

The Role of Prediction in Perception: Evidence From Interrupted Visual Search

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Recent studies of rapid resumption—an observer's ability to quickly resume a visual search after an interruption—suggest that predictions underlie visual perception. Previous studies showed that when the search display changes unpredictably after the interruption, rapid resumption disappears. This conclusion is at odds with our everyday experience, where the visual system seems to be quite efficient despite continuous changes of the visual scene; however, in the real world, changes can typically be anticipated based on previous knowledge. The present study aimed to evaluate whether changes to the visual display can be incorporated into the perceptual hypotheses, if observers are allowed to anticipate such changes. Results strongly suggest that an interrupted visual search can be rapidly resumed even when information in the display has changed after the interruption, so long as participants not only can anticipate them, but also are aware that such changes might occur.

Keywords: rapid resumption, prediction, perception, attention, visual search

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Prediction has an essential adaptive function, as it is fundamental to many high-level cognitive processes. Prediction is the basis for learning and decision making (e.g., Bayer & Glimcher, 2005; Schultz, 1998; Schultz, Dayan, & Montague, 1997); counterfactual thinking would be simply impossible without the ability to anticipate the consequences of one's own actions. Furthermore, prediction has been demonstrated to be important in language (e.g., Kamide, Altmann, & Haywood, 2003), time perception (Pariyadath & Eagleman, 2007), event comprehension (Zacks, Kurby,

Eisenberg, & Haroutunian, 2011), representing visual scenes (e.g., Enns & Lleras, 2008; Rao & Ballard, 1999), and more generally, in facilitating cognition (e.g., Kveraga, Ghuman, & Bar, 2007). The present study focuses on the role of prediction in visual perception. Specifically, we looked at the influence of goal-driven behavior on the early perceptual processes that underlie anticipation in a visual search task.

Both previous knowledge and the evaluation of the current situation contribute to the anticipation of future events. Consider the everyday task of crossing a street: the visual system integrates information about the cars' positions in different moments to create expectations about the future positions and coordinate the action of walking accordingly.

A simple mechanism involving prediction and confirmation is able to account for behavioral choices in humans (see Schultz et al., 1997). It has been suggested that prediction errors—deviations from the predicted outcome—are detected at lower-levels and integrated into higher-level mechanisms to guide complex behavior (Sutton & Barto, 1981; but see Bayer & Glimcher, 2005). Event Segmentation Theory (Zacks, 2004; Zacks, Speer, Swallow, Braver, & Reynolds, 2007), for instance, suggests that the mechanisms responsible for segmentation of events into meaningful units is based on the detection of prediction errors. Recent past and current information is combined into an *event model*, which guides predictions about what will happen next. The event comprehension system monitors errors in prediction. When these errors increase transiently a new event is detected; the model is discarded and replaced with a new one.

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A mechanism involving prediction and confirmation has also been suggested to underlie perception (Enns & Lleras, 2008), and has been formalized into models of visual awareness (Di Lollo, Enns, & Rensink, 2000; Enns & Lleras, 2008). Accordingly, perception is a two-stage process: hypothesis creation and confirmation. Hypotheses are created through feedforward connections, sent from the lower to the higher areas of the visual system; but only those that can be confirmed through a feedback signal, sent from the higher to the lower areas, result in perception. Hypotheses that fail to be confirmed are discarded and also fail to be consciously represented, triggering a new cycle of hypothesis creation and confirmation.

Convincing evidence for the existence of the hypothesis creation and confirmation cycle comes from the interrupted visual search task (Lleras, Rensink, & Enns, 2005; but see Enns & Lleras, 2008). The interrupted visual search task is very similar to a standard visual search, in which observers have to find, for example, a T-shaped stimulus (target) among L-shaped distractors (see Figure 1a). However, instead of giving the observer unlimited time to find

the target, the observer only gets brief 100 ms-long glimpses of the search scene, which alternate with blank displays that lasts 900 ms (or longer).¹ The key finding is that after an interruption, observers resume the visual search faster than they start a new one, giving correct responses as early as 200–300 ms when the display reappears after an interruption. According to the perception cycle hypothesis (Enns & Lleras, 2008), on the first glance, the target needs an entire cycle of hypothesis creation and confirmation to become available for explicit report. This two-stage process typically produces a unimodal reaction time (RT) distribution with a peak around 700 ms. If the observers fail to find the target after the first glance, they will need further glances at the display to find it. Thus, for all glances after the first one, the visual system is in one of two modes when the display reappears. A first possibility is that the visual system has no information about the target (no hypothesis about it has been created), in which case a hypothesis will need to be created and confirmed to elicit a response. If both of those processes can be completed before the next glance, then RT for those trials will look like RT on the first glance, with a peak around 700 ms. A second possibility is that when the display reappears, the visual system has already created a perceptual hypothesis of the target based on the previous glance. If that hypothesis is available, then it suffices to confirm it against the sensory input on the current glance, a much faster overall process. Lleras, Rensink, and Enns (2005, 2007) proposed that this type of trial is responsible for a second peak on the RT distribution, with latency between 200 ms and 300 ms. As a result, RT distributions in interrupted search tasks are usually bimodal: an initial fast peak (between 200 ms and 300 ms) indexing hypothesis-only confirmation in the current glance and a later peak (around 700 ms) indexing hypothesis creation and confirmation in the current glance. The appearance of the early, fast peak is a phenomenon that has been referred as to “rapid resumption” (Lleras, Rensink & Enns, 2005) and it has been taken as evidence that implicit memory is involved in visual search (Lleras et al., 2005). In fact, rapid resumption seems to occur because the visual system integrates memory for past events and the current information to engage in a predictive strategy, used to facilitate visual search. However, an alternative hypothesis has been suggested: that rapid resumption reflects merely a passive accumulation of sensory evidence. Van Zoest, Lleras, Kingstone, and Enns (2007) ruled out this possibility by showing that remembering previous displays is necessary for rapid resumption to occur. In fact, even if gaze distance from the target and the probability of giving a fast response are inversely correlated, simply landing a saccade on a nearby target’s location is not sufficient for rapid resumption to occur (Van Zoest Lleras, Kingstone, & Enns, 2007). In their Experiment 2, Van Zoest et al. (2007) used a gaze-contingent target presentation, in which the target was presented close to observers’ eye gaze after an interruption. The authors did not observe rapid resumption after a single contingent look. Instead, visual search was quickly resumed if the target was presented in the same location when the display reappeared one second later, suggesting that at least two successive presentations are needed for rapid resumption to occur. This result

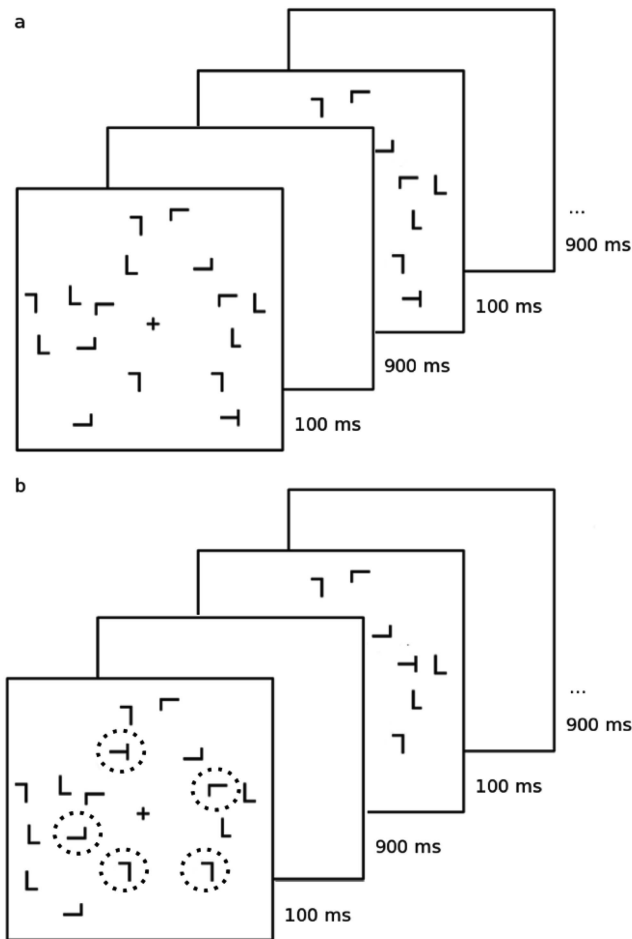


Figure 1. Schematic representation of the procedure. Across looks, target (“T”) appeared in either (a) one of the distractor locations and never moved or (b) one of the selected locations indicated by dashed circles (not displayed in the actual experimental display) and shifted among those locations, following the pattern described in the text.

¹ We will refer to the 100-ms display presentation as a glance or look and to the duration between one glance and the next as an epoch. Here, epochs last 1 s total.

is taken as evidence that rapid resumption does not depend on passive accumulation of evidence, but that memory of the previous display and integration of that information with the current display are necessary to guide perceptual processing. It is this integration of information gathered from a previous look (which produced a perceptual hypothesis) and information from the current look (which allows for the hypothesis to be confirmed) that allow visual search to be quickly resumed after an interruption.

Previous studies have shown that unexpected changes in the display can disrupt the rapid resumption phenomenon (e.g., Jungé, Brady, & Chun, 2009; Lleras, Rensink, & Enns, 2007). On the one hand, these findings confirm the existence of the perceptual cycle because they offer direct evidence that visual search is facilitated only when the perceptual hypotheses can be confirmed. Indeed, when the prediction cannot be confirmed—that is, when the ongoing stimulation changes before the hypothesis is confirmed—a new cycle is necessary to complete the visual search. On the other hand, they also reveal that perceptual hypotheses appear to be quite inflexible. Perhaps rapid resumption is more of an automatic stimulus-driven phenomenon, which is completed without much intervention from higher (more executive-level) cognitive functions. In fact, comparing the display's features before and after the interruption can be done without necessarily involving goal-oriented processes. Indeed, the role a person's goals and intentions on early attentional processes is still currently debated (see Lamy & Kristjánsson, 2013, for a recent review). One view suggests that both goal-driven and stimulus-driven factors contribute to guide visual search (e.g., Wolfe, Butcher, Lee, & Hyle, 2003) while the opposite view still argues that attentional selection is completely driven by external characteristics of the stimuli (e.g., Theeuwes, 2010). So it is still not clear whether goal-directed behavior can affect early attentional processes.

However, there are reasons to believe that the visual system is able to efficiently incorporate fast changes of the visual scenes to make predictions about future events. Most visual stimuli in real life do, indeed, move in space and time; yet, observers are usually able to quickly integrate information regarding past and present to infer something about the future. If the visual system were not able to incorporate rapid changes of the visual stimulus into goal-directed behavior, common daily tasks such as crossing the street would be impossible. Here we show that not only does rapid resumption rely on memory for previous displays, but that it also adapts to changes in the display, bringing new supporting evidence for goal-oriented modulation of early, attentional processes.

