Learning in shifts of transient attention improves recognition of parts of ambiguous figure-ground displays

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Previously demonstrated learning effects in shifts of transient attention have only been shown to result in beneficial effects upon secondary discrimination tasks and affect landing points of express saccades. Can such learning result in more direct effects upon perception than previously demonstrated? Observers performed a cued Vernier acuity discrimination task where the cue was one of a set of ambiguous figure-ground displays (with a black and white part). The critical measure was whether, if a target appeared consistently within a part of a cue of a certain brightness, this would result in learning effects and whether such learning would then affect recognition of the cue parts. Critically the target always appeared within the same part of each individual cue. Some cues were used in early parts of streaks of repetition of cue-part brightness, and others in latter parts of such streaks. All the observers showed learning in shifts of transient attention, with improved performance the more often the target appeared within the part of the cue of the same brightness. Subsequently the observers judged whether cue-parts had been parts of the cues used on the preceding discrimination task. Recognition of the figure parts, where the target had consistently appeared, improved strongly with increased length of streaks of repetition of cue-part brightness. Learning in shifts of transient attention leads not only to faster attention shifts but to direct effects upon perception, in this case recognition of parts of figure-ground ambiguous cues.

Keywords: attention, learning, depth, visual cognition, memory

Citation: Kristjánsson, Á. (2009). Learning in shifts of transient attention improves recognition of parts of ambiguous figure-ground displays. *Journal of Vision, 9*(4):21, 1–11, http://journalofvision.org/9/4/21/, doi:10.1167/9.4.21.

Introduction

Research over the last few decades has revealed that our visual systems clearly favor consistency over uncertainty, using the past to predict the future. Phenomena such as perceptual learning (Dosher & Lu, 2004; Gibson, 1963; Goldstone, 1998; Karni & Sagi, 1993; Sireteanu & Rittenbach, 2000; see Seitz & Watanabe, 2005 for an up-to-date discussion), priming (see e.g. Gabrieli, Fleischman, Keane, Reminger, & Morrell, 1995; Kristjánsson, 2006a, 2008; Schacter & Buckner, 1998; Warrington & Weiskrantz, 1968), contextual cueing (Chun & Jiang, 1998) and statistical learning (Fiser & Aslin, 2001) are clear examples of this. Recently evidence has accumulated for between-trial learning of various types of consistency in what may even be the most reflexive of visual behaviors, shifts of transient visual attention (Mackeben & Nakayama, 1993; Nakayama & Mackeben, 1989; see e.g. Kristjánsson, 2006b and Most & Simons, 2001 for review).

Transient attention was first described experimentally by Müller and Findlay (1988) and Nakayama and Mackeben (1989; see also Müller & Rabbit, 1989 and Posner, 1980 for some related findings). The key finding of the Nakayama and Mackeben study was that when a cue appeared there was strong facilitation of performance on a subsequently presented discrimination task almost immediately following the cue, but the efficacy of the cue diminished rapidly with longer times between cue onset and target onset (the *cue lead time*). If the briefly presented target followed the cue in quick succession (e.g. by 50–200 ms) discrimination performance was on the other hand strongly enhanced. The target was presented briefly, followed by a mask, since if the target appears for longer, observers may use what Nakayama and Mackeben termed sustained, or voluntary attention to perform the task. Sustained attention is only effective with a substantial delay between cue and target (~300 ms or more from the onset of the cue, see Wright & Ward, 2008 for an up to date, comprehensive overview). The boost in performance is, furthermore, larger for transient than sustained attention. Transient attention has since been shown to have dramatic beneficial effects upon visual performance in a variety of different visual tasks (see Carrasco, Ling, & Read, 2004; Kristjánsson & Sigurdardottir, 2008; Yeshurun & Carrasco, 1998 for some examples and Kristjánsson, 2006b for review) and importantly in the current context, Vecera, Flevaris, and Filapek (2004) found that transient attention can influence assignment of figure versus ground in ambiguous displays.

Associative learning in shifts of transient attention

Even though shifts of transient attention appear to be quite reflexive, some more recent lines of evidence

doi: 10.1167/9.4.21 Received October 16, 2008; published April 24, 2009 ISSN 1534-7362 © ARVO

indicate that associative learning can affect these seemingly reflexive attention shifts. Kristjánsson, Mackeben, and Nakayama (2001) showed that shifts of transient attention can be modified by the learning of basic relationships between cue and target in object-based coordinates. They found that if a target consistently appeared within a certain part of a peripheral cue (e.g. the right or left part), performance became better the more often it appeared within this part of the cue, irrespective of *where* in the visual field this occurred (in other words in object-based coordinates, distinguishing this learning from e.g. perceptual learning as it is traditionally defined, see the General discussion). This result was surprising in light of previous thinking about attention. Attention was often thought to be a bottom-up, stimulus driven reflex, automatically drawn to external abruptly appearing stimuli (see e.g. Jonides, 1981; Pashler, 1998; Theeuwes, 1991; Yantis & Jonides, 1984). Some results of Nakayama and Mackeben (1989) even pointed in the same direction. The results of Kristjánsson et al. showed, on the other hand, that transient attention is not as reflexive and primitive as some previous results had indicated, and that its operational characteristics can be modified according to need. This is consistent with research showing how attentional capture by an abruptly appearing object, sometimes thought to be automatic and obligatory (e.g. Yantis & Jonides, 1984) can actually be modified by the goals of the observer (Folk & Remington, 1999; Folk, Remington, & Johnston, 1992).

