Impaired selection of a previously ignored singleton: Evidence for salience map plastic changes

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Abstract

Spatial suppression of a salient colour distractor is achievable via statistical learning. Distractor suppression attenuates unwanted capture, but at the same time target selection at the most likely distractor location is impaired. This result corroborates the idea that the distractor salience is attenuated via inhibitory signals applied to the corresponding location in the priority map. What is less clear, however, is whether lingering impairment in target selection when the distractor is removed are due to the proactive strategic maintenance of the suppressive signal at the previous most likely distractor location or result from the fact that suppression has induced plastic changes in the priority map, probably changing input weights. Here we provide evidence that supports the latter possibility, as we found that impairment in target selection persisted even when the singleton distractor in the training phase became the target of search in a subsequent test phase. This manipulation rules out the possibility that the observed impairments at the previous most likely distractor location were caused by a signal suppression maintained at this location. Rather, the results reveal that the inhibitory signals cause long-lasting changes in the priority map, which affect future computation of the target salience at the same location, and therefore the efficiency of attentional selection.

Introduction

Irrelevant salient stimuli can cause unintentional capture of attention that interferes with the voluntary selection of the relevant information, a phenomenon known as distraction. To counteract distraction, humans can rely on different neuro-cognitive mechanisms for attenuating the negative impact of distracting stimuli (Chelazzi et al., 2019; Geng et al., 2019). The general idea is that distraction control can be achieved by means of suppressive signals, likely originating from the frontal lobes, which are applied to different distractor features (Cosman et al., 2018; Geng, 2014). Although it is still debated as to whether distractor suppression is under top-down control (e.g., Gaspelin & Luck, 2018; Liesefeld & Müller, 2019), or only automatically driven by the statistical regularities in the sensory input (e.g., Wang & Theeuwes, 2018a), it is clear that frequent distractors are less likely to capture attention, probably because they receive stronger suppression (e.g., Ferrante et al., 2018; Leber et al., 2016; Müller et al., 2009; Wang & Theeuwes, 2018b). For example, by means of the statistical learning (SL) of distractor location, capture is attenuated at the location where the distractor is most likely to occur, and this because suppression would be applied at the corresponding location, either at the priority map level (Wang & Theeuwes, 2018b, 2018a) or at the dimensions level (Zhang et al., 2019), although statistical non-spatial suppressive mechanisms are also possible (Stilwell et al., 2019).

Different evidence seems to suggest that the suppressive signals cause enduring alterations in the activity of the priority map. To begin with, target selection is impaired at the location where the distractor has frequently occurred in the past, even on distractor-absent trials (e.g., Wang & Theeuwes, 2018b). In addition, reduced capture by distractors and slower orienting towards targets at the high-probability distractor

location is observed for several trials after that the distractor is made equiprobable at all locations (Britton & Anderson, 2020; Duncan & Theeuwes, 2020). Although, as anticipated, these lingering effects suggest that the suppressive signal caused long-lasting changes (i.e. enduring weights depression) in the priority map (Britton & Anderson, 2020; Ferrante et al., 2018; Zelinsky & Bisley, 2015), an alternative possibility is that effects of SL of distractor location persist because the suppressive signal continues to be applied on the priority map until the cognitive system learns that the distractor has become equally likely at all locations. However, Valsecchi and Turatto (2021) have recently shown that the effects of spatial suppression at the most likely distractor location remain evident for approximately a hundred of trials also when the distractor is completely omitted during a genuine extinction phase. This result appears to be at odds with the possibility that suppression continues to be exerted on the map because it takes time to learn the new even distribution of distractor occurrences. Still, one may note that although in the study of Valsecchi and Turatto (2021) the distractor was totally omitted during the extinction phase, participants were not explicitly informed that at a certain point the distractor would have been removed, and therefore they may have (at least implicitly) expected the distractor to reappear. Hence, lingering effects of previous distractor suppression are not unambiguous evidence of enduring plastic changes in the priority map, as they would still be compatible with the maintenance of a proactive suppressive signal at the location where the distractor was most likely expected to (re)occur.