Therefore, the aim of this study was to test whether the perception cycle can incorporate predictable changes in a visual display. In Experiments 1a and 1b we manipulated the location of the target between looks at a visual search display—varying whether changes in location followed a predictable pattern—and we observed rapid resumption when predictable changes occurred. In Experiment 1c we found that constraining the target's path to a predictable sequence of locations did not further facilitate rapid resumption, suggesting that prediction is based on a coarse representation of the search display. Experiment 2 more closely compared the predictable and unpredictable changes within the same experiment and tested participants' knowledge of the target sequence change. Lastly,

Experiment 3 suggested that information sources other than location could guide prediction, by showing rapid resumption when the target's shape changed predictably.

Experiment 1: Changes of the Target's Location

Experiment 1a

Rapid resumption is disrupted or at least reduced when changes in the display occur between looks (Jungé et al., 2009; Lleras et al., 2005; Lleras et al., 2005). Lleras et al. (2005) first observed the disruption of rapid resumption after shuffling the identity (i.e., orientation) of all items in the display, during an interruption. Later, Lleras et al. (2007; Experiment 2) selectively shuffled the location of the distractors while leaving the target untouched, and observed a small reduction of rapid resumption. This result was confirmed in a separate study by Jungé, Brady, and Chun (2009), who also observed a significant reduction of fast RT after shuffling the locations of a subset of distractors between looks, but only when changes involved items located nearby the target.

Critically, in all these studies the display changes were unpredictable (Jungé et al., 2009; Lleras et al., 2005, 2007). In naturalistic settings many changes are predictable and entirely unpredictable changes may in fact be quite rare. Because of inertia, moving objects often change location and direction smoothly; this renders their changes in position predictable. For actions by humans and other intentional agents, constraints from goals render visual changes yet more predictable. It would therefore be sensible for the visual system to incorporate predictable changes into its perceptual hypotheses, taking advantage of the dynamics of the perceptual environment to guide perceptual processing. People's ability to integrate predictable changes into perceptual hypotheses and use them advantageously in a visual search task would support the idea that rapid resumption arises when observers are actively invested in an anticipatory strategy. Here we aim to evaluate whether prediction can be used to modify perceptual hypotheses in situations where the visual display changes between looks.

In Experiment 1a, the target changed locations between consecutive looks and could appear in a limited subset of locations. In order to enable observers to predict the forthcoming change, the target moved through a fixed sequence of five target locations throughout the trial and throughout the experiment. We compared this condition with a condition in which the target never moved from the location where it first appeared, which served as a baseline to evaluate rapid resumption. If observers can shape the ongoing perceptual hypotheses, rapid resumption should be preserved despite changes in the visual display as long as those changes are predictable. If the ability to anticipate forthcoming events is inflexible and only depends on low-level comparison between visual stimuli, we expect rapid resumption to be disrupted after a change in the display.

Method.

Participants. Seventeen volunteers ($M_{\text{age}} = 20.7$ years, $SD = 1.8$) participated in the experiment. All participants had normal or corrected-to-normal vision. They signed a consent form before the experiment and they were compensated \$8 or one psychology course credit for their participation.

Apparatus and stimuli. All stimuli (see Figure 1) were black and they were presented on white background, using a 21" color

CRT monitor running at 85 Hz. The experiment was programmed using Psychophysics Toolbox 2.54 (Brainard, 1997). Responses were gathered through a keyboard placed on a table in front of the participants. The target was a “T” and the distractors were “L” both occupying an area of $0.6^\circ \times 0.6^\circ$ of visual angle. The target could be tilted rightward or leftward; the distractors were displayed in all four possible orientations (rightward, leftward, upward, and downward).

The area was divided into 36 virtual locations of $2.3^\circ \times 2.3^\circ$ each. On each trial there was a target and 15 distractors scattered in an area of 15° visual angle, each randomly located in one of the 36 possible locations. A jitter ($\pm 1^\circ$ visual angle) was randomly added to each item to avoid collinear alignment.

Procedure. Participants sat on a comfortable chair in a dimly lighted, air-conditioned room. Head position was stabilized with a chin rest. Participants read the instructions as they appeared on the display and the experimenter answered questions as they arose. Participants were instructed to report the target orientation by pressing the right arrow if the “T” was tilted toward the right or the left arrow if the “T” was tilted leftward. Both speed and accuracy were emphasized in the instructions. After the instructions, participants were presented with a display showing the “T” oriented rightward and a second display showing the “T” oriented leftward. Each display disappeared only after the observer pressed the correct key on the keyboard.

Each trial started with the fixation point. After 2,500 ms the search display appeared for 100 ms; then, it was replaced by the blank to reappear after 900 ms. The search display/blank sequence was repeated up to 12 times while the observer produced a response.

There were two types of trials, which were intermixed: Change and No-Change trials. On Change trials, the target appeared in one of the five locations indicated by the dashed circles² (Figure 1b) and distractors occupied the remaining four chosen locations. The remaining 11 distractors were randomly placed in one of the other 31 possible locations (set size = 16). On any given Change trial, the target “moved” across successive glances, in a clockwise manner going from one of the five Change locations to the next, and replacing the distractor that had previously occupied that location (see Figure 2a). Once the target left a location, a new distractor replaced it at that location. This procedure was done to maintain the overall spatial context of the trial and avoid attention being drawn to locations either by the unexpected appearance or disappearance of an object (e.g., Theeuwes, 1991). In half of the trials the “T” was tilted rightward and in the other half of the trials the “T” was tilted leftward. Crucially, the “T” did not change orientation throughout the trial.

In the No-Change trials the target was randomly presented in one of the 31 remaining locations (indicated by the white squares in Figure 2), and during a trial, it always reappeared at the same location after each blank. To avoid contextual cueing³ (Chun, 2000), a distractor was placed in each of the five Change locations (gray squares in Figure 2) in the Change as well as in the No-Change trials; so that the subset of five locations selected for the target to Change was always occupied by one target and four distractors (Change trials) or five distractors (No-Change trials).

Participants completed 16 practice trials, in which only No-Change trials were presented, and then five experimental blocks of

80 trials each. They were instructed to take a small break between the blocks. The experiment lasted for about 40 min.

Results. Two participants were excluded from the analysis because of high error rates ($> 2 SD$ above the group mean). Trials in which the observer did not accurately report the target orientation (5.2%) and RT longer than 10,000 ms (4.1%) were considered as errors and excluded from the analysis.

Figure 3 shows the normalized distribution of correct responses for the first and the following epochs separately, across both types of trials. For the Change trials, the distribution of RT in the first epoch (following the first display presentation) was significantly different than the distribution following all the subsequent looks (Epochs 2–9), $\chi^2(9) = 328.05$, $p < .001$, Cramer’s $V = 0.35$ (comparison of RT distribution across 10 100-ms bins), as well as for the No-Change trials, $\chi^2(9) = 368.05$, $p < .001$, Cramer’s $V = 0.36$.

The observers’ response pattern during the first display presentation did not substantially change across the two types of trials, $\chi^2(9) = 6.99$, $p > .5$, Cramer’s $V = 0.07$. Nevertheless, response distributions after the second display presentation differed across trial type, $\chi^2(9) = 181.94$, $p < .001$, Cramer’s $V = 0.22$.

Fast RT were less frequent in the Change than in the No-Change trials, as revealed by the 2 (Epoch: First, Later) $\times$ 2 (Trial Type: Change, No-Change) ANOVA conducted on the proportion of RT faster than 500 ms.⁴ The ANOVA showed, as expected, an effect of epoch, $F(1, 14) = 138.12$, $p < .001$.

The proportion of fast RT in the first epoch ($M = 14.5$; $SE = 3.31$) was significantly lower than in the later epochs ($M = 53.6$; $SE = 2.44$). There was also an effect of Trial Type, $F(1, 14) = 8.78$, $p < .01$, with a larger proportion of fast RT in the No-Change ($M = 36.2$; $SE = 2.54$) than in the Change ($M = 31.9$; $SE = 2.43$) trials; but more important the interaction between trial type and epoch was significant, $F(1, 14) = 9.99$, $p < .01$. Post hoc tests of the means revealed larger proportion of fast RT in the No-Change than in the Change trials, but only in Epochs 2–9 ($p < .01$).

Discussion. The main result observed in the first experiment is that rapid resumption was preserved when the display changed between looks. There was the usual increase of fast (< 500 ms) correct responses observed in Epochs 2–9, and we observed the bimodal distribution that is typical of the rapid resumption phenomenon. This result indicates that changes to the search scene can be incorporated into the perceptual cycle to facilitate rapid vision. There was, however, one odd aspect to the results: whereas we observed an increase in fast responses in the No-Change condition (indicative of rapid resumption), the bimodal form of the RT distribution was not evident. This pattern of results is further discussed below.

² The dashed circles were not actually displayed during the experiment and are reported here in order to distinguish the Change location from the other locations.

³ Contextual cueing refers to the finding that visual search is facilitated in displays that were previously presented during the experiment. This finding also extends to small, repeated configurations of stimuli within a larger search array. Thus, we wanted to avoid the presence of items in the 5 Change locations to cue observers to the fact that the current trial contained a target within one of those 5 locations.

⁴ Such cut-off may seem arbitrary, but it has been previously shown to be a reliable indicator of the rapid resumption phenomenon (e.g., Jungé et al., 2009).

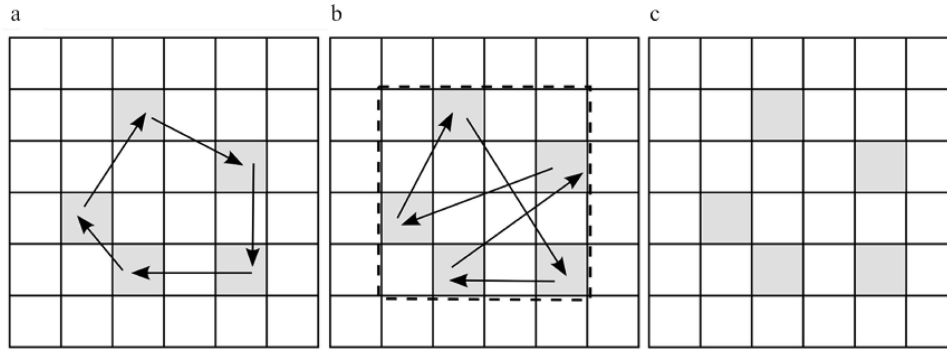


Figure 2. Simplified structure of the search display. The solid lines delineate the 36 possible locations for an item to occur. The gray squares indicate a selected location for the target to appear in the Change trials across the experiments. The arrows in the displays of (a) Experiment 1a; (b) Experiment 1b, indicate the location where the target would appear when presented in each of the five locations; and (c) Experiment 1c, the target could appear on any of the five locations on any given presentation, except that it was never presented on the same location for two subsequent looks. The dashed perimeter indicates the central locations (within 10° eccentricity) used in one of the analysis of Experiment 1b.

