Display probability modulates attentional capture by onset distractors

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Attention can be stimulus-driven and bottom-up or goal-driven and top-down. Bottom-up attention and, particularly, attentional capture are often thought to be strongly automatic, i.e., not modulable. For example, in visual search, it has been shown that salient distractors strongly attract attention even though observers were instructed to ignore them. However, it was also shown that the strength of distraction can be modulated by the display probabilities of the distractors. Hence, bottom-up attention seems not to be completely automatic. In these studies, the distractors were salient by color differences to the other items in the display. Such color distractors, however, do not necessarily trigger bottom-up attention. Here, we presented onset distractors, that is, distractors displayed after the onset of the other search items, which are thought to strongly elicit bottom-up attention and to capture eye movements. Varying the display probabilities of the onset distractors strongly modulated attentional capture. We suggest that modulation was due to statistical learning. This study adds further evidence that bottom-up processes are not completely automatic.

Keywords: visual search, attention, oculomotor capture, eye tracking, bottom-up processing, singleton distractor interference

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Introduction

It is well known that reaction times (RTs) in visual search paradigms can be influenced by two different attentional mechanisms: bottom-up (stimulus-driven) and top-down (goal-driven) attention. While bottom-up attention is usually driven by salient stimuli in the display, top-down attention is controlled by the observers' current intentions and goals. It has often been proposed that the allocation of bottom-up attention is a highly automatic process (e.g., Cohen & Magen, 1999; Mortier, Theeuwes, & Starreveld, 2005; Theeuwes, 1991, 1992; Theeuwes, Reimann, & Mortier, 2006). Theeuwes (1992) used a compound task (Duncan, 1985) to investigate the influence of an irrelevant singleton distractor on target detection. For example, stimuli consisted of squares and a green ring arranged on an imaginary circle (Figure 1A). Observers searched for the ring and determined the orientation of a line inside the ring. Either all squares were green or one square was red to distract attention (Figure 1B). RTs were significantly slower when the red distractor was present compared to when only the green squares were presented. When the target was defined in the color dimension, a less salient form distractor did not lead to a similar increase in RTs. This result was taken as evidence that attention is automatically captured by the most salient item in the display.

In a recent investigation, however, using a search paradigm similar to the one by Theeuwes (1992), it was shown that attentional capture by salient distractors might not be automatic. RTs were significantly longer when the distractor display probability was low (0.2) compared to when it was high (0.8; Müller, Geyer, Zehetleitner, & Krummenacher, 2009). In a follow-up study using the same paradigm, Geyer, Müller, and Krummenacher (2008) showed that not only manual RTs but also eye movement parameters were affected by distractor display probabilities. First, Geyer et al. (2008) found that when distractors were presented in only 20% of the trials, latencies of target-directed saccades were longer compared to conditions with higher distractor display probabilities. Second, it was

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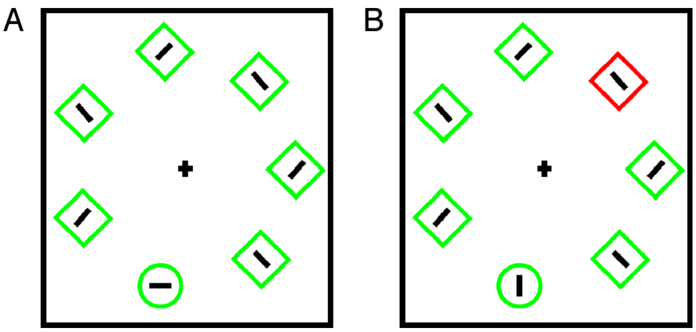

Figure 1. Illustration of the compound search displays used by Müller et al. (2009) and Theeuwes (1992). In this example, observers had to search for a form-defined target (a ring) and to indicate the orientation of the line within the target. A color singleton distractor may or may not be present. (A) Example without color singleton distractor. (B) Example with color singleton distractor (red square).

shown that the proportion of eye movements to the distractor likewise depended on the distractor display probability: the higher the probability, the lower was the proportion of saccades to the distractor.