Here we present results showing that impairment in target selection at the previous most likely distractor location are detectable even when the maintenance of a suppressive signal on the saliency map due to implicit expectations of distractor occurrence can be excluded, and this because the colour singleton distractor in the

training phase became the target of search in the subsequent test phase, when it appeared equally at all locations, and when no other singleton was present in the display. Our findings thus suggest that the consistent application of suppressive signals to the distractor location can cause long-lasting (depressive) changes in the priory map, probably via enduring modification in the input weights in the corresponding neural network, which in turn would modulate the bottom-up activity representing the distractor salience (Zelinsky & Bisley, 2015), and that these map alterations remain in place not only when the colour singleton distractor is removed, but also when the same colour singleton becomes the target of search.

Method

Participants

The sample size (18 observers) was determined to match the one that produced a reliable target position effect in the extinction phase of Experiment 3 of our previous study (Valsecchi & Turatto, 2021). Since in the current study the exact task in the most relevant comparison (colour singleton search post-training) differed from the one (shape singleton search) used in the previous study, we also computed the observed power for the target position effect in the test phase using G*Power 3.1.9.7 (Faul et al., 2007). This produced an observed power of 0.989 based on an effect size $dz = 1.068$. The data of 5 observers were not included in the analysis as they failed to reach 80% accuracy in the training phase.

Participants were recruited online through the Prolific online service (Prolific Academic Ltd, Oxford, UK), with the requirements of being between 18 and 40 years of age, having normal or corrected-to-normal vision, including colour vision, running the experiment on a desktop computer and being native speakers of English. No further

information about the observers was obtained. Observers were paid 5.75 GBP and the experiment lasted generally under 45 minutes.

All the experiments were carried out in accordance with the Declaration of Helsinki, and with the approval of the local institutional ethics committee (Comitato Etico per la Sperimentazione con l'Essere Umano, Università degli Studi di Trento, Italy).

Stimuli and procedure

The experiment was constructed using PsychoPy3 Version 2020.1.3 software (Peirce et al., 2019), and because of the COVID-19 pandemic restrictions experiments were run online using the Pavlovia web hosting service (Open Science Tools Limited, Nottingham, UK). However, previous studies have shown that similar online experiments replicated the pattern of results obtained with experiments conducted in the lab (Duncan & Theeuwes, 2020; Valsecchi & Turatto, 2021). The search arrays consisted of six red or green shapes (circles or diamonds) containing horizontal or vertical bars (Figure 1a). The eccentricity, based on the viewing distance that was required from the observers based on a segment displayed on the screen, was 3.4° of visual angle. The search arrays were presented until participants pressed either the "h" or the "v" key to indicate whether the bar contained in the target shape was horizontal or vertical, with a deadline of 2.5 s. Participants received a warning if they failed to respond correctly. In the training phase, the task was identical to that originally introduced by Wang and Theeuwes (2018b), so participants searched for a unique shape (either a diamond between circles or a circle between diamonds) while ignoring a colour singleton distractor (which was either a red element between green elements or vice versa). At the beginning of the test phase, participants were informed that all the shapes would have been the same (either all circles or all diamonds) and that they had to indicate as quickly and correctly as possible the orientation of the bar within the

uniquely coloured shape (red among greens or vice versa), which now became the target of search (Figure 1b).

In the training phase (387 trials, divided in three blocks of 129 trials each) the distractor (colour singleton) was absent in 41.9% of the trials, it was located at the high-probability location (chosen randomly for each observer)[1] in 46.5% of the trials and at each of the remaining low-probability locations in 2.3% of the trials, thus the distractor probability ratio between locations was 20/1, which is likely to produce a reliable target position effect (Lin et al., 2020; Valsecchi & Turatto, 2021). In distractor-absent trials, the target (shape singleton) was equally likely to appear at each location, whereas in distractor-present trials its location was chosen randomly in each trial among the locations not occupied by the distractor. In the test phase (216 trials; two blocks of 108 trials each) the colour singleton became the target and was presented in every trial and with equal probability at all locations.

[1] Choosing the high-probability distractor location randomly produced an unbalanced sample, where some locations were overrepresented. This, however, did not affect our main finding. Indeed, restricting the analysis to a subset of participants (N=12) for whom the high-probability location was balanced across all possible locations produced substantially the same results. In particular, the target position effect in the test phase was still significant, $t(11)=3.343$, $p=.006$, $d=0.965$.