Kristjánsson and Nakayama (2003) subsequently found evidence for such learning in shifts of transient attention in cases where the target appeared within a part of the cue which had certain featural characteristics, such as a certain colored part of the cue, or a part of the cue that had a certain shape (see Experiments 1 and 2 in Kristjánsson & Nakayama, 2003). As the target appeared more and more often in a row on the e.g. green colored part of the cue the better the discrimination performance became. Importantly, Kristjánsson and Nakayama (2003) also showed that this learning in transient attention shifts was not under any form of volitional or voluntary control. When observers were informed *beforehand* of the cue-target contingencies (were, for example, told that the target would always appear at the green end of cue) they were completely unable to utilize this information to aid their performance, while they *still* showed the distinctive learning pattern (Kristjánsson & Nakayama, 2003, Experiments 5 and 6).

Kristjánsson, Eyjólfsdóttir, and Jónsdóttir (2008) have then found examples of learning in the *temporal* domain, showing that transient attention is also quite sensitive to temporal consistencies. They found that performance on a cued discrimination task improves when cue lead times are consistent from trial to trial. So, for example, if the cue lead-time was e.g. 150 ms for a few trials in a row, performance improved considerably compared to when the cue lead times changed unpredictably from being e.g. 50, 100, 150 or 200 ms from one trial to the next. Again, the observers had no knowledge of this, while still exhibiting the learning. Finally this form of learning has also been shown by Edelman, Kristjánsson, and Nakayama (2007) to modulate express saccades, the fastest, and most reflexive of oculomotor behavior (Fischer & Boch, 1983; Fischer & Ramsperger, 1984; Ross & Ross, 1980; Saslow, 1967; see e.g. Fischer & Weber, 1993 and Kristjánsson, 2007 for review).

Taken together, the evidence above argues for a short-term memory system that automatically links features of objects to transient attention deployments (see e.g. Kristjánsson, 2006b and Nakayama, Maljkovic, & Kristjánsson, 2004 for review). Transient attention is not by necessity summoned *indiscriminately* to abruptly appearing stimuli, but shows implicit learning of the relationship between cue and subsequent target in object based coordinates, exhibiting flexibility in its operational characteristics, depending on the history of validities. This form of learning can be seen following the first repetition of cue-target contingencies, but then builds up over a series of trials with the same cue-target contingencies. This learning shares important characteristics with other attentional learning effects, such as priming in visual search (see e.g. Kristjánsson & Driver, 2008; Maljkovic & Nakayama, 1994; Sigurdardottir, Kristjánsson, & Driver, 2008).

Current aims

The results reviewed above have only revealed effects of learning in shifts of transient attention upon discrimination performance. But might such learning in attention shifts have more profound effects upon perception? Can such learning affect perception of aspects of the experimental display that are irrelevant to the experimental task itself, in this case recognition of figure-ground ambiguous displays (as shown in Figure 1).

The question of whether and how such learning may affect perception is somewhat problematic to address, however. Asking observers after they perform the discrimination whether they perceived things differently while the learning developed is fraught with potential confounds, biases and demand characteristics which might affect the results. Subsequent object recognition tests by forced-choice are, on the other hand, a more reliable test of any such effects upon perception. The experimental question was, for those reasons, addressed by asking whether learning in transient attention deployments would affect forced-choice recognition of stimuli ambiguous in terms of figure and ground which were used as cues in the discrimination task. Rubin (1915) found a large recognition advantage for parts of figure-ground ambiguous stimuli which were perceived as figure over parts assigned to the background, and many have since reported similar results (see e.g. Baylis & Driver, 1995; Driver & Baylis, 1996; Vecera et al., 2004).