Previous studies failed to observe rapid resumption when the display changed between looks (Jungé et al., 2009; Lleras et al., 2005, 2007; Van Zoest et al., 2007). However, it has to be noted that in all those studies, changes of the display occurred unexpectedly, randomly and therefore, unpredictably. In sharp contrast, in this experiment changes were predictable. The target locations changed between looks, but it was limited to a subset of locations, therefore making the target's location easy to anticipate. Hence, preprocessing of the target could be combined with online predictions regarding possible future target locations to create a dynamic perceptual hypothesis.

In trials where the target's location did not change, the percentage of fast RT was higher than that of trials in which the target's location changed between display presentations.

Response patterns after the second and following looks also differed across the two types of trial. Visual inspection of the distributions of RT (see Figure 3) suggests that RT in the Change trials are bimodally distributed, and the distribution of RT in the No-Change trials is unusually broad and unimodal, a result that seems at odds with the results that are typically found in inter-

rupted search tasks. This result was surprising to us because the no-change condition was basically a replication of prior rapid resumption experiments (see Lleras et al., 2005), when no changes to the display are implemented. That said, the observation of a clear and significant proportion of fast RT (faster than 500 ms) in the No-Change condition is evidence that rapid resumption was at play. The fact that two peaks in the distribution were not easily identifiable implies that there was some temporal smearing in the location of the first peak that was likely caused by the presence of the intermixed Change trials. Difference in the salience between the two types of trials could explain this unexpected finding. Because the participants noted the target "moving" they might have been expecting a change of target's location on each single trial, especially when the target appeared within the range of the Change (moving) locations. This hypothesis was directly tested in Experiment 1b.

Finally, as expected, no significant difference was observed between the response patterns of Change and No-Change trials in the first look. This result is important because it argues against the possibility that differences in rapid resumption rates across the

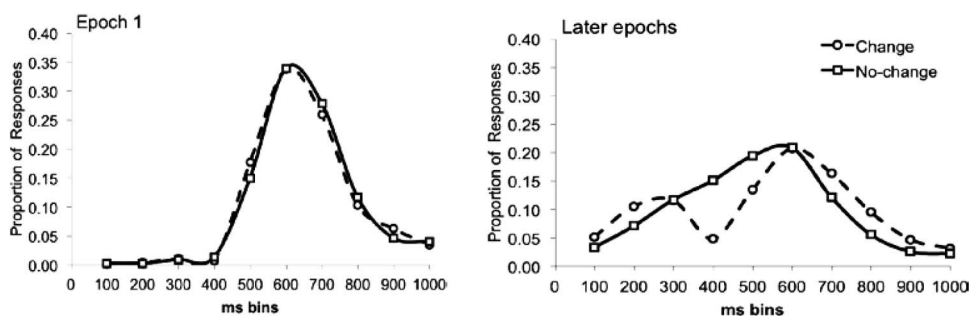


Figure 3. Normalized distribution of correct responses in Experiment 1a, where the target was presented in subsequent looks in a nearby location, following a circular pattern around the fixation point. The graph to the left shows the distribution of RT following the first display presentation and the graph to the right shows the distribution following all following looks (Epochs 2–9). The dashed line shows the distribution of RT in the Change trials and the solid line shows the distribution in the No-Change trials.

Change and No-Change displays were somehow due to incidental differences in difficulty between Change and No-Change displays. For example, one could argue that Change trials were easier than No-Change trials. It is the case that target locations in the Change condition were overall more eccentric than No-Change target locations (within 10° eccentricity). It is also possible that observers may have a central bias, or that monitoring five locations (as in the Change condition) was easier than monitoring 11 locations (as needed in the No-Change condition). However, the proportion of fast RT on No-Change trials was higher than on Change trials. If Change trials were easier, one would have expected the opposite result: a larger proportion of fast RT in the Change (easier) condition.

In sum, results obtained in this first experiment strongly support the idea that changes of the display can be included in the perceptual hypotheses, suggesting that prediction is involved in rapid resumption and, more in general in perception. Indeed, rapid resumption was not disrupted by changes in the display. Also, our results suggest that early, fast, nonconscious perceptual processes can be affected by high-level knowledge and goal-oriented strategies, actively updated on the basis of memory for previous visual events.

Experiment 1b

In Experiment 1a we showed that rapid resumption occurred even when the target's location changed from one look to the next. Thus, changes can be incorporated in the perceptual hypothesis. Furthermore, the previous experiment added evidence to the idea that rapid resumption is not the result of passive accumulation of evidence, confirming the role of prediction in rapid resumption. However, the pattern of locations (circular) chosen for the target to appear after each interruption was particularly noticeable and we wanted to confirm the results with a different pattern of displacement in the Change trials. Thus, we ran an experiment very similar to the previous one, with the only difference that the target displacement did not take place clockwise. Instead, the target reappeared in a nearby location, following a noncircular configuration (zig-zag). If the results obtained in Experiment 1a were not due to the specific pattern we chose for the target's location change, we expect to replicate them using a different target location's change configuration.

Another aim of Experiment 1b was to examine more closely the pattern of RT in the No-Change trials, which was unimodally distributed in Experiment 1a, contrary to what observed in previous studies that used comparable tasks (e.g., Lleras et al., 2005). One possibility is that observers virtually "divided" the visual display in two broad sectors: a more central one, in which the targets often moved, and a more peripheral one, in which targets never moved. It is likely in fact that the area surrounding the Change location was too broad (10° eccentricity) to allow a fine-grained spatial resolution, which included all the items' locations. Jungé et al. (2009) showed that only the area immediately close to the target has such a fine-grained spatial resolution, yet the areas distant from the target do not. They observed that, changing the locations of distractors close to the target interferes with rapid resumption, while changing the locations of distractors distant from the target does not. In our study, if a search strategy based on a fine-grained spatial resolution was not possible, a strategy based

on coarse subdivisions of the search display might have been more efficient. If details were not available, they could not obviously be anticipated to predicting forthcoming changes.

We hypothesized that the observer expected the target to move on each glimpse of the display, when the target appeared roughly in the area within the Change location eccentricity. If observers created a first perceptual hypothesis based on the prediction that the target's location was going to change, such a hypothesis cannot be confirmed if the target reappears in the same location after the interruption. Then, another hypothesis has to be created and confirmed, based on the prediction that the target is not going to move. According to previous studies (e.g., Van Zoest et al., 2007) we should observe the early phase of RT to arise only after the second look, that is, after the target appears in the same location twice.

To test this hypothesis, we compared the RT distributions in the No-Change trials after the first look with the RT distribution after the second and the third looks, considering only the location within the same eccentricity as the Change trials (10° visual angle).

Method.

Participants. Eleven volunteers ($M_{\text{age}} = 19.2$ years, $SD = 1.1$) with the same characteristics as the previous experiment participated in the study.

Stimuli and procedure. All stimuli and the procedure were identical to the previous experiment, except for the following. On each trial, when the search display reappeared after an interruption, the target was presented in one of the remaining four locations, following the pattern depicted in Figure 2b.

Results. Two participants were excluded from the analysis because of high error rates ($> 2 SD$ above the group mean). Trials in which the observer did not accurately report the target orientation (3.2%) and RT longer than 10,000 ms (3.5%) were considered as errors and excluded from the analysis.

Figure 4 shows the normalized distribution of RT for correct responses across both trial types for the first and following epochs separately. RT distributions changed from the first epoch to the later epochs; this was significant both in the Change trials, $\chi^2(9) = 175.92$, $p < .001$, Cramer's $V = 0.33$, as well as in the No-Change trials, $\chi^2(9) = 206.07$, $p < .001$. Also, the distribution of RT was different across the two types of trial, in both the first epoch, $\chi^2(9) = 20.81$, $p < .05$, Cramer's $V = 0.16$, and the later epochs, $\chi^2(9) = 90.94$, $p < .001$, Cramer's $V = 0.21$.

Again, we conducted a 2 (Epoch: First, Later) $\times$ 2 (Trial Type: Change, No-Change) ANOVA on the proportion of RT faster than 500 ms. The ANOVA revealed, as expected, an effect of epoch, $F(1, 8) = 96.77$, $p < .001$. The proportion of fast RT in the first epoch ($M = 16.9$; $SE = 4.36$) was significantly lower than in the later epochs ($M = 47.3$; $SE = 3.86$). The proportion of fast RT was higher in the Change trials, but the main effect of Trial Type did not reach statistical significance, $F(1, 8) = 4.11$, $p = .08$. More important, the interaction between epoch and trial type was significant, $F(1, 8) = 5.42$, $p < .05$. Post hoc tests of the means revealed a larger proportion of fast RT in the Change than in the No-Change trials, and such difference was observed only in the first epoch ($p < .05$).

Next, we looked at the normalized distribution of RT, excluding responses given for targets presented in the peripheral (more than 10° eccentricity) locations. Figure 5 shows the distribution of RT for target presented in the central locations (eccentricity within 10°; Figure 2b), after the first, second, and following looks sepa-

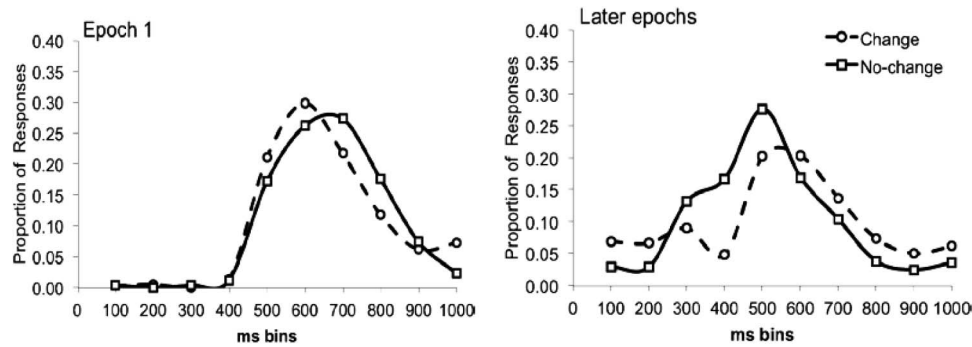


Figure 4. Normalized distribution of correct responses in Experiment 1b, where the target was presented in subsequent looks in a nearby location, following a zig-zag pattern. The graph to the left shows the distribution of RT following the first display presentation and the graph to the right shows the distribution following all following looks (Epochs 2–9). The dashed line shows the distribution of RT in the Change trials and the solid line shows the distribution in the No-Change trials.

ately. Results are summarized in Table 1. In the No-Change trials the distribution of RT in the first epoch differed from the second one ($p < .001$), but more important, the RT distribution of the second epoch differed from the third one ($p < .05$). As for the Change trials, the distribution of RT in the first epoch differed from that of the second and the third ($p < .001$), but the distribution of the second epoch did not differ from the third one ($p > .05$).