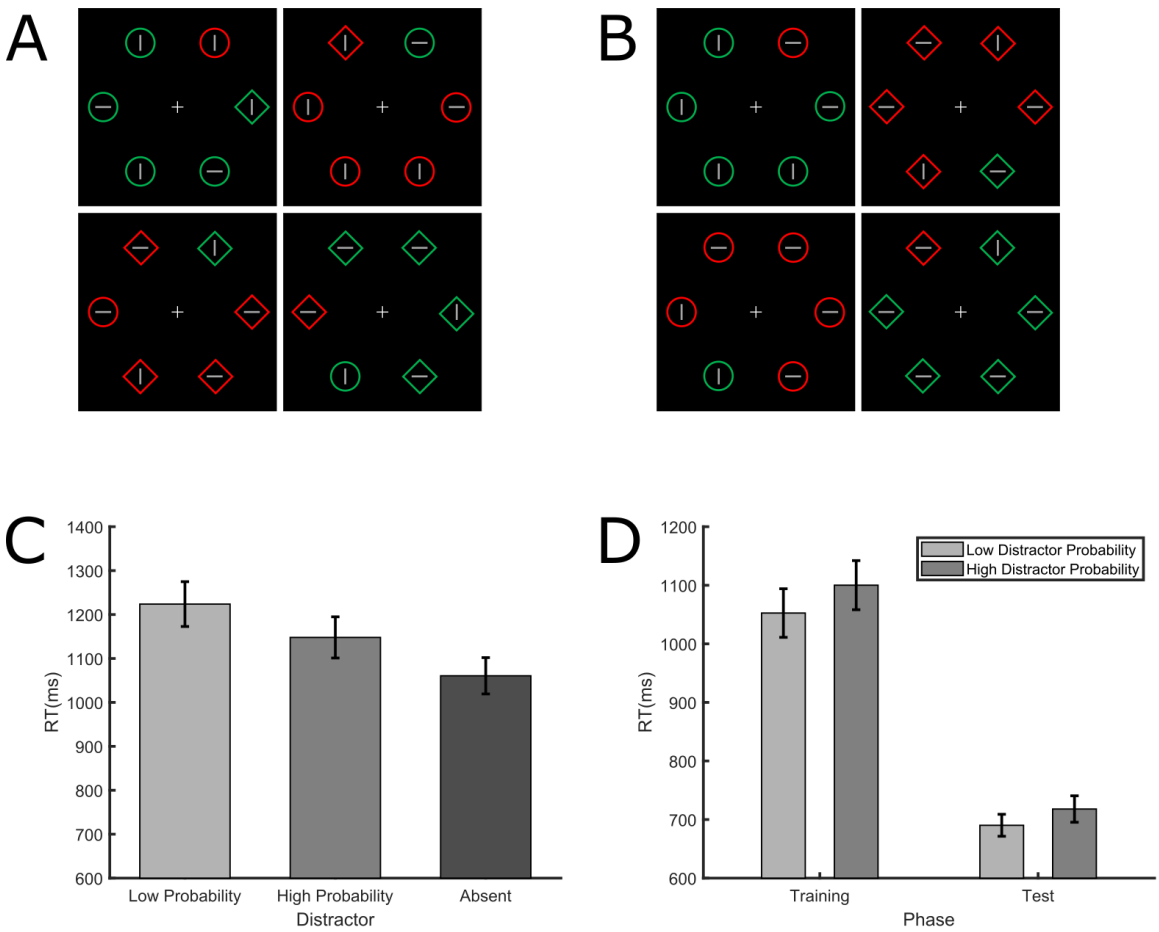

Figure 1. A) Examples of distractor present search displays in the training phase. Participants indicated the orientation of the bar inside the shape singleton (diamond among circles or circle among diamonds) while trying to ignore the colour singleton, which was more likely to occur at one location. The colour of the stimuli changed randomly between trials. B) Examples of search displays in the test phase. All stimuli had the same shape (all circles or all diamonds), and the target was the colour singleton, presented with equal probability at all locations. Again, the colour of the stimuli changed randomly between trials. C) RTs in the training phase as a function of distractor condition. RTs for target selection show that capture was attenuated at the high-probability distractor location relative to the low-probability distractor location. D) RTs for target selection as a function of whether the target appeared at the high- vs low-probability distractor location in the training phase (left histograms, only distractor absent trials) or in the locations in the test phase (right histograms). In both phases target selection was less efficient when the target appeared at the high-probability distractor location. Error bars represent Standard Errors of the Mean.