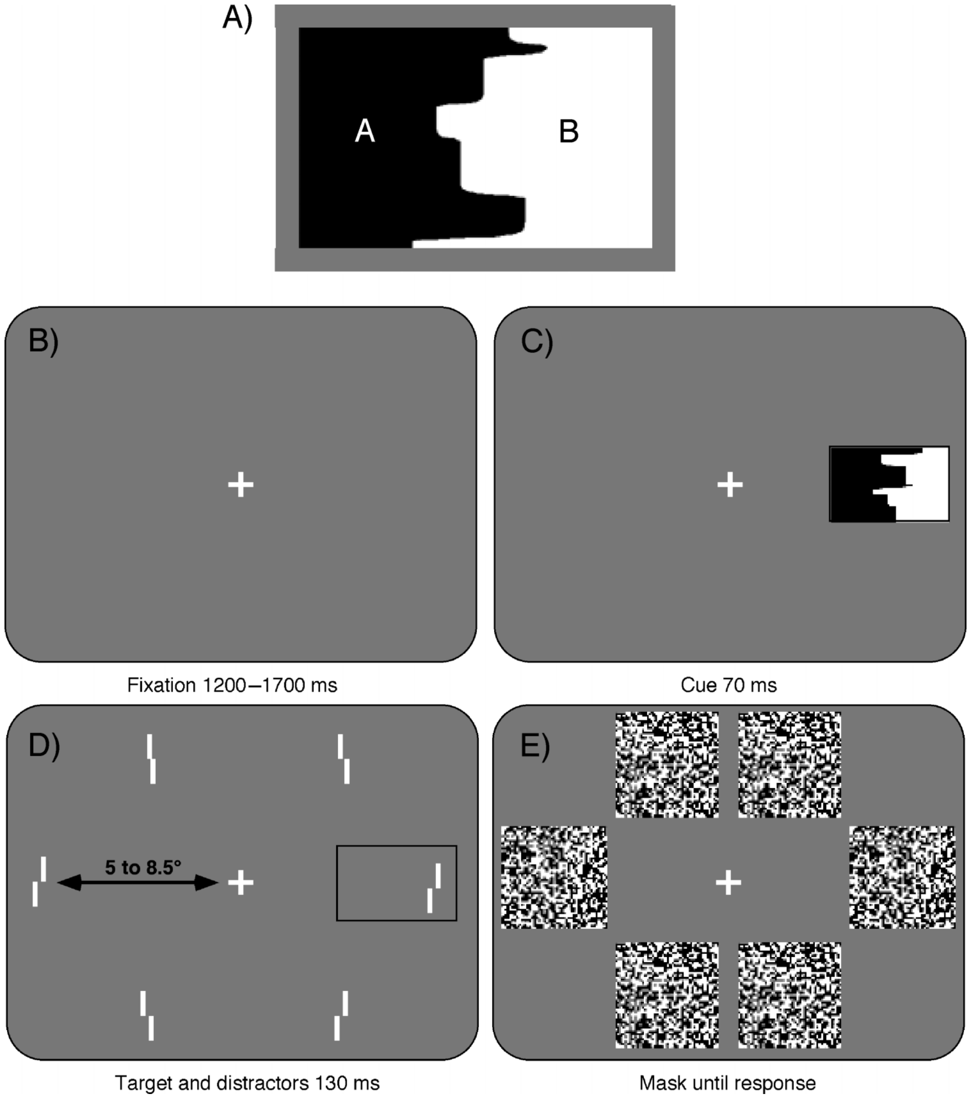

Figure 1. The stimuli used in the cued discrimination part of the experiment and the sequence of events. Panel A shows an example of an ambiguous figure-ground stimulus, where either the black part (marked A) or white part (marked B) can be seen as figure with the other serving as background (see e.g. Baylis & Driver, 1995; Rubin, 1915). In panels B to E the sequence of events on a single trial in the cued discrimination part of the experiment is shown. Each trial started with the presentation of a fixation cross followed by the cue. A black box surrounded the cue and remained in place when the figure-ground ambiguous cue had disappeared. The target then appeared within this square either where the black or the white part of the cue was presented previously (always the same part for each of the 48 different cues). The imaginary oval that the target and distractors appeared on jittered horizontally from trial to trial, by 0–3.5° (randomly determined for each trial) to prevent observers from using an implicit representation of the oval to guess the target location. Afterwards a local random-dot mask appeared at the locations where the cue, target and distractors had been presented. Note that the stimuli are not drawn to the scale used in the experiment (see Methods section for details).

Haijiang, Saunders, Stone, and Backus (2006; see also Seitz & Watanabe, 2003) have shown how perceptual learning can affect appearance *directly* rather than discrimination performance only. The question here is whether such effects might apply to learning in shifts of transient attention as well; that faster and more effective attention shifts may affect how well parts of these figure-ground ambiguous displays are subsequently recognized, compared to when no such learning occurs, and even strengthen figure-ground segmentation, perhaps through recruitment of additional attentional resources (see Vecera et al., 2004 for evidence that transient attention can affect figure-ground assignment).

Methods

The cues were based on stimuli introduced by Baylis and Driver (1995, see Figure 1, although the general design of stimuli of this sort is traceable at least as far back as to Rubin, 1915). The experiments were designed to investigate firstly whether faster attention shifts follow the repetition of cue-target contingencies from trial to trial in a task involving transient visual attention. Secondly, the experiments addressed whether such learning might affect recognition of parts of the cues.

The second question was addressed with forced-choice discrimination of whether a particular figure-part was part of a cue used in the cued discrimination task, measuring whether different rates of recognition will be observed as a function of where in a streak[1] of repetition the particular figure-ground display was used as cue. Before any effects of learning upon appearance can be inferred, however, it was first critical to determine whether any between-trial learning of where within the briefly presented cue the target would appear, occurred at all.

Participants

Three observers (two males) aged 23, 25 and 34 years participated, one (the oldest and the author), knew about the purpose of the experiment while the other two participants were unaware of the hypotheses that inspired the experiments. All participants had normal vision.