In both studies, attentional capture by distractors depended on feature differences within a dimension, for example, a red singleton distractor among green non-target elements (note that "redness" itself was not more salient than "greenness"). Hence, it was the "relative" feature or "odd one out" salience that directed search to the distractor (e.g., Nothdurft, 2000; Treisman & Gelade, 1980). While it is commonly accepted that such salient feature singletons "pop out" and can be searched efficiently, they do not always strongly capture attention as shown, for example, in paradigms investigating attentional capture with surprise trials (e.g., Gibson & Jiang, 1998; Horstmann, 2005; but see Horstmann, 2002). Feature contrast salience is different from *onset* salience of a stimulus that newly appears on a display. In several experiments, onsets have been shown to strongly capture attention (e.g., Jonides & Yantis, 1988; Yantis & Jonides, 1990). Jonides and Yantis (1988) claimed that onset stimuli capture attention purely automatically, in contrast to, for example, color- or luminance-defined stimuli (see also Franconeri, Hollingworth, & Simons, 2005; Yantis & Hillstrom, 1994).

The main goal of the present study was to study whether also onset capture is modulable by varying display probabilities. We found a strong modulation of attentional capture, which we relate to statistical learning (e.g., Chun & Jiang, 1998; Droll, Abbey, & Eckstein, 2009; Fiser & Aslin, 2001, 2002; Rosenthal, Fusi, & Hochstein, 2001; Saffran, Aslin, & Newport, 1996; Saffran, Newport, Aslin, Tunick, & Barrueco, 1997; Turk-Brown, Jungé, & Scholl, 2005). The higher the rate of the onset distractors, the stronger they were suppressed. This may occur explicitly (Müller et al., 2009) or implicitly (Müller, Heller, & Ziegler, 1995). Importantly, statistical learning is not due to simple suppression carried over from one trial to another. Our results support accounts arguing against a purely automatic and impenetrable attentional capture system (e.g., Bacon & Egeth, 1994; Eimer & Kiss, 2008; Folk & Remington, 2006, 1998; Folk, Remington, & Johnston, 1992; Found & Müller, 1996; Geyer et al., 2008; Müller et al., 2009, 1995).

Materials and methods

Observers

Observers were students of the Ecole Polytechnique Fédérale de Lausanne or the Université de Lausanne. They were paid 20 CHF per hour. Subjects were informed about the general purpose of the experiment and gave written consent. Participants were told that they could quit the experiment at any time. All observers were naive as to the purpose of the experiment. The experiment was approved by the local ethics committee.

The Freiburg visual acuity test (Bach, 1996) was applied to determine observers' visual acuity. To participate in the experiments, subjects had to reach a value of 1.0 (corresponding to 20/20) for at least one eye. All subjects had normal or corrected-to-normal visual acuity. The Ishihara pseudo-isochromatic color plates were used to test for red–green color vision deficiencies; one observer failed in this test and was excluded at this stage. Twenty observers participated.

Apparatus

Stimuli were presented on a PHILIPS 201B4 CRT monitor driven by a standard accelerated graphics card. The screen resolution of the CRT was set to 1024 by 768 pixels. The monitor's white point was adjusted to be D65. Color space was computationally linearized by applying individual gamma corrections to each color channel (8 bits per channel). A Minolta CA-210 display color analyzer was used for calibration measurements. Luminance measurements have been performed using a Minolta Luminance meter LS-100.

Observers viewed the monitor from a distance of 60 cm. An SMI eye tracker (iViewX HI-SPEED) with a sampling rate of 500 Hz (binocular tracking) and a tracking resolution of <0.01° was used. The eye tracker was fitted with a chin and forehead rest to minimize head movements during the experiment.