Results

Accuracy was generally high (90.9% in the training phase, and 97.3% in the test phase) and was not further analysed. We performed three separate analyses on RTs, after applying the outlier removal procedure based on median absolute deviation (MAD; Leys et al., 2013) and further removing RTs longer than 2,500 and shorter than 200 ms (see Valsecchi & Turatto, 2021). Overall, 2.7% of all trials were rejected in the analyses based on distractor location, and 3.8% in the analyses based on target location.

Training phase. The first analysis concerned the *distractor location effect* in the training phase[2] (Figure 1c). Here the results confirmed previous findings showing that participants were less affected by the distractor when this appeared at the high-probability than at the low-probability location, $t(17)= 3.42$, $p=.003$, $d=. 806$ (e.g., Wang & Theeuwes, 2018b). Furthermore, in both conditions RTs were longer than in the distractor-absent condition (high vs no-distractor, $t(17)= 7.084$, $p<.001$, $d=1.669$; low vs. no-distractor $t(17)= 7.209$, $p<.001$, $d=1.699$), thus showing that the colour singleton distractor captured attention. The second analysis dealt with the *target location effect* in distractor-absent trials during the training session (Figure 1d, left histograms). Again we confirmed the expected reverse effect, i.e. RTs were longer when the target appeared at the high-probability distractor location compared to the low-probability distractor location, $t(17)= 3.229$, $p=.005$, $d=.761$.

Test phase. The final and crucial analysis regarded the *target location effect* in the test phase (Figure 1d, right histograms), which revealed that even though in this phase participants were required to search for the colour singleton (i.e. the previous

[2] Trials in which the distractor appeared at the same location as in the previous trial were removed from the analysis in order to rule out that SL effects were solely due to inter-trial priming.

distractor), they were still slower at responding when it appeared in the previous high-probability than low-probability distractor location during the training phase, $t(17)= 4.534$, $p<.001$, $d=1.068$. We then performed a finer-grain temporal analysis of the target location effect by dividing the test phase in four consecutive 54-trial bins, but we found no evidence of significant changes in RTs across bins ($F < 1$).

In addition, irrespective of the target location, as expected (see, Theeuwes, 1992) when the target was a colour singleton the search task became much faster (by approximately 300 ms) as compared to the training phase, where the target was a shape singleton, $t(17)= 10.338$, $p<.001$, $d=2.436$ (compare the left vs right histograms of Figure 1d).

Discussion

Although colour singleton distractors can capture attention, mounting evidence shows that different cognitive and neural mechanisms can be implemented to attenuate, or even eliminate, such unwanted distraction (Chelazzi et al., 2019; Geng et al., 2019). A possible mechanism to control distraction relies on the possibility to suppress the distractor representation in visual areas via inhibitory signals, likely originating from the frontal lobes (Cosman et al., 2018). With this regard, a shared view is that such suppressive signals would attenuate the distractor saliency peak in the priority map (Ferrante et al., 2018; Wang & Theeuwes, 2018b), or in earlier dimension-based or feature-based maps (Gaspelin & Luck, 2018; Liesefeld & Müller, 2019). More debated is whether suppression can be implemented in a proactive way (i.e. in anticipation of the distractor occurrence) or just in a reactive way (i.e. after the distractor occurrence), although perhaps both mechanisms are feasible (van Moorselaar & Slagter, 2020). In particular, it has been suggested that once information concerning the most frequent

distractor location has been extracted from the environment, suppressive signals are exerted at such location in the priority map (e.g., Ferrante et al., 2018; Wang & Theeuwes, 2018b), leading both to a reduced distractor interference and to an impaired target processing (also see the *Signal Suppression Hypothesis*, Gaspelin & Luck, 2018a; Sawaki & Luck, 2013).