The experiment consisted of two parts, a cued discrimination task (see Figure 1) and a subsequent test of recognition for the parts of the ambiguous figure-ground displays used as cues where the target always appeared, compared with recognition of the parts of the cue (see Figure 3) where the target *never* appeared and with false "recognition" of such stimulus parts never presented before. Each observer participated in 5600 trials in the cued discrimination task (56 blocks of 100 trials run over a period of 3 to 4 days, dependent on the convenience of the observer). All observers participated in at least 30 practice trials beforehand, or until they were comfortable with performing the discrimination task, and did so without too much error. Data collection took about 5 hours in total for each observer. Following the cued discrimination part of the experiment the participants underwent a 576 trial recognition test for the 2 parts of all the 96 figure-ground ambiguous displays (both the 48 used as cues as well as the 48 new ones which the observers had not seen before, see details below), to determine whether the main manipulation of where within a streak a particular cue was used had an effect upon the observers' recognition of the part of the cue where the target consistently appeared. Each part was presented three times in total during the recognition test.

Materials

Stimuli were presented on an 85 Hz CRT screen with a spatial resolution of 1024 by 768 pixels, controlled by a 400 MHz Power PC G4 computer. Custom software, programmed in C utilizing the VisionShell function library, was used for stimulus presentation. A central bright (46.5 cdm^{-2}) cross, serving as a fixation marker, was present throughout, and observers were instructed to maintain fixation on it during the whole experiment (see Figure 1).

Stimuli

96 different figure-ground ambiguous displays (as shown in Figure 1A) were generated for each observer, 48 were used as cues for the discrimination task, and the subsequent recognition test, while 48 were new figure-ground displays used as baseline for the recognition test.

A random curve-generating algorithm was developed in Matlab to create the figure-ground ambiguous displays. The algorithm was a modified version of the one used by Baylis and Driver (1995). A 412 point vector was randomly divided into 20 to 70 point "steps" displaced either to the left or the right (decided randomly) by 40–140 points. This produced a random jagged contour which was subsequently smoothed with a 15 point smoothing algorithm[2], resulting in outlines similar to the ones seen in Figures 1A, 1C and 3A. The top 6 and bottom 6 points were then omitted from the vector since the smoothing algorithm did not apply properly to these extreme values of the vector. One side of each contour was then randomly colored black (.7 cdm^{-2}) and the other white (47.5 cdm^{-2}). The size of each of the figure-ground displays on the screen was 2.5° by 1.2° at a 57 cm viewing distance. The stimuli were presented on an approximately mid-gray (21.7 cdm^{-2}) background. An algorithm prepared to control the presentation order ensured that 16 figure-ground displays (of the 48 used as cues) appeared on trials 1 to 2 within streak of repetition of target appearing within the part of cue with the same brightness; 16 on trials with streak length 3 to 4; and 16 on trials 5+ within a streak. The probability that the target would appear within the part of the cue with the same brightness on consecutive trials was thus >.5 (as was the case in the studies by Kristjánsson et al., 2001 and Kristjánsson and Nakayama, 2003) to generate the desired number of trials for each streak length (which once again was determined by the presentation algorithm discussed above). Streak length was independent of whether the target appeared on the black or white part of the cue. The same cue was always presented in the same orientation. A black box (line thickness 8′) surrounded the cue and stayed in place when the cue disappeared until the mask was presented. The Vernier acuity stimuli were presented in white, the length of each line of a pair was 1.3° and the line thickness was 12′. The displacement to the left or right was by 4′. The local random-dot (black or white, same brightness as on the cue) masks were 2.5° by 2.5° (dot size = 12′).

Procedure

The observers started by performing the cued Vernier acuity discrimination task, where they had to decide whether the top line of the two in a pair (see Figure 1D) was displaced to the right or left relative to the lower one. On any given trial, the target appeared randomly in one of the six possible locations (see Figure 1C). The other locations contained distractor Vernier acuity stimuli, presented simultaneously to the target, which were irrelevant to the task. To prevent the observers from using an internal representation of the imaginary oval that the target and distractors appeared on to determine where within the cue the target would appear, the center of the oval jittered randomly (horizontally) from one trial to the next by 0° to 3.5°. The fixation point was, however, always in the same location. The distance of the Vernier acuity target from the central fixation point varied thus by 5° to 8.5° from trial to trial (a similar spatial uncertainty was applied in Kristjánsson et al., 2001 and Kristjánsson & Nakayama, 2003).

A trial started with the presentation of a central fixation cross, followed 1200 to 1700 ms later (determined randomly) by the cue, presented for 70 ms (see Figure 1). The Vernier acuity discrimination stimulus followed (presented for 130 ms). The discrimination stimulus appeared either where the black or white part of the cue was previously presented. Importantly it *always* appeared on the same colored part of each cue, in order to measure the effects of different streak lengths on recognition of the figure-ground ambiguous displays. This whole stimulus presentation was then followed by local random dot masks which covered the area where each of the cue, target and distractors appeared (see Figure 1E).

