor patches caused the memory for colour to decay). Second, the amount of memory loss is correlated with the difficulty of the interpolated task, such that the easiest task caused the least and the most difficult the most interference.

In our previous work we have discussed distinctness of PoP as compared to other priming phenomena. Given that priming effects appear to be specific to a particular object (e.g., Park & Kanwisher, 1994), and that the greatest priming tends to be observed when visually identical stimuli are required (e.g., Roediger, 1990), it has been postulated that priming may serve to establish a representation of an object (e.g., Schacter, 1990). In our task, however, possibly due to different functional requirements discussed later, the attention-driving feature, not the object, is remembered.

The second distinguishing feature of the PoP is its duration. There are two other short-tem priming effects: Semantic priming and masked priming. Semantic priming, as assessed in lexical decision tasks, typically does not survive more than one intervening item (Neely, 1991), and when it persists for more than 1–2sec appears to be due to the perceptual part of the task, not its semantic component. PoP, as we have shown on several occasions, decays gradually over 5–8 trials. Masked priming, on the other hand, is both much shorter than PoP, decaying in less than 200msec, and a result not of two separate perceptual events but of a single event. The prime is presented briefly and immediately followed by the target so that the prime is not perceived separately (see Forster, Booker, Schacter, & Davis 1990).

We therefore believe that PoP, with its distinct characteristics, may reflect its different function, the subject we discuss next.

Possible functional role of PoP

Let us now think more broadly, and speculate as to the possible functions of such a memory system. Why would we have such a memory? Why would it have its particular temporal characteristics and stimulus specificity? Why should such a memory be implicit rather than explicit?

Our thinking is predicated on the working assumption that PoP is not simply a laboratory curiosity, but reflects the operation of one of the most important visual integrative systems that higher primates are likely to possess, the system for directing focal visual attention and guiding saccadic eye movements (see Fischer, 1987; Posner 1980). Recent studies in our laboratory (McPeek et al.

1999) provide independent support for this view. Using similar displays, we show that the execution of saccadic eye movements requires focal attention and that successive eye movement latencies to same-colour targets show a pattern identical to that of PoP. Thus, PoP characterizes, in part, a functional mechanism for a more efficient focusing and directing of attention and a more efficient execution of saccadic eye movements. Seen in this new context and thinking more broadly as to the nature of a visual cognitive system that could both direct and benefit from such shifts of attention and gaze, we outline later how PoP might play a specific and necessary role.

First, let us consider what has been thought, at least implicitly, about visual perception over the years, and contrast it with some rather surprising new findings which have emerged only very recently. Most investigators, particularly when thinking about the role of eye movements, have taken vision to be more or less a picture of the world, that eye movements were necessary to more effectively sample the picture at higher resolution (using the fovea) and perhaps with more salience. A somewhat different view emerged with the notion of pre-attentive vision (Julesz, 1984; Treisman & Gelade, 1980), arguing that there was a form of perception distributed over the whole visual field but occurring only at a primitive level, analysed for example by the feature detectors of early vision with no further processing. Although these notions were very different, each assumed some sort of limited vision simultaneously occurring over the visual field, to be enhanced selectively by attention and foveation.

Against this backdrop of thinking have come some startling findings that may constitute the beginnings of a significant paradigm shift. They suggest that visual perception is surprisingly tenuous, that we are visually aware only of what we are specifically interested in and attending to (Nakayama, 1990). O'Regan (1992), strongly echoing earlier thinking (Gibson, 1950; MacKay, 1973), argues that the world itself can be regarded as a memory, that vision at any given instant need not be rich at all, but could occur "just as needed", sampling the world via a very narrow bottleneck of attention. These ideas are strikingly confirmed in studies using natural scenes as stimuli. Here, large changes have been made during saccadic eye movements (Grimes, 1995; McConkie & Zola, 1979), in flickered scenes (Rensink et al., 1997), during sudden distractor appearances (O'Regan, Rensink, & Clark, 1999), and in movie cuts (Levin & Simons, 1997). Observers are astonishingly "blind" to some of the largest changes. Yet, if such changes are pointed out to them, they are so salient that it is almost unimaginable that they were invisible moments earlier. These findings demonstrate that visual attention is needed to be aware of scene elements and that without such attention we are essentially blind. "In attentional blindness" can also be seen in very impoverished laboratory displays, where observers without attention do not report the most salient stimulus in the scene (Mack & Rock, 1998; Mack, Tang, Tuma, & Khan, 1992).[4] Very recently it has also been shown that so called "pre-attentive" aspects perception actually require visual attention as well (Joseph, Chun, & Nakayama, 1997). Finally, in experiments recording eye movements during a visuo-motor task, Ballard, Hayhoe, Lizard, and Whitehead (1992) show that we seem to make an unusual number of eye movements to recently fixated portions of a scene. This constant need for "checking" suggests that at any given moment, our short-term visual memory is surprisingly limited.