Stimuli

The initial display contained 6 red discs (CIE chromaticity coordinates: x = 0.6289, y = 0.3317; luminance:

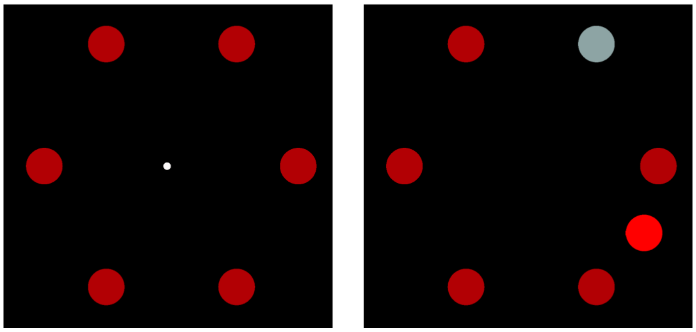

Figure 2. Illustration of the search displays. (Left) The fixation display is shown. (Right) After 600 ms, one of the red discs turned gray. Observers had to make a saccade to this target disc. In a certain proportion of trials, a red onset distractor (right panel, clock position 4) was presented simultaneously with the color change. This onset distractor appeared in a position in between two of the discs (but never next to the target).

4.2 cd/m^2) presented equally spaced on an imaginary circle with a radius of 9.6° of visual angle around the center of fixation (Figure 2). One disc changed into an isoluminant gray disc (luminance: 4.2 cd/m^2) that could appear at one out of four display locations, namely, the upper and lower, left and right locations. This disc was the target and observers were required to make a saccade to its location.

In a predefined proportion of trials, additionally, a red onset distractor disc appeared at the same time as the target (CIE chromaticity coordinates: x = 0.6289, y = 0.3317; luminance: 14.0 cd/m^2, a pilot experiment showed that with a luminance of 14.0 cd/m^2, observers made a saccade to the onset distractor in approximately 50% of the trials). The onset distractor (OD) was presented on the same imaginary circle in between two disc locations but never next to the target. The OD was separated from the target by 30°, 90°, or 150°. Possible OD locations were at "clock positions" 2, 4, 8, and 10 (not at 6 or 12). All discs had a diameter of 80 arcmin.

At the beginning of each trial, a fixation point (diameter of 6 arcmin) was presented in the middle of the screen. After 300 ms, the discs were presented. Six hundred milliseconds after the disc onset, the color of the target disc changed (either with or without a simultaneously presented OD). The fixation dot disappeared at the same time. The target, the remaining discs, and the OD (if presented) stayed on the screen for 1200 ms after target onset. The next trial started 800 ms afterward. If the latency of observers' initial saccades exceeded 250 ms relative to the target onset, acoustical feedback in the form of a low-pitch tone was given, indicating that observers initiated the saccade too slowly; if saccade latency was below 250 ms, a high-pitch tone feedback was given. Observers were informed about the paradigm, particularly, about the occurrence of ODs but not their display probabilities.

Design and procedure

The observers' task was to make a saccade as fast and accurately as possible to the target. Observers were also instructed to subsequently fixate the target if they had accidentally made an eye movement to the OD instead of the target. The display probability of OD trials was varied across blocks. The percentage of OD trials within a block was 0%, 20%, 50%, 80%, or 100%. Two experimental conditions were used. In the "run-up" condition, observers were first presented with blocks containing no ODs (0%), followed by 20%, and up to 100% ODs. In the "run-down" condition, blocks were presented in the opposite order, that is, in the first block 100% ODs were presented, followed by 80%, down to 0%. While in the run-up condition the likelihood to ignore ODs was expected to be low in the beginning of the experiment (particularly in the 20% OD condition immediately following the initial 0% OD block), it was expected to be high in the run-down condition. Each block contained 100 trials. Observers completed two consecutive blocks of each of the five OD conditions. Within a block, OD trials and no-OD trials were randomly interleaved. OD positions were randomly distributed between the four possible positions (clock positions 2, 4, 8, and 10). Observers were randomly assigned to one of the two experimental conditions (run-up or run-down).

Data analysis

The time from target onset to the initiation of the first saccade was measured (saccade latency). Saccades with latencies faster than 80 ms or slower than 600 ms were discarded before data analysis. Saccades were defined as directed to one of the items (e.g., OD or target) if the initial fixation was inside a region extending ±7.5° of visual angle relative to one of the item locations. Trials were discarded from analysis when the fixation on the central point preceding presentation of the display items deviated by more than 1 arcdeg from the center of this point. In the main analyses, only trials with ODs were considered. The 0% OD and 100% OD conditions (which have no or 100% OD trials) were not included in the main analyses but used for a post-hoc analysis of saccade latencies.