However, the reduced capture and the increased target selection impairment found at the most frequent distractor location do not necessarily imply that enduring modifications (i.e., weights changes) have occurred in the priority map. Indeed, previous findings of lingering SL of distractor location effects after the distractor probabilities are equalized (Britton & Anderson, 2020; Duncan & Theeuwes, 2020), or during a true extinction phase when the distractor is completely removed (Valsecchi & Turatto, 2021), can be the result of a suppressive signal that is proactively maintained at the previous most frequent distractor location, either because of the distractor presence (although equalized at all locations), or because the distractor was expected to reappear.

However, by making the distractor of the previous training phase the target of search in the test phase, we excluded that any lingering effect of the previous distractor spatial statistics on target processing could be accounted for by the presence of a suppressive signal proactively maintained on the colour singleton location, as such singleton became the target, and no more distractors were presented in the display.

Notwithstanding, we found that target selection was still impaired at the previous most likely distractor location, supporting the hypothesis according to which suppressive signals do induce plastic and relatively enduring changes in the priority map (Britton & Anderson, 2020; Ferrante et al., 2018; Zelinsky & Bisley, 2015). It should be noted that changes in the map weights at the location representing the distractor

were robust enough to influence target selection even when this was a highly salient colour singleton, as shown by the fact that participants became extremely fast at finding it. In other words, the high peak of activation at the colour singleton location, which was used to guide search, was not able to overcome the depressive changes induced in the priority map during the previous training phase. While it seems reasonable to assume that the longer the period of suppression the more stable the weights changes in the map will be, in the present experiment we found no evidence of suppression extinction after approximately 200 trials, namely no progressive reduction of the target location effect during the test phase. The enduring suppressive effect reported here is in line with recent findings showing that effects of SL of distractor location can persist for a hundred of trials in a true extinction phase when the distractor is completely removed (Valsecchi & Turatto, 2021), and similarly with evidence showing that once the grabbing power of an onset is reduced with training, it remains attenuated for days or weeks (Turatto et al., 2018). These lingering suppressive effects might seem at odds with the results of Wang and Theeuwes (2020), who showed that the spatial distribution of suppression achieved via SL can be quite flexible, rapidly adapting to changes in the distractor statistical regularities in space. However, as we have already discussed elsewhere (Valsecchi & Turatto, 2021), the different findings could be explained by noting that introducing a new distractor spatial bias might be different from removing such bias. Indeed, failing to adjust the pattern of suppression to the distractor new spatial contingencies would make the attentional system very vulnerable to distraction at the new high-probable distractor location, whereas maintaining the previous suppressive bias when in fact the distractor is now equally likely to occur at each location, or disappears altogether, would have less severe distracting consequences. For these reasons, one might speculate that the pattern of suppression in

the saliency map is more readily adjusted when a new distractor spatial bias is detected then when a previous bias is removed, because the distractor occurrence is equalized across locations (e.g., Ferrante et al., 2018), because the distractor is omitted (Valsecchi & Turatto, 2021), or because it becomes the target of search (as in the present study).

We would like to point out that although we interpreted our results as showing that suppressive signals at the distractor location caused plastic changes in the priority map, perhaps an alternative possibility is that the act of suppressing the colour singleton became, trial after trial, an habitual suppressive response (Ferrante et al., 2018; Jiang & Sisk, 2019), which then perdured in a quite automatic fashion in the test phase, despite the colour singleton was the target. In principle this explanation does not require the assumption that the lingering negative effects shown at test are index of enduring plastic changes in the priority map, although a habit formation must still represent a persistent plastic change likely occurring in the striate nucleus (Tricomi et al., 2009; Yin & Knowlton, 2006). This scenario would be compatible with evidence showing that, once formed, habits are responses automatically emitted even when they are no longer necessary or desirable (Adams & Dickinson, 1981; Miller et al., 2019; Robbins & Costa, 2017), which could explain why in the test phase the suppressive response continued to be applied to the colour singleton despite it was the target of search.