Discussion. The results of this second experiment replicated the finding that rapid resumption can be obtained after the changes of the target's location across looks. Thus, both experiments strongly support the idea a change can be incorporated in the perceptual hypotheses, if such change is in-line with the observer's expectations.

Both Experiment 1a and 1b also revealed an interesting, unexpected result. Contrary to the Change trials, when the target was presented in the same location after an interruption, the distribution of RT after the first epoch was unimodal. As mentioned earlier, this result was surprising because the bimodal distribution is typically observed in experiment using comparable conditions (e.g., Lleras et al., 2005). Also, contrary to Experiment 1a, during the first epoch the amount of fast RTs in the Change condition was larger than in the No-Change condition, confirming that observers might have been biased to attend to the central locations more than to the peripheral locations. However, it is worth noting here that neither the previous nor the following experiments replicated this pattern of results; in fact, except for Experiment 1b, the percentage of fast RT in the No-Change trials was always higher than in the Change trials.

To better understand these results, we looked at the distribution of RT in the No-Change trials, limiting the analysis to the responses given for targets presented within the same eccentricity as the Change trials—that is, within 10° from fixation. It is possible indeed that trials in which the target changed were more salient than those where the target did not change, encouraging observers to restrict their focus of attention on locations closer to the center and ignoring locations closer to the periphery. Results (see Figure 5) revealed that, after restricting the analysis to the central locations, rapid resumption occurred even when the target's location did not change across looks. Furthermore, the observer's distribu-

tion of RT after one glance was substantially different from the one obtained after both the second and the following glances. In the third epoch, the early peak of RT occurred earlier if compared with the second, and to the first. Moreover, the distribution of RT collected in the Epochs 3–9 was virtually identical between the Change and No-Change trials, suggesting the same response pattern in the two conditions, after the display was presented twice. This result is similar to the one reported in Van Zoest et al. (2007), in which rapid resumption was not observed until the target was presented twice in the same location.

In sum, the results of the Experiments 1a and 1b of the present study showed that the first, implicit stage of the perception cycle could be dynamically adapted to ongoing display's changes.

Experiment 1c

So far, we have seen that a goal-directed strategy could be used to facilitate visual search. An intriguing possibility is that predictable movement patterns allow the perceiver to anticipate the exact location of the target on the subsequent look, and participants used this fine-grained location information to improve search performance. Experiments 1a and 1b support the idea that observers use a predictive strategy to maximize the efficiency of perception, by showing that changed that can be anticipated preserve rapid resumption. However, they indirectly suggest the possibility that observers were not anticipating the exact location of the target on the subsequent look, but simply restricting the visual search to a subset of central locations after the second look (see Figure 5).

In Experiment 1c we wanted to look at the specific strategy used by participants for anticipating aspects of the visual display. It is possible that observers were able to memorize (explicitly or implicitly) the sequence of locations and to use such information to precisely predict the forthcoming target's location. This would reveal a fine-grained representation of a large portion of the visual display. However, it seems unlikely that viewers can create such a detailed representation of the scene after one glance. Furthermore, both theory (e.g., Di Lollo et al., 2000) and experimental evidence (e.g., Jungé et al., 2009) suggest that this might not be the case.

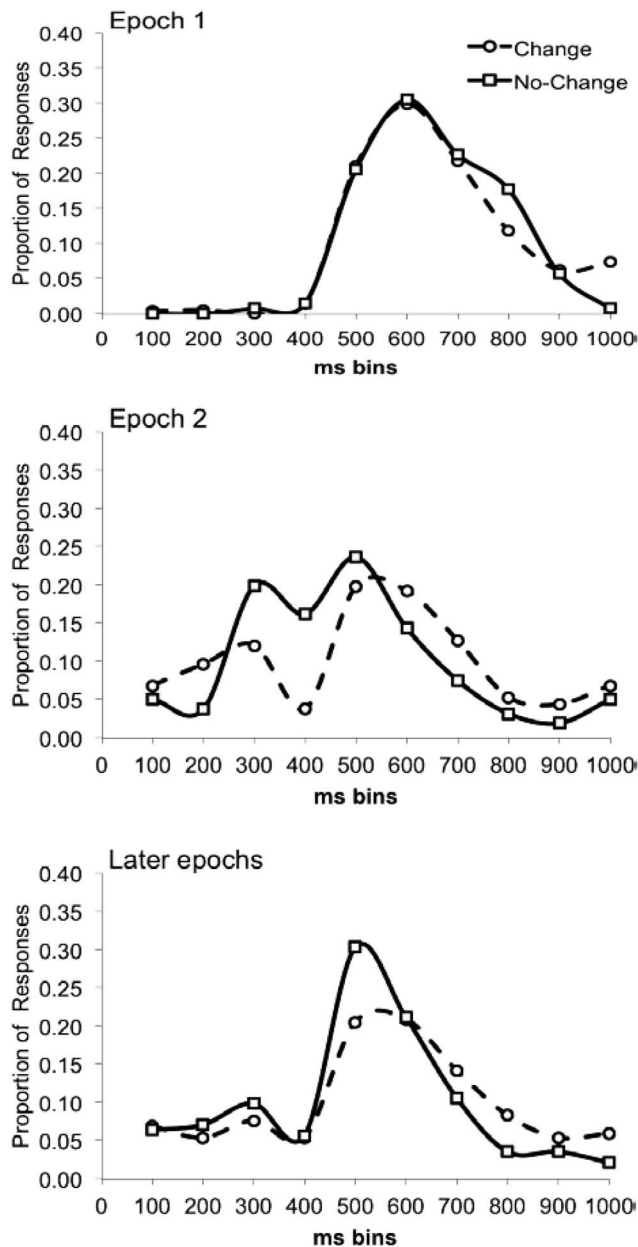


Figure 5. Normalized distribution of correct responses in Experiment 1b, considering only the central locations (10° eccentricity). The top panel represents the distribution of RT following the first display presentation, the middle panel represents the distribution after the second display presentation and the bottom panel represents the distribution following all following looks (Epochs 3–9). The dashed line shows the distribution of RT in the Change trials and the solid line shows the distribution in the No-Change trials.

Another possibility is that, after one glance, observers are able to create a coarse representation of the area where the target was most likely to appear, to subsequently restrict the search on the basis of some rough information about the display. To test this hypothesis, we conducted an experiment with the exact same design as in Experiment 1a and Experiment 1b,

with the only difference that, in the Change trials, after each interruption the target reappeared in a randomly selected location, instead of following a predetermined pattern.

If the ability to rapidly resume a visual search when changes occurred during an interruption depends on a detailed prediction of the forthcoming target's location, we expect rapid resumption to be disrupted—or at least decreased—if such location is not precisely predictable. If rapid resumption relies on a coarse representation of the target area, we expect it to be preserved, despite uncertainty regarding the forthcoming change.

Method.

Participants. Seventeen volunteers ($M_{\text{age}} = 19.2$ years, $SD = 1.1$), with the same characteristics as the previous experiment participated in the study.

Stimuli and procedure. All stimuli and the procedure were identical to the previous experiment, except for the following. On each trial, when the search display reappeared after an interruption in the Change trials, the target was presented in one of the remaining four locations, randomly selected from the subset depicted in Figure 2c. On each trial, the target had the same probability to appear in any of the five selected locations, except for the one where it was prior the interruption.

Results. One participant was excluded from the analysis because of the large error rate (> 2 SD above the group average). Trials in which the observer did not accurately report the target orientation (3.6%) and RT longer than 10,000 ms (1.7%) were considered as errors and excluded from the analysis.

Figure 6 shows the normalized distribution of RT for correct responses across both trial types. Observers responded in the first epoch significantly different from the later epochs in both the Change trials, $\chi^2(9) = 448.41$, $p < .001$, Cramer's $V = 0.39$, and the No-Change trials, $\chi^2(9) = 502.75$, $p < .001$, Cramer's $V = 0.40$. The distribution in the first epoch $\chi^2(6) = 2.72$, $p > .8$, was not different across type of trials. On the contrary, the distribution after the later epochs differed across trial types, $\chi^2(9) = 211.13$, $p < .001$, Cramer's $V = 0.22$.

The 2 (Epoch: First, Later) $\times$ 2 (Trial Type: Change, No-Change) ANOVA conducted on the proportion of RT faster than 500 ms revealed, again, an effect of epoch, $F(1, 15) = 302.94$, $p < .001$. The percentage of fast RT in the first epoch ($M = 18.8$; $SE = 2.19$) was significantly lower than that of the later epochs ($M = 55.62$; $SE = 1.63$). There was also an effect of the trial type, $F(1, 15) = 47.21$, $p < .001$, with a larger proportion of fast RT in the No-Change ($M = 42.65$; $SE = 2.04$) than in the Change ($M = 31.7$; $SE = 2.19$) trials; but more important the interaction was significant, $F(1, 15) = 50.42$, $p < .001$. Post hoc tests of the means revealed larger proportion of fast RT in the No-Change than in the Change trials, but only in the Epochs 2–9 ($p < .001$).

Discussion. The results of this experiment are straightforward: Rapid resumption was still observed even when precise information regarding the forthcoming target's location was not available. Observers seem to be able to create a coarse representation of the area surrounding the target and to use that information to make a probabilistic inference on the target's location, when such inference is needed. Such conclusion is in accordance with models of visual perception that hypothesize a feedforward first sweep of activation as responsible for the creation of a nondetailed representation of the visual scene (e.g., Enns & Lleras, 2008). It is also in line with previous studies showing that a detailed spatial rep-

Table 1
Summary of the Analysis in Experiment 1b (Zig-Zag), Comparing Across the First, Second, and Third Epochs in Both, Change, and No-Change Trials

Epochs	Trial Type						Third Epoch
	Change			No-Change			Change vs. No-Change
	First vs. second	First vs. third	Second vs. third	First vs. second	First vs. third	Second vs. third	
χ^2	188.92**	147.74**	16.49	100.22**	60.08**	20.86*	15.32
Cramer's V	0.45	0.34	0.13	0.58	0.47	0.26	0.13

* $p < .05$. ** $p < .001$.

resentation is restricted to the area closely surrounding the target (Jungé et al., 2009). However, this experiment does not exclude that a small, but reliable decrease of rapid resumption occurred in the previous experiments. As previously noted, it is difficult to compare different populations of subjects because rapid resumption varies substantially across observers (see Jungé et al., 2009). We thus ran another experiment, to evaluate whether rapid resumption decreased after introducing uncertainty regarding the possible target's location after each interruption.