Results and discussion

Saccade destinations

Figure 3 shows the percentage of initial saccades to the OD as a function of the proportion of ODs. Initial saccades of the 20%, 50%, and 80% conditions were subjected to an ANOVA with the within-subject factor

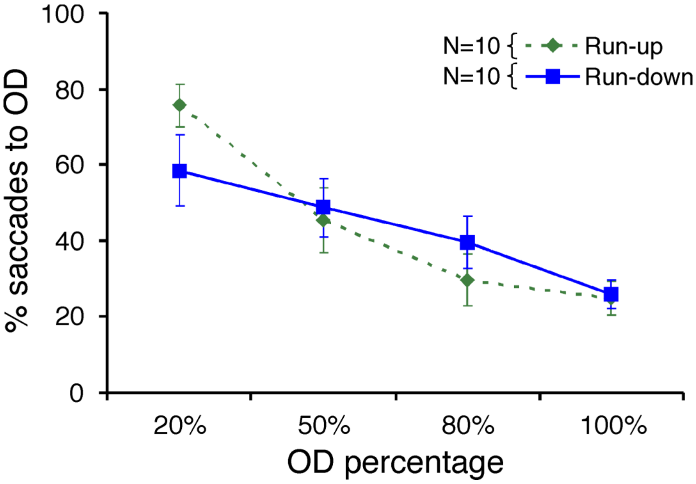

Figure 3. Percentage of saccades to the OD as a function of OD percentage (20%, 50%, 80%, and 100%) for the run-up and run-down conditions. In both conditions, more saccades landed on the OD when the OD percentage was low. If saccades were not modulable, flat functions would have been expected. However, this was not the case. No significant interaction was observed. Only the 20%, 50%, and 80% conditions were statistically analyzed. Error bars indicate the standard error of the mean.

"OD percentage" (20%, 50%, and 80%) and the between-subject factor "run-direction" (run-up and run-down). The ANOVA revealed a significant main effect of OD percentage ($F(2,54) = 9.21$, $p < 0.001$). Neither a main effect of run direction ($F(1,54) = 0.045$, $p = 0.83$) nor an interaction between the two factors ($F(2,54) = 1.71$, $p = 0.19$) was significant. The significant main effect of OD percentage was due to a strong decrease of the rate of saccades to the OD with an increase of OD percentage in both the run-up and run-down conditions. Pooling the data of the two conditions (run-up and run-down) revealed that the attentional capture rate in the 20% condition was almost two times as large (67.0%) as in the 80% condition. In the 50% condition, attentional capture was higher compared to the 80% condition and lower compared to the 20% condition. The 100% condition was not included in the main analysis because it was the first condition in the run-down group and used for the familiarization with the task and setting up expectancies for the subsequent blocks (as the 0% condition in the run-down group). Even though this condition was mainly used to build up expectancies, the attentional capture rate was still lower compared to the 80% condition (Figure 3).

We expected a significant interaction between OD percentage and run direction. First, the capture probability was expected to be higher with lower OD display probability. Second, practice increases over the course of the experiment and was expected to reduce the attentional capture rate. Practice in the run-up condition coincided with an *increasing* OD percentage. Hence, both practice and OD percentage should have facilitated the task. In the run-down condition, on the other hand, practice coincided with a *decreasing* OD percentage. While practice facilitated the task, the decreasing OD percentage impeded performance. However, although a corresponding trend was observed, the potential interaction was not significant (see above).

Intertrial analysis

The main effect of OD percentage (the decrease of OD capture rate with higher OD percentage) could be due to intertrial effects. If observers are able to suppress saccades to the OD in trials that are *preceded* by OD trials more efficiently compared to trials that are not preceded by OD trials, a similar pattern of results would be observed. For example, in the 80% condition, the majority of OD trials was preceded by OD trials, while in the 20% condition OD trials were only rarely preceded by OD trials. These intertrial effects may reflect inhibition of the OD dimension carried over to the next trial. To investigate whether the main effect of OD percentage was due to such intertrial effects, we conducted an intertrial analysis. Because there was no significant interaction between the run-up and run-down conditions in regard to the OD capture rate (Figure 3), the data of the two conditions were pooled. We compared the OD capture rate in trials that were preceded by OD trials (ODOD in Figure 4) with the capture rate in trials that were preceded by no-OD trials (nODOD in Figure 4).