Following the Vernier acuity test, the observers performed a test for recognition of parts of the figure-ground display used as cues. Two conditions were used for comparison: 1) The 48 parts of the figure-ground stimuli used as cues where the target *never* appeared. If recognition of the parts of the cue where the targets always appear is good we should expect that recognition for the part where the target did not appear should be bad since recognition for jigsaw-fit backgrounds of stimuli perceived as figure is quite poor (essentially at chance, presumably because edge assignment and in subsequence figure ground assignment is an obligatory process in vision; Baylis & Driver, 1995; Driver & Baylis, 1996; Kristjánsson, 2006c; Rubin, 1915). 2) The 96 parts of the 48 figure ground displays that were generated for each observer but never used as cues, so the observers had not seen them before. For this recognition test, the 48 figure-ground stimuli used as cues, and the 48 new stimuli were split apart (as shown in Figure 3). Therefore, recognition for 96 "old" or previously presented figure *parts* was compared to recognition of 96 "new" figure parts which the observers had not seen before. The observers were instructed to answer the following question (by pressing the appropriate key): "Have you seen this figure part before? (Yes/No)". Each of the 192 figure parts were presented foveally in random order (until response) and each was presented 3 times, so the recognition test consisted of 576 trials run in 3 blocks of 192 trials. The figure parts were always presented in the same brightness ("black" or "white") as they had been presented in as cues (if they were part of the cue set in the first place). They were presented on the same mid-gray background and in the same orientation as they had been in the cued discrimination experiment. The participants were informed that 50% of the trials would present a stimulus-part (used as cue) that they had seen before, but also that 50 percent of the stimuli would be new. The two naive observers had no idea that there would be a subsequent recognition test, when they performed the discrimination task.

Results

The main question of interest was whether figure-part recognition would be better for parts of cues that appeared

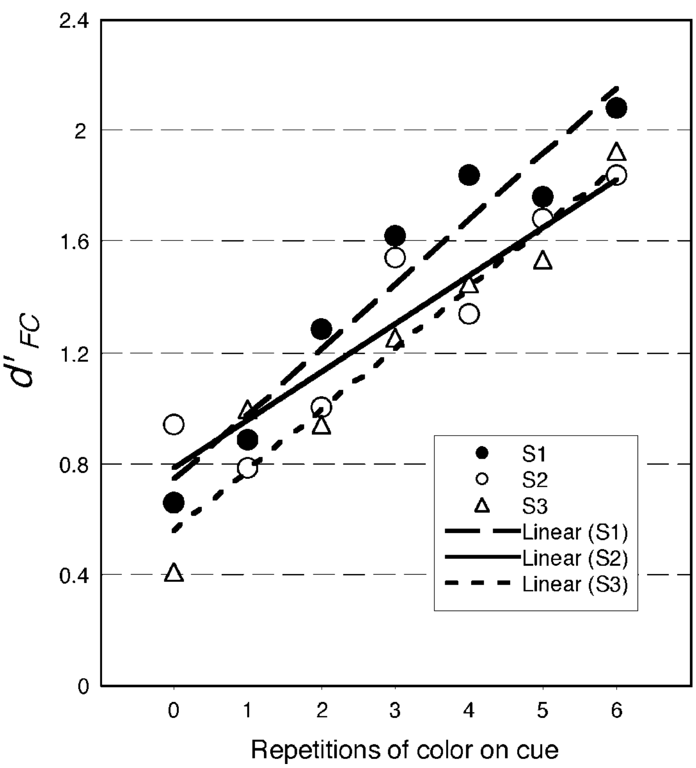

Figure 2. Performance for the three observers (S1, S2 and S3) on the Vernier acuity task as a function of how many times in a row (a "streak") a target appeared on a part of the cue of the same brightness (shown in d'_{FC} for two-alternative forced choice discrimination tasks for the three observers; see Methods section for details). Observer S3 was the only one who was aware of the hypotheses inspiring the experiments. The lines denote the best linear fits to the d'_{FC} scores for each individual observer.

later in streaks of repetition of cue-part brightness. First, however, it was necessary to establish that the manipulation regarding the brightness of the cue led to learning effects similar to those seen before by Kristjánsson and Nakayama (2003). If no such learning would be seen there would be little point to measuring any effects of streak length upon perception of the figure-ground ambiguous cues.

Figure 2 shows performance on the Vernier acuity task as a function of where, in a streak of repetition of cue-part brightness, the target appeared. In other words the further along the abscissa we go the larger the number of consecutive trials of the target appearing where a part of the cue of the same brightness had been (irrespective of absolute location on the screen and orientation of cue with regard to the brightness of its parts). Shown is Vernier acuity performance in d'_{FC} for 2 alternative forced choice tasks (Wickens, 2002;[3] see also Hacker & Ratcliffe, 1979). Performance improved strongly for all observers (increases of d'_{FC} of ∼.9 to ∼1.4) the more often in a row the target appeared within the part of the cue of the same brightness. Clearly it is quite beneficial for performance on this task if the target consistently appears on the same colored part of the cue on consecutive trials. This learning occurs in object-based, rather than space-based coordinates, since the observers never knew where on the screen the target would appear on any given trial nor where the black and white parts of the cue would appear. This result replicates, in essence, what Kristjánsson and Nakayama (2003) found (their Experiment 1).