Experiment 2: Implicit Sequence Learning

Experiment 1b revealed that observers roughly divided the search display in two regions: central and peripheral. It seemed like if each time the target appeared in the most central area, observers expected it to appear in a different location after an interruption. This result suggests that observers were able to integrate this prediction into early stages of the visual search. A core assumption of the perception cycle hypothesis (Enns & Lleras, 2008) is the implicit nature of predictions. It is generally accepted that perceptual hypotheses are created through the first feedforward sweep of neural activity, triggered by the stimulus onset at an implicit level and therefore, outside of awareness (e.g., Enns & Lleras, 2008; Jungé et al., 2009; Lleras, Rensink & Enns, 2007). There are two possibilities. First, it is possible that observers created an implicit attentional setting, which drove their attention, consequently facilitating the resumption of previously interrupted

visual search. That contingencies between cues and targets can be learned implicitly has been demonstrated in other visual domains (e.g., Lambert, Naikar, McLachlan, & Aitken, 1999). Alternatively, it is possible that participants in our Experiment 1 developed an explicit strategy, based upon the trials in which they happened to see the target in two or more consecutive glimpses. The interrupted search task fails to distinguish between these two possibilities, even in the original study (Lleras et al., 2005)—where the search display remained untouched between two subsequent looks. In Lleras et al. (2005), observers most likely assumed that the display remained unchanged across looks, even in the implausible circumstance that they never noticed the target in two subsequent presentations. Thus, implicit perceptual hypotheses in rapid resumption could be the result of explicit conjectures about the visual display. In support of this possibility we observed that, in a postexperimental questionnaire, all the participants reported that they had noticed some changes of the display occurring in some of the trials. Thus, observers may have developed an explicit strategy based on their beliefs about the target's locations, to facilitate visual search.

Can rapid resumption be observed when the forthcoming change is not explicitly known? To evaluate this possibility, we conducted an experiment using the same locations as Experiment 1b (Figure 2b) and intermixing trials with predictable and unpredictable changes into the experiment. The procedure was intended to discourage participants from using explicit visual search strategies,

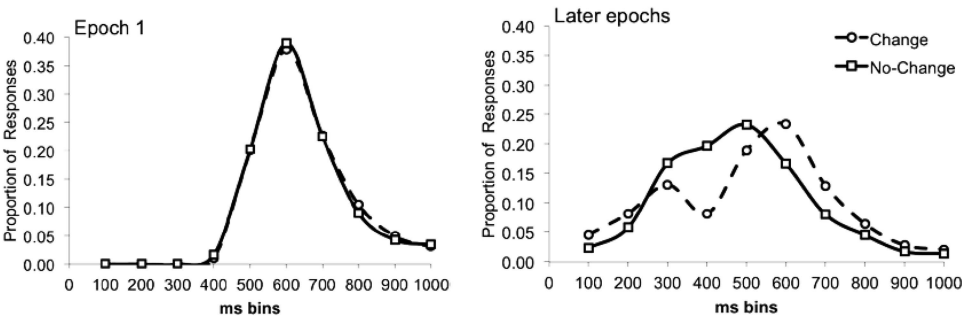


Figure 6. Normalized distribution of correct responses in Experiment 1c, where the target was randomly presented in subsequent looks in one of the remaining Change location, so that on each look the possibility for the target to appear in each of those locations was one out of four. The graph to the left shows the distribution of RT following the first display presentation and the graph to the right shows the distribution following all following looks (Epochs 2–9). The dashed line shows the distribution of RT in the Change trials and the solid line shows the distribution in the No-Change trials.

such that even if observers were aware of display's changes, they remained unaware that some of the changes followed a repetitive structure. In addition, the procedure allowed us to closely compare predictable and unpredictable trials within the same experiment, to evaluate whether introducing uncertainty regarding the possible target's location after each interruption reduced the amount of rapid resumption.

Hence, Experiment 2 aimed to evaluate the possibility that implicit sequence learning can facilitate an interrupted visual search, even if the observer is not engaged in an active search strategy.

Method

Participants.

Seventeen volunteers ($M_{\text{age}} = 19.2$ years, $SD = 1.1$), with the same characteristics as the previous experiment participated in the study. Procedure.

The stimuli were identical to those of the previous experiments. The procedure was very similar to the previous experiment with the only exception that there were three types of trial, which were intermixed: 50% (160) were No-Change, 25% (80) were Predictable Change, and 25% (80) were Unpredictable Change trials. Predictable Change trials were identical to Change trials in the in Experiment 1b (Figure 2b). Unpredictable Change trials were identical to Change trials in the in Experiment 1c (Figure 2c). In addition, immediately after the task, observers were presented with a postexperimental questionnaire containing four questions, in which they were asked: (a) whether the target moved between looks, and (b) whether the target location sequence was random. Then, two target's sequences were presented. The target appeared for 500 ms on each of five locations, which could be (a) randomly selected or (b) the same used in the Predictable Change trials.⁵ The target was the only item in the display and the order in which the two sequences were presented was counterbalanced between subjects. After watching both sequences the observers were asked two more questions: (c) which of the two sequences was used during the experiment, and (d) to indicate their confidence on a 5-point Likert-type scale (ranging from *not confident at all* to *extremely confident*). The answers were used to assess the participants' knowledge regarding the target's locations sequence.

Results

Two participants were excluded from the analysis because of high error rates. Trials in which the observer did not accurately report the target orientation (12.3%) and RT longer than 10,000 ms (2.1%) were considered errors and excluded from the analysis.

Results obtained from the postexperimental questionnaire indicated that eight out of 15 observers correctly recognized the sequence used in the experiment. A binomial test revealed that this percentage was not higher than expected by chance ($p = 1.0$). Except for one (confidence rating = 4), all the participants reported confidence ratings between 1 and 3 ($M = 2.5$, $SD = 0.9$). A logistic regression also revealed that observers' confidence did not predict their accuracy in indicating the right sequence ($p > .5$).

The analysis comparing the distributions in the first epoch with the distributions of the later epochs revealed significant difference in all three conditions (all $ps < .001$). The distributions of RT in the Predictable Change and Unpredictable Change trials were not significantly different ($\chi^2(9) = 11.79$, $p > .2$, Cramer's $V = 0.08$; nonetheless, the No-Change distribution was significantly different

from both, the Predictable Change, $\chi^2(9) = 81.92$, $p < .001$, Cramer's $V = 0.17$, and the Unpredictable Change trials, $\chi^2(9) = 89.11$, $p < .001$, Cramer's $V = 0.17$ (see Figure 7).⁶

To rule out the possibility that small differences in the amount of fast RT existed between the predictable change and the unpredictable change trials, we also performed a 2 (Epoch: First, Later) $\times$ 3 (Trial Type: No-Change, Predictable Change, Unpredictable Change) ANOVA on the proportion of RT faster than 500 ms. The ANOVA revealed, as expected, an effect of epoch, $F(1, 14) = 56.82$, $p < .001$. The proportion of fast RT in the first epoch ($M = 24.7$; $SE = 3.42$) was significantly lower than in the later epochs ($M = 51.9$; $SE = 3.71$). The analysis also showed an effect of the trial type, $F(2, 28) = 4.78$, $p < .05$, mostly driven by a larger amount of fast RT in the No-Change condition ($M = 41.98$; $SE = 2.17$), with respect to both Predictable Change ($M = 37.78$; $SE = 4.02$) and Unpredictable Change ($M = 36.17$; $SE = 3.44$) conditions (both $ps < .001$). Most important, the interaction was also significant, $F(2, 28) = 13.34$, $p < .001$. Post hoc tests of the means revealed that the amount of fast RT in the first epoch was lower than in the later epochs in all change conditions ($ps < .001$). Nonetheless, higher amounts of fast RT were only observed in the No-Change trials ($M = 60.41$; $SE = 2.82$), if compared with both Predictable Change ($M = 47.24$; $SE = 4.79$) and Unpredictable Change ($M = 48.06$; $SE = 4.24$) conditions ($p < .01$ and $p < .001$, respectively) and only in the later epochs (see Figure 8).

In sum, although evidence for rapid resumption was found in all three conditions, it was larger for the No-Change condition.

Discussion

In Experiment 2, rapid resumption was again observed for moving targets. This result is in line with the previous experiments in this study confirming that changes of the display do not necessarily disrupt rapid resumption. Critically, rapid resumption was observed in both predictable and unpredictable conditions, implying that participants were unable to take advantage of the exact sequence of target locations.

The failure to find an advantage of the predictable change trials helps to better understand the phenomenon of rapid resumption and distinguish it from other visual phenomena. Studies on implicit sequence learning (for a review see Cleeremans, Destrebecqz, & Boyer, 1998; but see Shanks & St. John, 1994, for a different perspective) suggest that long sequences of locations (more than 10) can be learned implicitly. In an implicit sequence-learning task, however, observers are typically exposed to many repetitions of the entire sequence, before revealing learning through a decrease of RT in response to a target appearing in the expected location. Assuming that participants in our study did not intention-

⁵ The target was also presented in the same sequence as Experiment 1b.

⁶ Despite the general lack of confidence, about half of the observers correctly recognized the sequence used in the experiment. Indeed, some of these observers could have been somewhat aware of the target's sequence of locations. Thus, we compared the distribution of RT for observers who correctly guessed which sequence was used in the experiment (aware group) with the distribution of RT for observers who did not recognize the right sequence (unaware group). Neither the responses' distribution of the aware group, $\chi^2(9) = 6.70$, $p = .7$, Cramer's $V = 0.09$, nor the responses' distribution of the unaware group, $\chi^2(9) = 11.16$, $p > .2$, Cramer's $V = 0.12$, differed between Predictable and Unpredictable Change trials.

ally withhold their response voluntarily across multiple display presentations,⁷ the possibility exists that observers never saw the entire sequence at once. Previous studies (e.g., Lleras et al., 2005) suggested that observers might not consciously access the target, before they give a response. If this is true, it is also possible that observers never explicitly accessed any of the target's location, preceding the one in which the target appeared when the observer responded. Then again, Lambert et al. (1999, Experiment 3) observed effects of implicitly learned cue target associations with low visibility, unconsciously perceived cues. Accordingly, in our experiment we should have observed increased rapid resumption in the predictable trials, compared with the nonpredictable trials, even if the target was not consciously perceived in any of the looks that preceded a correct response. However, contingency between cues and targets in Lambert's experiment was much simpler than ours, involving only two cue-target locations and only four possible cue target combinations. The failure to observe increased rapid resumption in nonconsciously perceived complex sequence changes does not exclude the possibility that the rapid resumption phenomenon can arise in response to simpler, unconsciously perceived contingency between displays in subsequent looks.

The postexperimental questionnaires suggested that participants were generally unaware of the predictability of the target's changes—or if they were, they failed to learn the sequence of events. Interestingly, they also failed to incorporate predictions about the target's specific location into a perceptual hypothesis.

It is important to point out that this result does not argue against the idea that the display changes were shaping the perceptual hypotheses. In fact they were, even if the prediction was based on a coarse subdivision of the search display rather than on the specific target locations. Knowing that the target can appear in one of few possible locations likely allowed participants to update their perceptual hypothesis and anticipate (i.e., predict) the upcoming target location with more confidence that they would have in absence of such information. Indeed, restricting the search to few locations in a complex display represents a huge reduction in uncertainty on where the target will appear next. It is reasonable to assume that participants used such information to facilitate visual search.