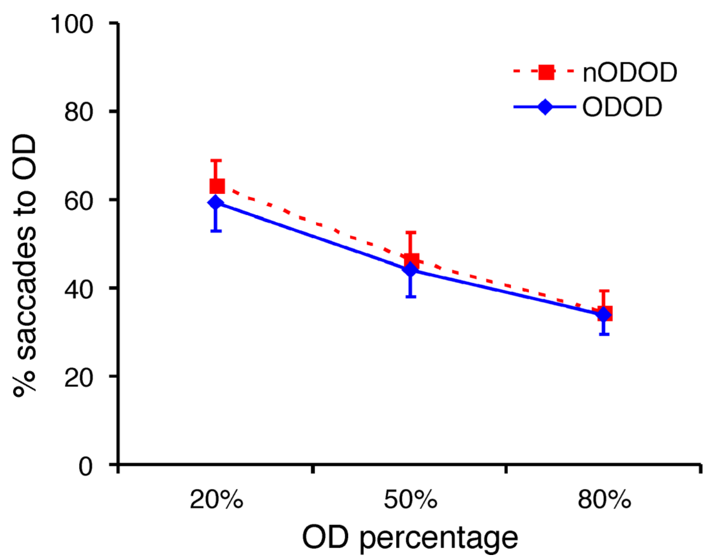

Figure 4. Intertrial analysis. Percentage of saccades to the OD as a function of OD percentage (20%, 50%, and 80%) for OD trials that were preceded by either a trial containing an OD (blue line, ODOD) or trials containing no OD (red line, nODOD). No difference was found between the two conditions (ODOD and nODOD). Error bars indicate the standard error of the mean.

As shown in Figure 4, the capture rate did not depend on the presence or absence of an OD in the preceding trial. An ANOVA with the within-subject factors "OD percentage" (20%, 50%, and 80%) and "intertrial priming" (preceding trial containing an OD or not) revealed a significant main effect of OD percentage ($F(2,112) = 11.25$, $p < 0.001$) but no effect of intertrial priming ($F(1,112) = 0.153$, $p = 0.697$). (We performed the same analysis with the additional constraint that in preceding OD trials attention was not captured and found no change of the pattern of results.) Evidence for intertrial priming would have been a lower OD capture rate in OD trials that were preceded by OD trials (that either captured attention or not) compared to preceding no-OD trials.

Saccade latency

Figure 5 shows the latencies of the initial saccades as a function of OD percentage for the run-up and run-down conditions. In the main analyses, only the 20%, 50%, and 80% conditions were considered. Latencies are shown separately for saccades to the target and to the OD, respectively. Latencies were subjected to a mixed ANOVA with the between-subject factor "run direction" (run-up and run-down) and the within-subject factors "OD percentage" (20%, 50%, and 80%) and "saccade landing site" (target and OD). We found a significant main effect of run direction ($F(1,106) = 41.04$, $p < 0.001$) with shorter saccade latencies in the run-down (176.77 ms) compared to the run-up (201.20 ms) condition. Further, the main effect of saccade landing site was significant ($F(1,106) = 187.54$, $p < 0.001$) with shorter latencies to the OD (162.88 ms) than to the target (215.09 ms). No significant main effect was found for OD percentage ($F(2,106) = 2.80$, $p = 0.07$). No interaction was significant.

In both the run-up and run-down conditions, saccades directed to the OD were faster than saccades to the target. The difference in saccade latencies might be explained by two (interdependent) effects. First, the high luminance increment of the ODs might have expedited the generation of a space-based saliency signal relative to the lower color saliency of the target. Second, saccade latencies to the target might have been slower because of (costly) suppression of saccades to the OD in these trials.

It is interesting to note that saccade latencies were not affected by the proportion of ODs presented within a particular block of trials (with the exception of somewhat higher latencies to targets in the run-up 20% OD condition compared to the 50% and 80% OD conditions). This suggests that saccade latencies were determined by processes that are not accessible by observers' long-term strategies, speaking in favor of a pure bottom-up effect.