As explained in the Methods section, 48 of the 96 figure-ground stimuli generated for each observer were selected as cues and were then assigned to appear within designated parts of streaks of repetition of cue-part brightness (16 in streak positions 1 and 2, 16 in streak positions 3 and 4 and 16 in streak positions 5 or higher[4]). The target always appeared within the same colored part of any particular cue. In a test where the observers were instructed to answer the question "was this particular figure-part used as a cue in the preceding discrimination experiment?", we could measure whether more effective attention shifts (following repetition of cue-target contingencies, as shown in Figure 2) would lead to increased recognition of the parts of the figure-ground ambiguous cues where the target appeared (see Figure 3A). The proportion of cue-parts correctly identified as previously presented is shown in Figure 3B. As the target appeared more often on the part of a cue of the same brightness (the white symbols on the right, connected by a line), the likelihood increased that this part of the cue would be

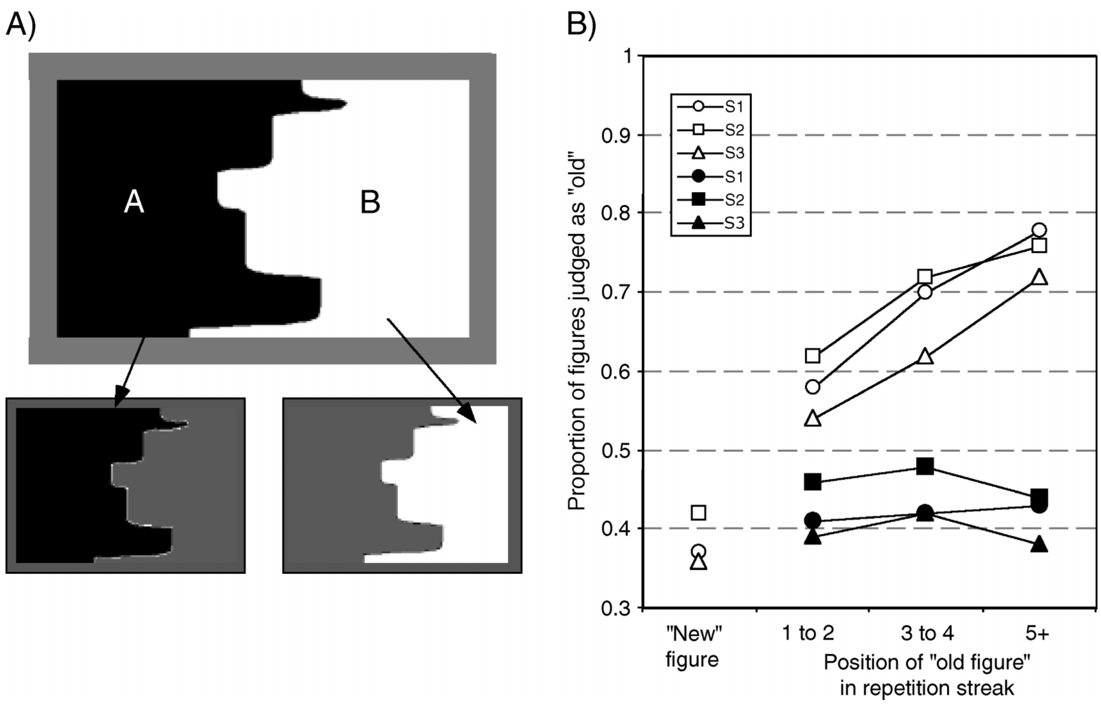

Figure 3. The results of the recognition test of the cue-parts. Panel A shows an example of the recognition test performed following the discrimination task. The parts of the figure-ground displays were presented in isolation on the screen (as shown at the bottom in panel A) and the observers had to respond whether they had seen these figure parts before (in the discrimination part of the experiment). Panel B shows the proportion of parts of figures correctly identified as being part of the cue set, for the three observers, as a function of where in a streak they were presented. The black symbols denote recognition for parts of cues where the target *never* appeared, while the white symbols show recognition of the parts where the target consistently appeared (for any single cue). The leftmost white symbols (disconnected from the others) denote false "recognition" or false alarms for the new figure-parts never presented before. Observer S3 was the only one who was aware of the hypotheses inspiring the experiments.

correctly identified as previously presented. Furthermore, the display parts that appeared in the latter parts of streaks (3 to 4 and 5 or more) were more often correctly recognized as parts of previously presented cues than the ones used in positions 1 and 2, and importantly this was only true for the parts of the cues where the target consistently appeared. Recognition performance was no better than chance for the cue-parts where the target never appeared (black symbols), and did not differ from the false alarm rate for the new figure parts (white symbols on the left). This was the case for all three observers.

This result is in agreement with the seminal studies of Rubin (1915), and others since, see Introduction), who found that observers were far more likely to recognize previously presented displays when they were perceived as figure than when they were perceived as ground, but the results in addition suggest that this becomes more pronounced with the strength of shifts of transient attention (consistent with Vecera et al., 2004).