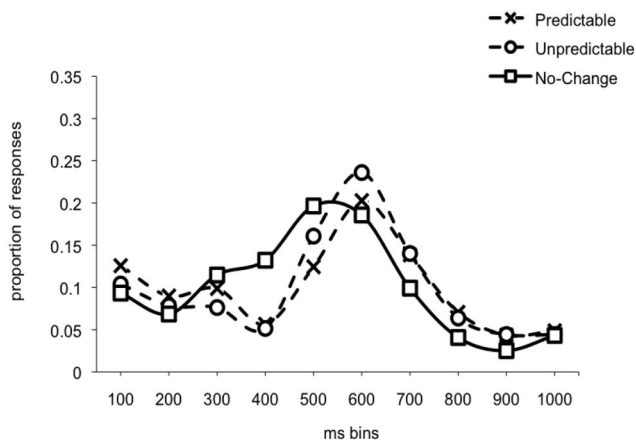


Figure 7. Distribution of RT in Epochs 2–9 of Experiment 2, in all three conditions.

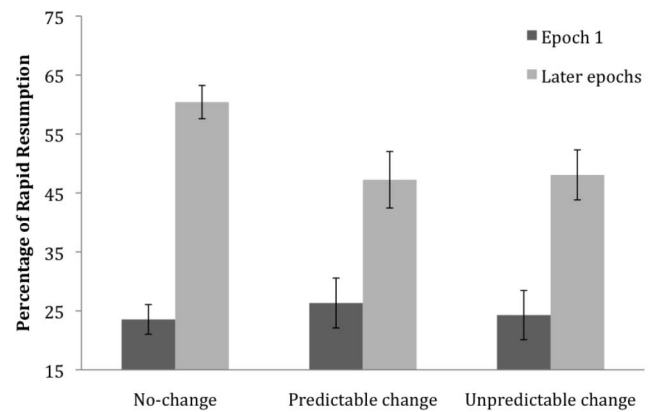


Figure 8. Percentage of RT faster than 500 ms, as a function of the trial type (No-Change, Predictable, and Unpredictable Change trials) in both the first and the later epochs.

In sum, even if some forms of implicit learning—such as in implicit sequence learning (e.g., Destrebecqz & Cleeremans, 2001) or contextual cueing (Chun, 2000)—seem to be able to facilitate stimulus processing, in this situation implicit sequence learning either did not occur, or if occurred, could not facilitate visual search. Instead, this experiment offers evidence in favor of coarse location prediction (such as predicting that a very small subset of locations will contain the target) and against precise location prediction (such as predicting the exact sequence of target changes), which was likely impossible or at least very difficult to achieve in the context of our procedure.

Learning Across Experiments

An assumption underlying this study is that the advantages observed for predictable search displays were due to learning over repeated trials. It is reasonable to assume that at the beginning of the experiment, during the first few blocks, knowledge about those locations was weak, and by the end of the experiment observers were able to predict them more precisely. Thus, we decided to test this possibility, by looking at the development of the rapid resumption phenomenon, across both trial types. We expected to observe an increase of the rapid resumption rate throughout the experiment, but only in the Change trials. We ran a mixed $2 \times 5 \times 3$ ANOVA with Trial Type (Change, No-Change) and Block (1–5) as within-subjects variables and Experiment (Experiment 1a, Experiment 1b, and Experiment 1c) as a between subjects factor, to see whether the proportion of fast RT increased throughout the experiment, as it is expected in any visual task. Specifically, we expected the proportion of fast RT to increase in the Change more than in the No-Change trials, which would suggest that learning occurred. Only responses given after the second look (Epochs 2–9) were included in the analysis. One participant from the Experiment 1a could not be included in this analysis because he or she always responded in the first epoch during the fifth block. The Greenhouse-Geisser correction of the degrees of freedom was used

⁷ Most of the correct responses (over 80%) were given within the third look.

when data violated the sphericity assumption. Table 2 shows the means and standard error for Experiment 1a, 1b, and 1c across all trial types.

Figure 9 shows the percentage of rapid resumption (RT faster than 500 ms) as a function of five blocks (80 trials each) in the experiment. The ANOVA revealed an effect of Trial Type, $F(1, 36) = 14.99$, $p < .001$, with the percentage of fast RT in the Change condition ($M = 48.4$; $SE = 1.8$) lower than the No-Change condition ($M = 56.1$; $SE = 2.1$). The effect of block approached significance, $F(2.768, 99.66) = 2.54$, $p = .06$, revealing the tendency to a linear trend, $F(1, 36) = 3.67$, $p = .06$.

The analyses also revealed a significant effect of experiment, $F(2, 36) = 6.38$, $p < .01$ and a significant interaction between experiment and trial type, $F(2, 36) = 4.71$, $p = .01$, with a larger percentage of fast RT in the No-Change than in the Change trials for Experiment 1a ($p = .01$) and Experiment 1c ($p < .001$) conditions, but not for Experiment 1b.

More important the trial type by block interaction was significant, $F(4, 144) = 3.38$, $p = .01$. Post hoc analysis of the means revealed that, for the Change trials, the proportion of fast RT increased significantly in the third and forth blocks with respect to both, the first and second blocks ($ps < .05$); the percentage of rapid resumption in the first block was also lower than in the fifth block ($p < .05$). Such increase was not observed in the No-Change trials. Post hoc tests also revealed that rapid resumption in the Change trials was smaller than in the No-Change trials in the first ($p < .001$), second ($p < .001$), third ($p < .01$), and fifth ($p > .01$) blocks, but not in the fourth. This result may reveal a qualitative difference between the facilitation (fast RT) observed across trial types.

Table 2
Mean (M) and Standard Error (SE) of the Amount of Rapid Resumption, Expressed in Percentage of RTs Faster Than 500 ms

Experiment	Trial type	Change		No-Change	
	Block	Mean	Std. error	Mean	Std. error
Circular	1	38.662	3.762	49.362	3.453
	2	38.116	4.331	51.104	4.446
	3	46.247	3.829	56.045	4.346
	4	52.000	5.587	57.563	4.512
	5	48.051	5.116	53.342	4.390
Zig-zag	1	43.394	4.692	53.840	4.306
	2	44.653	5.402	49.513	5.545
	3	50.196	4.776	45.958	5.420
	4	48.511	6.968	38.950	5.628
	5	51.230	6.381	46.966	5.476
Random	1	45.637	3.519	65.609	3.230
	2	49.559	4.051	63.740	4.159
	3	56.611	3.582	72.172	4.065
	4	60.739	5.226	67.156	4.221
	5	51.870	4.786	70.678	4.107

Note. The means are displayed for Experiments 1a (circular), 1b (zig-zag), and 1c (random) separately in both the change and no-change conditions.

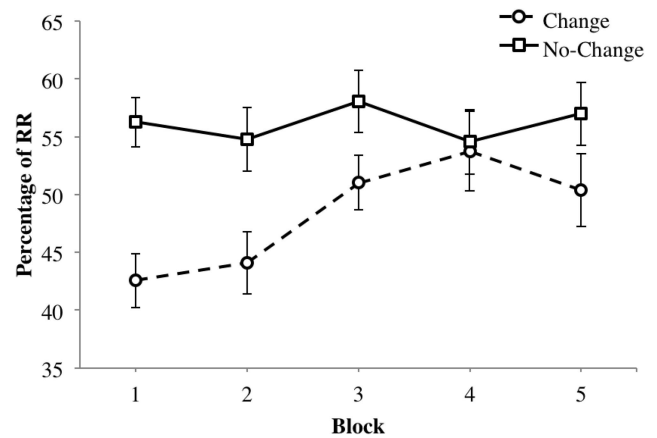


Figure 9. Percentage of rapid resumption as a function of the block (80 trials) in the Experiment. Experiments are collapsed and include Experiments 1a, 1b, and 1c.

Experiment 3: Target Identity Change

So far, and surprisingly in light of previous studies (Jungé et al., 2009; Lleras et al., 2005; Lleras, Rensink, & Enns, 2007), we showed that changes of the display failed to disrupt rapid resumption, if those changes were consistent with the observer's expectations. As mentioned earlier in the article, however, a distinctive property of the changes occurring in the displays of the previous studies is randomness. If anticipation is driving the rapid resumption effect, the preservation of the ability to resume the visual search after the interruption in case of predictable changes should not be surprising after all.

However, the results of Experiment 1 and 2 suggest that predictability alone might not be sufficient to activate a predictive strategy based on all the available information. Both, Experiment 1b and Experiment 2 suggest that our participants might have been using a strategy based on a coarse representation of the visual search display, rather than using fine-grained prediction to locate the target after the location has changed.

In support of these hypotheses, Lleras et al. (2005) showed that rapid resumption is disrupted if the item's identities are scrambled between looks, but it is preserved if the distractors' locations are scrambled (Lleras et al., 2007). Jungé et al. (2009) delved deeper into the issue and found that the decrease or rapid resumption after changes of the item's locations is mainly due to the items that closely surround the target. These results reveal that perceptual hypotheses predominantly contain target's features; contrary to the featural resolution of the target, the featural resolution of nearby search items is quite coarse. They also suggest that when relevant aspects of the display do not perfectly match the previous one, observers are not able to rapidly resume the interrupted visual search. It follows that irrelevant aspect of the search display might be ignored and might fail to be incorporated in the nonconscious perceptual hypothesis. If that is the case, details regarding the changes of the visual display that are not relevant for the current task/goal might also fail to be incorporated, despite being predictable.

In all the experiments we presented so far, the participants' goal was to report the target's orientation. Therefore, the target's loca-

tion was relatively irrelevant to perform the experimental task, although it is reasonable to assume that knowing the approximate location where the target will appear on each display presentation could have facilitated the task.

If that is the case, introducing a change that's relevant for the task should force observers to incorporate that change into the perceptual hypothesis. The presence of a relevant change in the visual display also allows us to test another interesting possibility: that the resolution of the perceptual hypothesis might also change, adapting to the new task demand. In other words, if tracking the exact location of a target might not be relevant to report the orientation of the target, tracking the unceasingly changing orientation of a target should be.

In Experiment 3, the target orientation change sequence was repeated so that observers could learn it, and thus predict the target's orientation after few presentations of the display. After the first phase, the orientation sequence was disrupted, allowing us to assess the degree to which the predictable sequence was facilitating performance. Contrary to what observed in previous studies (Jungé et al., 2009), changes of the target's identity should preserve rapid resumption, as long as those changes are predictable. To prevent our experimental manipulation from being confounded with the temporal sequence of the experimental blocks, the predictable target's change sequence was resumed in the third block and for the rest of the experiment.

The aim of this experiment was to confirm that prediction of the forthcoming events plays a fundamental role in rapid resumption. In addition, this study aims to reveal whether fine-grained changes can be also incorporated in the perceptual hypothesis.