Thus, visual attention plays a much more important role in perception than previously suspected. Rather than just modulating perception, it is its vital prerequisite. Conscious perception outside the confines of attention is almost nonexistent, and this invisible territory has become much larger. As such, the system responsible for the rapid shifts of attention and eye movements bears indeed a much greater burden than previously thought in maintaining our contact with the world. It is estimated that we make 2–4 saccadic eye movements every second of our waking lives and at least as many focal attentional deployments. As such, the system makes approximately 200,000 such shifts per day. (Contrast this with heartbeats, which occur at only half the rate.) Eye movements can have a voluntary quality, but most of the time we make them without notice. Yarbus (1967), for example, shows very different patterns of eye fixations over the same picture in response to alternative questions put to the observer regarding the scene. Thus, we have a curious combination of conscious and automatic control, with the bulk of eye movements conducted without any burdensome supervision.

Given these considerations, we believe that an implicit memory system for shifting attention and controlling eye movements could be extremely beneficial. Such an implicit yet primitive system can facilitate the return to recently attended targets and locations, thus filling the gap given by our lack of a conscious appreciation of the scene at any given moment. It could bias intentional shifts and eye movements without need for a supervisory control, and would ensure that objects of recent interest would be repeatedly sampled. Furthermore, the short-tem nature of the memory would make sure that the appropriate biasing would be up to date, tuned to the current objects of interest.

NOTES

(1) The effects of shape and response are confounded. As we were interested in the focusing of attention we purposely separated colour, which drives attention, from the shape, which requires attention. In the paper we therefore use terms shape and response intermittently or together.

(2) Extended and frequent practice on this task, running thousands of trials every week for several months or longer, reduces the amount of printing, at times even making it difficult to observe. This has happened to the author VM. Priming is easily re-established by reducing the colour difference between target and distractors, for example making them different hues of yellow. In this experiment, however, as we needed the verbal report of the target colour, we opted to use red and green because they we more easily distinguished and named. Consequently, the author VM could provide us with the explicit report, but there was no priming observed in her data.

On a more general note, it is possible that the reduction of priming after extensive practice is an effect of long-term learning. We have not explored this effect as only the author VM has had sufficient and frequent practice on the task that appears to be necessary for the result. Occasionally, however, we have taken advantage of the reduced colour difference condition in order to increase the priming signal and/or to avoid floor effects. Thus, the colour stimuli are at times red and green, and at times ochre−yellow and orange−yellow. The colour noted in every experiment, but it is not inherently relevant to the description of the priming.

(3) In all experiments values shown are means of reaction times for correct trials or percentage errors. Values that fell outside three standard deviations were excluded (about 1% of trials). Error bars represent standard error of the mean, and are means of all values unless otherwise noted.

(4) An alternative interpretation has been offered by Wolfe (1999) who interprets the lack of report of presented stimuli as a failure of short-term memory rather than perception. Since the report of something just perceived requires at least some form of short-term memory, Wolfe's provocative hypothesis remains as a logical possibility and one that at present cannot be distinguished from the account outlined earlier. Yet, in this context the consequences remain the same, namely that outside the domain of visual attention there exists no useful or available conscious perception when needed for some other purpose immediately thereafter. As such, we think it appropriate to retain the terminology used here.

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