Note that the cue-parts used in streak positions 1 to 2 were more often correctly identified as having been presented in the cued discrimination task than the new cue-parts, and the cue parts where the target never appeared. This, most likely, reflects a general benefit of attention shifting to the location of these parts (where the target appeared) which becomes more pronounced with learning.

General discussion

There are two main conclusions to be drawn from the results reported here. Firstly, the more often a target appeared on a part of the cue of a certain brightness (either black or white), the better the Vernier acuity performance became, indicative of learning in shifts of transient attention, consistent with previous results of Kristjánsson and Nakayama (2003). The main new finding here, however, is that these learning effects affect subsequent recognition of parts of figure-ground ambiguous displays as measured by a delayed recognition test. This indicates that the learning of attention shifts not only aids discrimination performance but can have a more profound effect upon perception, increasing the likelihood that parts of these displays are recognized on a subsequent memory test.

One possible account for the results is that attention shifts are stronger and/or faster (through recruitment of additional attentional resources) the more often the target appears on a part of the cue of a particular brightness and that this then influences figure-ground assignment. Vecera et al. (2004) showed that when a briefly presented ($\sim$50 ms) attentional cue is presented within one region of an ambiguous figure-ground display, this affects figure-ground assignment. The results here are entirely consistent with this, but in addition raise the possibility that such effects become even stronger with learning in attention shifts. While the results here strongly suggest that figure ground assignment becomes more efficient as more attentional resources are recruited to the region of the cue with learning of cue-target relations (consistent with the findings of Vecera et al., 2004), the results are, however, also consistent with the possibility that figure-ground segmentation is strong for cues in all positions in the repetition streaks, and the observers simply remember the figural shape better with learning, and further experimentation will be needed to decide between the two possibilities.

The observed benefit of repetition of cue-target contingencies seems, however, unlikely to simply reflect that the contour or the cue pattern itself is more easily recognized with learning, since this should entail that recognition for the parts of the cue where the target never appeared would, at the very least, be better than for the completely new parts, but this was clearly not the case. Rather, the fact that recognition of these parts was no better than the false alarm rate for new figure parts strongly suggests that the cue parts where the target appeared were very efficiently split from their background (see, for example, Driver & Baylis, 1996).

It is important to note that these effects as a function of streak length are over and above simple effects of attention shifts upon recognition of the cue parts (which can be seen for streak lengths 1 to 2 in Figure 3). Had this simply been an effect of attending to the cued location (as found before by Vecera et al., 2004), recognition performance should not have improved with increased length of streaks of repetition of cue-part brightness, but performance should have been equal for all streak positions.

Relation to other learning effects upon perception

Perceptual learning has often been thought to be a relatively low-level, retinotopic process. Dosher and Lu (2004; see Gibson, 1963 and Gibson & Gibson, 1955 for slightly different definitions) stated: "improvements in performance are claimed to reflect perceptual learning, […] whenever the performance is shown to be specific to either a retinal location or to a basic stimulus dimension such as orientation or spatial frequency." This is indeed consistent with what many have found (Ahissar & Hochstein, 1997; Fahle, Edelman, & Poggio, 1995; Karni & Sagi, 1993; see e.g. Goldstone, 1998 for review). This has been contrasted with what is sometimes referred to as *cognitive learning* assumed to reflect changes at higher processing levels (Dosher & Lu, 2004).

Such views of perceptual learning have been challenged by some recent findings, however. Sireteanu and Rittenbach (2000) investigated learning in visual search tasks and found that perceptual learning in such tasks can generalize over visual fields, different locations, interocularly and even between different tasks. Other such evidence comes from studies where learning has been found to affect visual appearance. Haijiang et al. (2006) showed how a change in visual appearance could be modulated by a process reminiscent of classical conditioning. Their finding was that signals that were repeatedly paired with a certain rotation direction of an ambiguous stimulus influenced subsequent perception. Their observers viewed rotating bi-stable Necker cubes. Stereoscopic disparity and occlusion were used to influence the perceived direction of rotation. In a critical manipulation, stimuli completely unrelated to the task were presented, and unbeknownst to the observer, some were coupled with one rotation direction while others with the other rotation direction. Over time, their observers started to "learn" this relationship, so that these seemingly unrelated stimuli influenced perceived rotation direction of ambiguous stimuli. Haijiang et al. concluded that "an individual new signal can be recruited by the visual system for the construction of visual appearance" (p. 483) and that this demonstrated that such learning went beyond simple improvements in discrimination ability (as is indeed what the current results demonstrate; see Backus & Haijiang, 2007 for some further elaborations upon this result).