To examine the somewhat unexpected difference found in saccade latencies of the run-up and run-down conditions, respectively, saccade latencies to targets in blocks with 0% and 100% OD were analyzed. While the 0% condition yielded a significant difference (204.77 ms and 179.91 ms for the run-up and run-down conditions, respectively; $t(18) = 2.899$, $p = 0.01$), the 100% OD condition did not (212.97 ms and 211.89 ms; $t(18) = 0.126$, $p = 0.90$). Moreover, in the 100% condition saccade latencies to the OD were also not significantly different (164.84 ms and 159.74 ms; $t(17) = 0.730$, $p = 0.48$). While these results might reflect an effect of the experimental manipulation, an interpretation in terms of different overall performance of observers in the two conditions is also possible (see General discussion section).

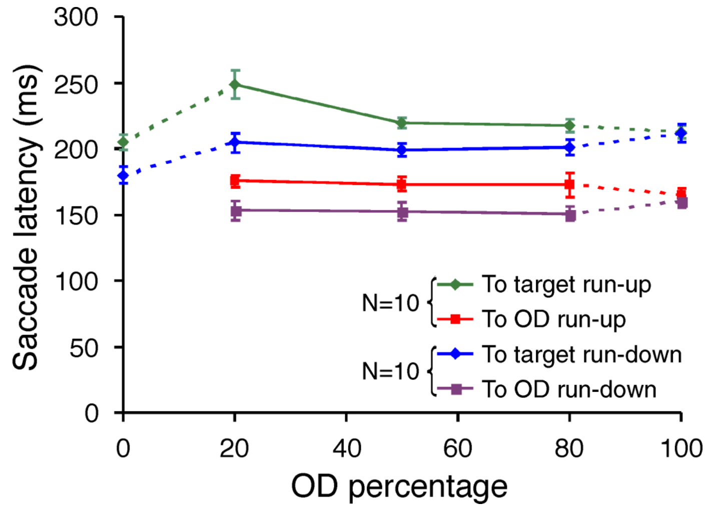

Figure 5. Saccade latencies as a function of OD percentage for the run-up and run-down conditions and for initial saccades to the target or to the OD. For the 20%, 50%, and 80% conditions, latencies were shorter for saccades to ODs compared to targets in both the run-up and run-down conditions, respectively. In the run-down condition, latencies were shorter for saccades to targets as well as ODs compared to the run-up condition. There was no effect of OD percentage. The 0% and 100% conditions were analyzed separately from the other conditions. While latencies in the 0% condition were different, in the 100% condition (for both saccades to the ODs and targets) they were not. The dashed lines indicate that the 0% and 100% conditions were not part of the main analysis. Error bars indicate the standard error of the mean.

General discussion

It is generally accepted that two different attentional mechanisms operate in visual perception: top-down (or goal-driven) and bottom-up (or stimulus-driven) attention. Less agreement is found about the degree of automaticity or modulability of bottom-up attention. Specifically, it is under debate whether or not bottom-up attentional capture is entirely automatic (e.g., Yantis & Jonides, 1990). While some researchers argued for a purely automatic process (e.g., Cohen & Magen, 1999; Mortier et al., 2005; Theeuwes, 1991, 1992), others questioned that bottom-up attentional capture is automatic but instead can be modulated (e.g., Bacon & Egeth, 1994; Eimer & Kiss, 2008; Folk & Remington, 2006, 1998; Folk et al., 1992; Geyer et al., 2008; Müller et al., 2009, 1995). Here, we showed that attentional capture by onset distractors (ODs), which are assumed to be the strongest cues to elicit bottom-up attention, was modulated by the display probability of the ODs. Hence, our findings strongly suggest that bottom-up attentional capture is not purely automatic (for the relation of attentional and oculomotor capture, see also Godijn & Theeuwes, 2002; Irwin, Colcombe, Kramer, & Hahn, 2000; Ludwig & Gilchrist, 2002, 2003; Theeuwes, Kramer, Hahn, Irwin, & Zelinsky, 1999; Wu & Remington, 2003). No trial-by-trial modulation was observed. We suggest that modulation in the present study was due to statistical learning.