If predictable fine-grained feature changes can be incorporated in the perceptual hypothesis, we expect to observe rapid resumption after the target's orientation changed, as long as such orientation is predictable—that is, first block. We expect rapid resumption to be disrupted in the second block, when the target's orientation was chosen randomly, and therefore, unpredictably, but we also expect to observe rapid resumption when the target's change sequence is resumed (e.g., third block).

Method

Participants. Twenty-nine volunteers ($M_{\text{age}} = 19$ years, $SD = 1.2$) participated in the experiment. All participants had normal or corrected-to-normal vision. They signed a consent form before the experiment and they were compensated \$8 or one psychology course credit for their participation.

Stimuli. The stimuli (see Figure 10) were very similar to those of the previous experiments, except for a few differences described below. The target was a "T" and the distractors were "L" both occupying an area of $0.6^\circ \times 0.6^\circ$ of visual angle. Each distractor (L) was tilted 45° clockwise and there were four possible targets, oriented in four possible directions (see Figure 10): 45° (up-right), 135° (down-right), 225° (down-left), and 315° (up-left).

Procedure. The procedure was very similar to that of the previous experiments, except for the following: Participants were instructed to respond "right" or "left," based on the target direction. If the target was tilted either 45° or 135° , "right" was the correct response. If the target was tilted either 225° or 315° , "left" was the correct response.

On each look the target's orientation changed. During the first block, the target changed orientation after each look in steps of 90° clockwise, such that if the orientation in the first look was for example down-right, in the second look it would be down-left, in the third look up-left, and so on. During the second block of the experiment, the target's orientation was chosen randomly on each look, such that the same orientation was never chosen twice in a row. After the second block, the clockwise sequence of target changes between looks, such that Blocks 3, 4, and 5 were the same as Block 1.

Participants completed 16 practice trials, in which the target did not change orientation, and then five blocks of 80 trials each.

Results

Two participants were excluded from the analysis because they failed to complete at least four blocks⁸ of the experiment. Five participants were excluded from the analysis because of high error rates ($<57\%$ accuracy).

Trials in which the observer did not accurately report the target orientation (11.2%) and RTs longer than 10,000 ms (0.3%) were considered errors and excluded from the analysis.

We compared the distribution of RTs in the Blocks 1, 3, and 4—in which the target orientation changed predictably moving clockwise—to the distribution of RTs in the second block—in which the target's orientation changed unpredictably being chosen randomly on each display presentation (see Figure 11).

In all blocks (1–4), the distribution of the first epoch differed from the distribution in the later epochs (all $ps < 0.001$).

The three most relevant comparisons are between Block 1 versus Block 2, Block 2 versus Block 3, and Block 3 versus Block 4. As a reminder, we expect the later epochs of the second block to differ from those in the first and third block, but we do not expect a difference between Blocks 3 and 4.

The distribution of the first epoch (Figure 11, top panel) did not significantly differ across blocks, in none of the three relevant comparisons (all $ps > .05$).

By contrast, the distribution of the later epochs in Block 2 significantly differed from both Block 1, $\chi^2(9) = 656.12$, $p < .001$, Cramer's $V = 0.44$, and Block 3, $\chi^2(9) = 157.30$, $p < .001$, Cramer's $V = 0.22$. Importantly, the distribution in Block 3 did not significantly differ from Block 4 ($p < .05$; Figure 11, bottom panel).

Three participants were excluded from the analysis of variance because they never/always answered in the first epoch on at least one block of the experiment. That left us with 19 participants on whom we performed a 2×4 ANOVA with block (1–4) and epoch (first, later) as within-subjects variables on the percentage of rapid resumption (RT faster than 500 ms).

Results revealed a significant effect of epoch, $F(1, 18) = 195.12$, $p < .001$, and a significant effect of block, $F(1.97, 35.4) = 5.46$, $p < .01$, but more important, it showed a significant interaction, $F(3, 54) = 13.71$, $p < .01$. As expected, post hoc analysis of the means revealed that the proportion of fast RT in the first epoch was lower than in the later epochs ($ps < .001$). More important, it showed that, for the first epoch, the proportion of fast

⁸ Due to time constraints, not all the participants completed all five blocks of the experiments.

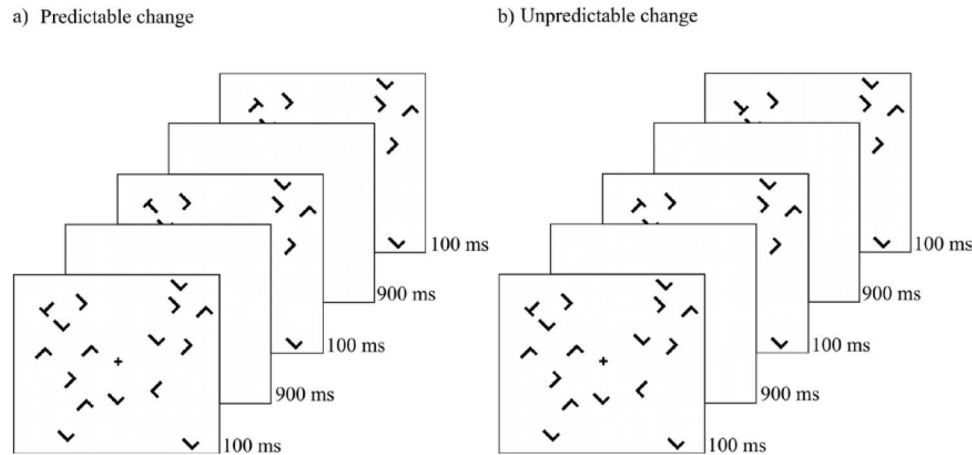


Figure 10. Sequence of events that occurred on each trial of Experiment 3: (a) Predictable change (Blocks 1 and 3–5), in which on each look the “T” appeared rotated by 45° clockwise; (b) Unpredictable change (Block 2), in which the “T” appeared rotated by 45° in one of the possible four direction—in which the “T” orientation was never the same in two consecutive looks. The sequence of display (100 ms)–blank (900 ms) presentation was repeated for 12 times or until the participant gave an answer by pressing a key on the keyboard.

RT in the third ($M = 13.64$; $SE = 3.47$) and fourth ($M = 14.96$; $SE = 2.87$) blocks increased significantly with respect to both, the first ($M = 5.41$; $SE = 1.95$) and second ($M = 8.36$; $SE = 2.03$) blocks ($ps < .05$). In the later epochs, however, the proportion of fast RT in the second block ($M = 49.30$; $SE = 2.90$) significantly decreased ($p < .001$) with respect to the first block ($M = 60.24$; $SE = 2.93$). In addition the proportion of fast RT third ($M = 62.01$; $SE = 3.59$) and fourth ($M = 57.25$; $SE = 3.71$) blocks significantly increased with respect to the second block ($p < .01$ and $p = .05$, respectively). Importantly, the first block did not significantly differ from neither the third, nor the fourth block ($ps > .5$), although the proportion of fast RT showed a small but significant decrease (4.7%) in the fourth block, with respect to the third one.

Discussion

The results are clear: The pattern of responses typical of the rapid resumption phenomenon developed when the display changed between looks, but only when the sequence of changes was predictable. Indeed, it abruptly disappeared when such sequence was disrupted and reappeared nonetheless when the sequence was resumed. This finding has two important implications: First, it shows that observers are able to quickly resume an interrupted visual search, by anticipating the forthcoming display, even in case lower level characteristics of displays do not match; second, it shows that the resolution of the visual representations can be fine grained, and can contain details regarding the target's shape.

In Block 1 we observed rapid resumption—both the bimodal distribution and a higher proportion of fast responses—interestingly, compared with any control condition that we have ever run, the amount of rapid resumption was substantially increased such that the first peak is even higher than the second peak in the RT distribution. In Block 2, the random rotation of the target destroyed rapid resumption: A single later (500–600 ms) peak was observed and the proportion of rapid responses dropped significantly, when

compared with Block 1. Lastly, in Blocks 3 and 4, we observed a unimodal distribution with its peak shifted leftward (400–500 ms) and an increase of fast RTs, comparable with the rates observed in Block 1.

The disappearance of the bimodal shape in the distribution of Blocks 3 and 4, when the predictable target's sequence of change across looks was resumed, might seem surprising at first. However, it fits with the general pattern of results we observed in this study (see Experiment 2 and supplemental section): that observers' goals and expectations play a role in the emergence of the phenomenon of rapid resumption. Block 1 was technically identical to both Blocks 3 and 4. However, there is an obvious difference between the two: Block 1 came first, and likely shaped our participants' expectations regarding the experiment. Block 3 and 4 however, came after the sequence was disrupted (i.e., in Block 2), and it is reasonable to assume that such disruption might have changed the participants' expectations about the task and the predictability in the experiment.

Experiment 3 also revealed another intriguing aspect of rapid resumption: that the resolution of the nonconscious perceptual hypotheses might change based on the current goals and task demands. In fact, Experiment 1c and Experiment 2 in this study seemed to suggest that details about the visual scene were sacrificed in favor of a more effective search strategy based on the coarse spatial representation of the visual search display. Experiment 3 instead suggests that fine-grained details are available, and can be used to facilitate visual search.

One important difference between the experiments might have contributed to this result: Although both Experiments 1 and 2 required the participants to report the target shape, only in Experiment 3 did the shape change between looks. That is, in Experiment 1, featural resolution of the target was neither directly related to the task, nor strictly necessary to successfully complete the task. However, in Experiment 3, storing details regarding the target's features was directly relevant to the task. Indeed, we observed that

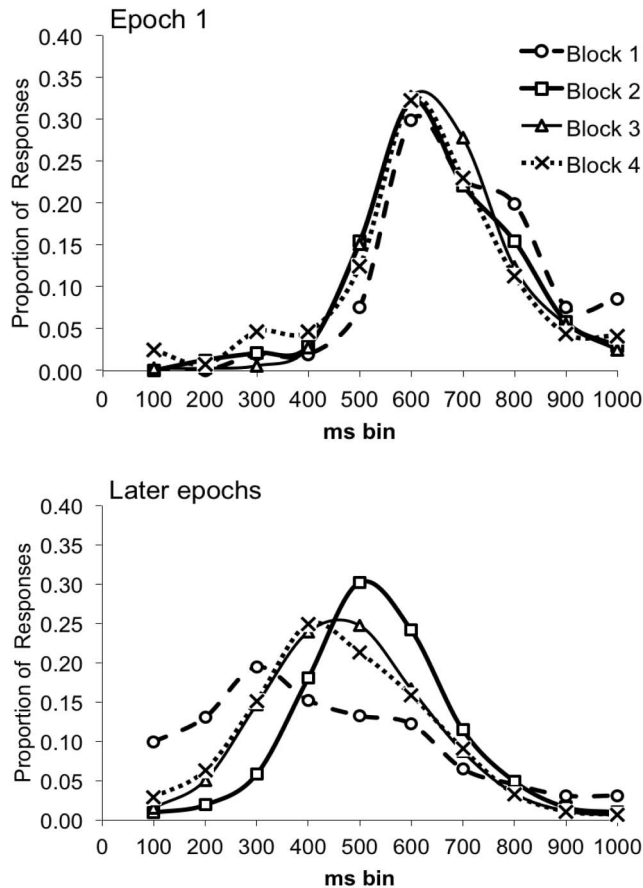


Figure 11. Normalized distribution of RT observed in the first epoch (top panel) and for the following epochs (bottom panel) displayed for each experimental block in Experiment 3.

changing the orientation predictably increases the amount of rapid resumption and produces the typical bimodal distribution characterized by a very early peak of very fast RT (<500 ms). In other words, the observers' task goals might be modulating the level of detail stored in the visual representation.