A related finding was reported by Seitz and Watanabe (2003) who found implicit learning of an irrelevant and subliminal feature that was positively correlated with target presentation. They investigated a visual learning phenomenon introduced by Watanabe, Náñez, and Sasaki (2001), who found that while observers performed an attentionally demanding discrimination task presented foveally, learning of sub-threshold motion occurred. Seitz and Watanabe (2003) then showed that this perceptual learning could be specific to motion direction, when paired with the target, while not when paired with distractors. When a particular motion direction was consistently paired with the targets, motion direction discrimination thresholds improved for the direction paired with the target while this did not occur for the other directions. The conclusion that Seitz and Watanabe drew from their study was that reinforcement learning can affect motion detection thresholds and that such learning can occur outside the focus of attention (see Seitz & Watanabe, 2005, for further discussion). This is consistent with the current results, since figure-ground assignment was completely unrelated to the discrimination task in the present study and the naive observers had no idea that their recognition of these figure parts would be tested following the discrimination task.

Perceptually ambiguous stimuli, intermittently presented, tend to be interpreted in the same way on each presentation, while their perceived nature tends to fluctuate when they are presented continuously (Leopold, Wilke, Maier, & Logothetis, 2002). Recently, Brascamp, Knapen, Kanai, Noest, van Ee, and van den Berg (2008) presented observers with directionally ambiguous rotating spheres (using two-dimensional induced depth) and binocularly rivalrous stimuli. Brascamp et al. found that these two perceptual tendencies reflect a short-lived effect of the latest percept, as well as a more persistent influence reflecting the percept that has been proportionally dominant during a preceding period of at least one minute. The visual system seems biased toward previous interpretations but in this case the interpretation seems to reflect the operation of mechanisms with different time constants. Brascamp et al. suggested that such history biases share characteristics with learning in shifts of transient attention (see e.g. Kristjánsson, 2006b, for review). While no such differential effects are addressed in our current study, such questions would be of great interest for future studies of learning in paradigms of this sort.

As mentioned before, many studies have not found perceptual learning effects of task irrelevant features, however. Shiu and Pashler (1992) did not find perceptual learning of Vernier acuity stimuli when the task called for a brightness discrimination rather than acuity judgments (which was then task irrelevant; see also Ahissar & Hochstein, 1997; Fahle et al., 1995). Seitz and Watanabe (2005) argued that the studies failing to find perceptual learning of task-irrelevant features lacked a consistent relationship between the task-irrelevant features and the task. In the current experiments the learning is of irrelevant features, that nevertheless do indeed have a consistent relationship with the discrimination target, consistent with the claims of Seitz and Watanabe. While one may define perceptual learning as something retinotopically specific or feature specific, the aforementioned results, along with the current ones, certainly entertain a blurring of distinctions between perceptual learning, on the one hand, and "cognitive" learning on the other, since the latter term clearly does not apply well to these examples, nor the present results.

Conclusions

Overall, the current results show how what may be our most reflexive and primitive visual behavior, shifts of transient visual attention, show learning of what has gone before, and that this learning leads to improved recognition of parts of briefly presented ambiguous figure/ground displays. Such effects of learning in transient attention shifts upon perception are more direct than the effects that have been demonstrated before, raising the possibility that learning in attention shifts can modulate figure-ground assignment. This learning is reminiscent of a number of recent examples of how perceptual learning can be more flexible than previously thought. The findings here suggest that this learning in shifts of transient attention can have direct effects not only upon discrimination performance but more generally upon how we organize our visual environment.

Acknowledgments

This research was supported by the Human Frontiers Science Program and the Research Fund of the University of Iceland, and was carried out while the author was an honorary research fellow at the Institute of Cognitive Neuroscience, University College London. Aaron Seitz, Karen Dobkins, and two anonymous reviewers are thanked for very helpful comments upon previous versions of this manuscript.

Commercial relationships: none.

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Footnotes

[1]Streak length is defined as the number of times (or consecutive trials) the target appeared within the part of the cue of the same brightness.

[2]The 15 point smoothing algorithm was the following (applied to the lateral values of each of the 412 pixels along the vertical extent of the vector representing the figure outline): $S_i = (F_{(i-7)} + 2F_{(i-6)} + 3F_{(i-5)} + 4F_{(i-4)} + 5F_{(i-4)} + 6F_{(i-2)} + 7F_{(i-1)} + 8F_i + 7F_{(i+1)} + 6F_{(i+2)} + 5F_{(i+3)} + 4F_{(i+4)} + 3F_{(i+5)} + 2F_{(i+6)} + F_{(i+7)})/64$, where F_i is the value of the *unsmoothed* contour vector at position i and S_i is the value of the *smoothed* contour vector at position i (this algorithm is a modified version of the one introduced by Baylis & Driver, 1995).

[3]d'_{FC} denotes the difference between two distributions (in this case of response to each displacement, left or right) as with the more well known d'. Note that it is, of course, arbitrary in this case which distribution is considered to be "signal" and which one "noise" but d'_{FC} measures essentially the psychophysical distance between perceived displacement to the right or the left. Note that $d'_{FC} = 2Z(P_C)$, so that $d'_{FC} = (\sqrt{2})*(d')$, where P_C denotes the proportion correct. See Wickens (2002) for detailed discussion.

[4]As explained in the Methods section, a presentation algorithm ensured that there was an equal number of trials in each group of streak lengths to control for effects of frequency of appearances upon recognition of the cues.

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