Attentional capture by the OD depended on the percentage of OD trials within a block: The higher the percentage of ODs, the smaller the proportion of saccades captured by the ODs. Contrary to previous findings (Müller et al., 2009), we did not find an interaction between the run-up and run-down conditions. Such an interaction was hypothesized because practice effects and decreasing capture probability (due to increasing OD percentage) go hand in hand in the run-up condition but not in the run-down condition. While there was a tendency for such an interaction, the lack of significance might point at only a small effect of practice as larger practice effects would have resulted in a steeper curve in the run-up condition and a shallower curve in the run-down condition. Similarly, it shows that even with practice, observers in the run-down condition were not able to overcome the increasing capture probability, or likewise in the run-up condition to benefit even more from decreasing capture probability.

Intertrial transitions in which an OD trial was preceded by another OD trial were higher in blocks with high OD percentage compared to low OD percentage. This higher OD–OD trials frequency might have caused the OD percentage effect (the lower capture rate with higher OD percentage), for example, because of intertrial priming (e.g., Maljkovic & Nakayama, 1994, 1996; Walthew & Gilchrist, 2006). However, no such effect was observed. The OD capture rate in OD trials preceded by OD trials was not higher than in trials that were preceded by trials without an OD. This finding indicates that the modulation of the capture rate was not due to simple intertrial effects but rather caused by global stimulus characteristics emerging from a certain number of trials. On the other hand, we did not find an interaction between the run-up and run-down conditions, which indicates that the modulating effect did not accumulate over multiple blocks, i.e., modulation occurred within blocks (or conditions). It might be that the mechanisms responsible for monitoring the statistical properties of the stimuli were "reset" with the breaks between the individual blocks. It remains to be investigated how many trials are required to yield a display probability effect. Taken together, learning of the statistical properties in the present study occurred on a level between intertrial priming (Maljkovic & Nakayama, 1994, 1996) and "high level" top-down control (e.g., Müller, Reimann, & Krummenacher, 2003). While the exact mechanisms remain unknown, implicit short-term memory as in contextual cueing might be mediating the extraction of statistical information (see also Chun & Jiang, 1998; Geng & Behrmann, 2002, 2005; Hillstrom, 2000).

The examination of saccade latencies showed that latencies to the targets were always longer than to the ODs. This supports the assumption that a strong bottom-up signal was generated by the OD. There was no main effect of OD percentage (comparing the 20%, 50%, and 80% OD conditions). Overall, latencies in the run-up condition were higher compared to the run-down condition. A similar difference was found in the 0% condition (no-OD trials) but not in the 100% condition. We can only speculate whether this difference in all conditions, except the 100% condition, reflects effects of the experimental manipulation or is inherent to initial group differences. It could be argued that longer latencies in the run-up compared to the run-down condition were due to the different learning histories during the first blocks. While observers in the run-down condition learn early during the course of the experiment to suppress saccades to the OD, observers in the run-up condition do not (as observers in the latter group start with 0% distractors, which does not require suppression). The shorter latencies to the target in the run-down condition compared to the run-up condition could therefore reflect a maintained effective suppression of saccades to the OD. However, it is unclear why this effect was only observed in terms of saccade latencies but not in the rate of attentional capture where no differences between the two conditions was found. Moreover, the suppression does not explain why also latencies to the ODs are shorter in the run-down compared to the run-up condition. One potential source for shorter saccade latencies in the run-down group, namely express saccades (i.e., saccades with very short latencies, Fischer & Ramsperger, 1984), was excluded by investigating individual saccade latencies (the shortest latency to the target was 145 ms). Although we tend to interpret the differences in saccade latencies to be due to initial group differences and not to the experimental manipulation, further research is needed to disentangle these possibilities.

To conclude, in past experiments, it has been shown that attentional capture can be modulated when the distractors are feature-defined, for example, by a color difference. In the present experiment, we showed that modulation is even possible when distractors are onset stimuli that strongly capture attention. The results are due to implicit statistical learning operating on a relatively short time scale.

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