In sum, this last experiment shows that observers can integrate fine-grained changes of objects' visual features in the perceptual hypotheses and even more surprising, that changes in those details can be integrated into the perceptual hypotheses as long as they are predictable.

General Discussion

These results say several important things about visual search. First, rapid resumption was observed even after changing relevant aspects of the search display—such as the target's location or shape—as long those changes are predictable, confirming that prediction underlies rapid resumption. Second, goal-driven inferences could be used to update nonconscious perceptual processes, such as those hypothesized to be involved in the preprocessing of the visual scene—for example, rapid resumption. Third, display's changes have to be consciously accessible, for observers to be able to include them into the perceptual hypothesis. Fourth, observers

seem to rely on coarse spatial information rather than exact spatiotemporal sequence, when precise information about the display is not available. However, details about the visual display can be dynamically incorporated into the perceptual hypotheses when available and relevant to the observer's current goals.

Predictable Versus Unpredictable Changes

Changes of the display have been previously shown to disrupt rapid resumption (Jungé et al., 2009; Lleras et al., 2005, 2007). Here, on the contrary, rapid resumption was preserved after changes of the target's location. The crucial difference between our study and the previous studies is predictability. In our Experiments 1a and 1b, the target's location changed between looks, but could be inferred given the previous location. In our Experiment 3, the target shape changed, but it could be predicted given the previous target's direction. In both cases, observers used preliminary information regarding the display to facilitate visual search after an interruption.

Even a coarse representation of the display is enough to guide prediction in an interrupted search task. In our Experiments 1 and 2, observers used their expectation about the target's location, to coarsely restrict the visual search to a subset of locations. In our Experiment 3, observer's used details about the target direction to precisely predict the subsequent target shape and facilitate visual search. In addition, our Experiment 3 shows that it is possible for observers to adapt their predictive strategy based on how much detail is available and how much is required for the completion of the experimental task.

We argue that the knowledge about the previous display and prediction about the forthcoming event were combined into a perceptual hypothesis, which was updated during the interruption to be confirmed in the next presentation, despite changes in the search display.

Goal-Oriented Strategy Over Early Visual Processes

The ability to quickly resume the visual search after an interruption, during which a change occurred, reveals that high-level inferences, guided by an observer's strategy, can be used to update implicit perceptual processes. According to Lleras and colleagues (e.g., Lleras et al., 2005; Enns & Lleras, 2008), perceptual hypotheses are created at a nonconscious level because their content is not available for explicit report if the observer is only given one presentation of the search display. Yet, our results suggest that implicit perceptual hypothesis can integrate anticipation of changes occurring in a dynamic visual scene. That is, even when physical appearance of the perceptual hypotheses did not match between looks, the hypotheses could yet be confirmed.

Other studies reported effects of observer's implicit intentions on early visual processes—for example, unconscious priming (e.g., Anson, 2004) and metacontrast masking (e.g., Enns & Oriet, 2007; Gellatly, Pilling, Cole, & Skarratt, 2006). Similar effects on implicit visual processes have been also reported on a similar alternating presentation procedure (e.g., Cole, Kentridge, Gellatly, & Heywood, 2003; Cole, Kentridge, & Heywood, 2004). Cole, Kentridge, Gellatly, and Heywood (2003) for example, reported a series of experiments in which

participants had to detect the presence of a change in a typical change detection task (see [Simons & Levin, 1997](#)). The critical comparison in [Cole et al. \(2003\)](#) study was between the onset of a new item in the display and the offset of the same item—that is, the item disappearing from a location previously occupied. Participants were asked to indicate whether a change had occurred between two continually alternating displays. When the change involved the offset (disappearance) of an item in the search display, [Cole et al. \(2003\)](#) observed a unimodal distribution with a peak of responses around 500 ms. When the change involved the onset (appearance) of a new item in the search display, they observed a bimodal distribution with peaks around 300–400 ms and 700–800 ms. To explain their results, the authors propose a “confirmatory frame hypothesis,” in which they argue that sometimes a single presentation might not be enough for the observer to become aware of a change that occur in the visual display. In this case, observers might “sense” that a change occurred, but need to wait for the next frame for the hypotheses to be confirmed.

It is possible that a similar mechanism is at play in our experiments.⁹ Relying on the idea of “object file” formulated by [Kahneman, Treisman, and Gibbs \(1992\)](#) the authors suggest that temporary visual representations are created for visual objects. When the objects change, the file typically only needs to be updated. However, some changes (e.g., the onset of a brand new object in the search display) may trigger the creation of a new file. Similarly in our study, when the visual display changes predictably, the visual representation only needs to be updated. However, unpredictable changes may require the creation a new file.

[Cole et al. \(2003\)](#) argue that higher-level representations seem to be modulating lower-level detection of transient luminance changes. Similarly, in our experiments, higher-level predictive mechanisms seem to be driving lower-level detection of the target’s characteristics. In sum, in both studies, the observers’ strategy appears to be affecting early visual processes.

Explicit Versus Implicit Predictions

These results suggest that explicit knowledge regarding changes of the display is needed for the goal-oriented inferences to affect early visual processes. In Experiment 1 observers were aware of the target’s location sequence and were able to quickly resume the interrupted visual search. In fact, in Experiment 2 (and those reported in the supplemental material) observers were not aware of the repetitiveness of the target’s location and they were also unable to quickly resume the visual search after the interruption.

That said, it is important to note that rapid resumption does not seem to be the mere result of changes in the attentional strategy. One may argue in fact that rapid resumption in our experiments might be a byproduct of the observers’ explicit strategy to restrict the attentional focus to the central locations because that is where the salient items were presented (see Experiments 1a–1c). However, only Experiment 1b suggested that observers were facilitated after the first look, when the target appeared in the central most locations. As previously noted, if participants were restricting the focus of attention to the center, the search in the Change trials should have been

facilitated (higher rate of fast RT). In fact, except for Experiment 1b the opposite was observed, with consistently higher rate of rapid resumption in the No-Change trials.

The learning slopes observed across experiments were consistent with the idea that Change and No-Change trials developed differently throughout the experiment. Higher rates of RT faster than 500 ms was always observed when the target’s location was repeated, and did not substantially increase during the experiment. On the contrary, trials where the target was displaced showed a lower rate of rapid resumption, which significantly increased during the experiment.

Taken together, these findings may suggest the existence of two qualitatively different types of facilitation in rapid resumption: an advantage driven by physical appearance—triggered by low-level feature similarity—and a goal-driven advantage due to the observer’s predictive strategy, which does not rely on low-level features matching.

The original version of the interrupted visual search task ([Lleras et al., 2005](#)) does not allow distinguishing between these two types of facilitation. In fact, observers were both, presented with subsequent displays that matched regarding their low-level characteristics, and potentially using an explicit goal-directed strategy, driven by the understanding of the static nature of the display. Our Experiment 2, however, allows us to separate the effects of the explicit strategy—based on the explicit knowledge that changes are occurring in the display—from the effect of the implicit facilitation driven by low level similarities between subsequent displays—when the target did not change. Additional support to this hypothesis comes from Experiment 3, where both the bimodal pattern of RT and the high rate of fast RT were observed at the beginning of the experiment (Block 1), but only the increase in fast RT—not the bimodal distribution—was observed in the last part of the experiment (Blocks 3 and 4). The first and last parts of the experiment were technically identical, except for the participants’ exposure to an unstructured block of trials between the two, which we argue might have disrupted their motivation to engage in an active predictive search strategy, smearing the RT distribution slightly rightward. Critically, an increase in the proportion of fast RT was still observed, indicating that the advantage of low-level features matching was still there.

Resolution of the Perceptual Hypothesis

Experiment 1 (especially 1c) and Experiment 2 clearly supports the idea that perceptual hypotheses can be coarse but still facilitate perception. This may suggest that limits of the visual system prevent fine-grained representations from being created with only one glance. To overcome this limit, the visual system might choose which details to include in the perceptual hypothesis, based on the task demands. It should be noted, however, that this does not exclude the possibility that more details can be included into the perceptual hypotheses. In fact, Experiment 3 suggests that details and changes related to those details could be dynamically incorporated into the perceptual hypotheses.

⁹ Although it is worth noting here that the hypothesis that rapid resumption is the consequence of participants’ strategy of voluntarily withholding their response until the next frame has been examined before, no convincing evidence in favor of it has been found ([Lleras et al., 2005](#)).

Previous studies reached the same conclusion (e.g., Jungé et al., 2009; Lleras et al., 2007). Lleras et al. (2007) showed that the distribution of RT lacks of the early peak if the target color changes but only if observers are responding to the target's color (Experiment 4), and the early phase of RT reappears if observers are responding to its orientation (Experiment 3). Jungé et al. (2009, Experiment 3) extended this finding by showing that only changes of the display involving distractors with the same luminance as the target interfere with the rapid resumption phenomenon. The attentional focus also modulates the spatial resolution of the perceptual hypotheses, as suggested by the finding that only changes in the display involving items nearby the target reduce rapid resumption (Jungé et al., 2009).

Our results support and extend this conclusion, showing that observers adapted their search strategy based on the task characteristics. In our Experiment 1, observers might have found advantageous to create a coarse representation of the display, so that all the salient locations could be included. In fact, a more detailed representation of the target's features (or location) could not further facilitate visual search. Nonetheless, we observed that predictions based on a coarse spatial resolution were still able to guide visual search by enabling rapid resumption.

When the details of the target (i.e., its precise shape) became relevant to the task, observers were able to integrate changes of such details into the perceptual hypothesis, confirming that the phenomenon of rapid resumption is sensitive to the task demands.

In sum, our result strongly support the idea that an active prediction about both what is present as well as lawfully changing in the world allows visual search to be rapidly resumed after an interruption and add to the growing number of studies that, more generally, attribute to prediction a central role in human cognition. Going back to our initial example about visual perception during street crossing, imagine being about to cross the street and seeing a car on the farther lane start to pass a large truck on the lane closest to us. Momentarily, the car is occluded by the truck, and then it reenters our field of view as it overtakes the truck. What our study shows is that seeing even a glimpse of that car before it is obscured by the truck allows us to more readily scrutinize it once it reappears. But this savings in processing occurs precisely because we have a mind to scrutinize cars in the street and we actively anticipate the occluded car returning into view. Predictions about the world are thus an integral part of our perception of the world.

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