In the literature there are conflicting findings regarding whether SL produces long-lasting direct effects (i.e., effects of the local distractor probability on distractor processing, or effects of local target probability on target processing) and indirect effects (i.e., effects of the local distractor probability on target processing, and vice versa). In our previous study we demonstrated that, provided that the distractor probability was largely uneven across locations, direct effects of SL of distractor

location[3] survived an extinction phase in which no distractors were presented, and indirect effects based on target location could be detected in the extinction phase (Valsecchi & Turatto, 2021). Ferrante et al. (2018), on the other hand, tested both direct and indirect effects of SL of both target and distractor locations directly after SL was acquired. Their results showed that SL of target location induced lingering direct effects, but fast decaying indirect effects, while also the direct effects of SL of distractor location seemed to vanish rapidly. The permanence of SL of distractor location after a one-day interval has been evaluated, and the results showed that SL only lasted when distractors shared the same dimension as the target (both orientation singletons), but not when the distractors were color singletons (Sauter et al., 2019). More recently, Di Caro and Della Libera (2021) measured SL of target and distractor locations using saccade landing position as an index of attention allocation. They reported that SL of target location survived a one-day break, but SL of distractor location was only detected when tested immediately after training, and lasted only for 144 trials, which they interpret as a sign of a quickly decaying effect. Possibly, a common finding seems to be that indirect effects are weaker than direct effects for SL of distractor location (Ferrante et al., 2018; Valsecchi & Turatto, 2021), especially when the unbalance between the high vs low probability location is not extreme. It should be noted that Ferrante et al. (2018) used a probability ratio below 6:1, but ratios of at least 8:1 might be needed to elicit reliable indirect effects (Lin et al., 2020; Valsecchi & Turatto, 2021). Effects that are weaker during training might also be harder to detect during extinction. In general, however, accommodating all the conflicting reports will require to systematically evaluate the role of the different experimental parameters that have been used in different studies,

[3] Notice that in our previous study, as in the present one, the manipulation of distractor probability was associated with an unbalance of target occurrence.

including the number of stimuli and possible locations in the search array, the timespan across which the lingering effects are measured, the probability ratio during training and the dissociation of target and distractor SL. Our task was designed to test the transfer of SL between different search tasks and is not well suited to chart the time course of isolated direct and indirect effects of SL of distractor and target occurrence for at least three reasons. First of all, our training scheme was modelled directly on the paradigm used by Wang and Theeuwes (2018b), where the disproportionally high probability of distractor occurrence at one location was also associated with a lower probability of target occurrence. This means that we cannot in principle distinguish SL of distractor and target occurrence, although we know that they can occur independently (Ferrante et al., 2018, Di Caro and Della Libera, 2021, Zhang et al., 2019). Secondly, in our study the reported lingering effect does not identify clearly as direct or indirect. We measured the lingering effect of SL of distractor location based on target location in the test phase, which would qualify as an indirect effect, but the target in the test phase was the same color singleton whose location had been learned previously, which is akin to a direct effect. We can only speculate that by having used the same dimension to define distractors in the training phase and targets in the test phase we might have enhanced the temporal stability of the learning effect (e.g., Sauter et al., 2019). Third, the length of our test phase overlapped with the time span where Di Caro and Della Libera (2021) still detected the decaying effect of distractor SL, meaning that a longer test phase would have been necessary to characterize the time course of the phenomenon.

Finally, our results are also relevant to our understanding of how statistical information concerning the spatial distribution of the stimuli might be used in the SL of distractor location phenomenon. If participants had created a task-independent

statistical representation of the most likely state of the world (here the location of the colour singleton), they should have been able to use it both to suppress the likely singleton position when it was the distractor, and to flexibly enhance the same location when the singleton became the target, similar to what is observed in probability cueing (Geng & Behrmann, 2005). Our results indicate that, on the assumption that such task-independent probability representation of the salient stimuli spatial distribution does exist, and that can be used to efficiently direct attention in the world, in fact this information cannot be used to completely overcome the effects of plastic changes that may have occurred in the priority map.

Open Practices Statement

The data for the experiment reported here will be made available through the Zenodo repository (link to be added). The experiment was not preregistered.

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