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Learning to resist distraction by spatially predictable luminance transients and color singletons: same or different mechanisms?

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Abstract

Stimuli that appear abruptly in the visual field or differ from the surrounding stimuli based on a given visual feature have the potential to capture attention and interfere with the visual search process if they are not targets. When both types of distractors appear with higher likelihood at a given location, observers can learn to reduce their impact (distractor-location effect). In the case of feature-singleton distractors, this can imply a cost for processing targets that appear at locations associated with a high distractor probability (target-location effect). This has been proposed as evidence that distractor interference originates in the competition between distractors and targets within an attentional map, whose inputs can be modified by experience. In this study, we conduct a series of experiments showing that while on the one hand confirmed previous finding related to feature-singleton distractors, on the other hand they consistently showed that learning to predict the spatial occurrence of luminance transients induces a distractor-location effect in the absence of a target-location effect. Combining this finding with the fact that interference by luminance transients were larger when distractors are far from the target position, we suggest that different mechanisms are responsible for the reduction of distractor interference in the case of color singletons and luminance transients.

Keywords

Visual Search; Distraction; Statistical Learning; Feature Singleton; Luminance Transient; Abrupt onsets

Introduction

The ability to use the statistical regularities of the environment to optimize the uptake of information and emission of appropriate behavioral responses is a fundamental skill of both humans and animals. In the domain of attention and visual search, there is ample evidence that when observers are exposed to a setting in which targets and/or distractors appear with non-homogeneous spatial probabilities, they can learn both to respond faster to targets appearing at the most likely locations (Jiang, 2018; Shaw & Shaw, 1977) and/or to be less distracted by distractors appearing at the most likely distractor locations (Ferrante et al., 2018; Goschy et al., 2014; Huang et al., 2022; Theeuwes et al., 2022; Valsecchi & Turatto, 2021, 2023; Wang & Theeuwes, 2018b; Zhou et al., 2022). One common interpretation of the finding that observers can be less distracted by irrelevant salient stimuli appearing at likely locations has been in terms of some sort of suppression or down-weighing taking place in one or more map-like attentional representations of space (Ferrante et al., 2018; Liesefeld & Müller, 2019; Theeuwes et al., 2022; van Moorselaar & Slagter, 2020).

In order to gain a more specific understanding of the nature of the representations affected by the learning process, researchers commonly evaluate the conditions under which the learning of distractor statistics affects the processing of other stimuli at the same location, such as targets, probes, and different distractors. If we assume that inhibition is applied within an overarching priority map, inhibiting a location commonly associated with distractors will reduce capture at that location (usually defined as the *distractor-location effect*), but also hinder the orienting of attention towards targets appearing at the same high-probability distractor location (usually defined as the *target-location effect*). The target-location effect, associated with the distractor-location effect, is commonly observed (Sauter et al., 2018; Valsecchi & Turatto, 2021; Wang & Theeuwes, 2018b, 2018a) in variations of the

additional-singleton paradigm introduced by Theeuwes (1992), in which observers search for a shape-singleton target while trying to ignore possible color-singleton distractors. The target-location effect is typically measured through response times (RTs), but there is also evidence that the reduction of attentional priority at likely distractor locations does induce a decrease in perceptual sensitivity (Van Moorselaar & Theeuwes, 2021), consistent with the observation of reduced neural excitability in the portions of early visual cortex that code for locations where distractors are expected (Ferrante et al., 2023).

With respect to the relation between the target-location and the distractor-location effects, it is worth noting some differences. First, while the distractor-location effect can be produced on the basis of a relatively small imbalance in distractor occurrence probability, the emergence of a target-location effect generally requires a larger imbalance, such as when distractors appear at least eight times more often at one location compared to others (Lin et al., 2021; Valsecchi & Turatto, 2021). Prominently, when the mapping of colors to targets and distractors is fixed, rather than swapping randomly from trial to trial as in Wang and Theeuwes (Wang & Theeuwes, 2018b), the target-location effect is absent or largely reduced, whereas the distractor-location effect is still reliably observed (Allenmark et al., 2019; Zhang et al., 2019). This finding has been interpreted within the framework of the dimension-weighting account (Liesefeld et al., 2019; Liesefeld & Müller, 2019), which states that visual search is performed on the basis of a general priority map that combines the weighted signals from different dimension maps. Based on task constraints, observers might upweight the signals from one dimension map and downweight the signals from other maps (for example, they might upweight the signals from the shape dimension and downweight the signals from the color dimension when searching for the shape singleton while expecting the presence of a color singleton). Within this framework, a dissociation between target-location and

distractor-location effects occurs because observers can selectively apply a local suppressive signal within the map that represents the distractor dimension, without changing the activation in the map that represents the target dimension, and most crucially without exerting any suppressive effect on the general priority map, which is dimension blind (Liesefeld & Müller, 2021; Zhang et al., 2019). Consistent with this framework, neuroimaging evidence indicates that filtering can occur in different neural structures depending on whether target-distractor similarity allows for a dimension-specific filtering strategy (Zhang et al., 2022).

The abovementioned evidence thus seems to indicate that the possibility to ignore a salient distractor, typically presented in the form of a color singleton, is achieved by means of spatial suppression, as attested by the target-location effect. However, a different scenario might emerge when one considers luminance-transient distractors.

Luminance transients can act as exogenous cues by capturing attention even if they are task-irrelevant and, to a certain extent, even if observers are instructed to ignore them (e.g., Jonides, 1981; Yantis & Jonides, 1990). Nonetheless, we recently demonstrated that luminance transient distractors, like color-singleton distractors, can be better ignored when they are more likely to occur (also see, Valsecchi & Turatto, 2023; De Tommaso & Turatto, 2023). At least in the case of luminance transients, the learning process that leads to the distractor-location effect coexists with a decrease in distraction over time, which is consistent with the habituation of attentional capture (e.g., Turatto, Bonetti, & Pascucci, 2018; Turatto & Pascucci, 2016; Turatto & Valsecchi, 2023), although even extensive experience with luminance transients does not necessarily make capture disappear completely (Ruthruff et al., 2019). Similarly to what has been found with feature-singleton distractors (Allenmark et al.,

2022), this decrease in distraction is driven mostly by the experience with distractors that is cumulated locally (Turatto & Valsecchi, 2023).

Crucially, however, in one of the experiments that we conducted using luminance transients as distractors (Valsecchi & Turatto, 2023, Experiment 3), we allowed, on some trials, luminance transients and targets to occur at the same location, both within a trial, i.e. with the luminance transient acting as a congruent exogenous cue, and across trials, which allowed us to test for the target-location effect. In this case, we failed to find a target-location effect, whereas the distractor-location effect was clearly evident.

This dissociation might be interpreted in different ways. First of all, it is simply possible that because targets and distractors were presented at the same location in ¼ of the trials, the distractor acted as a congruent cue for the target location, which might have reduced the observers' motivation to suppress the distractor. This, in turn, might have reduced the target-location effect. Secondly, it is possible that distractors and targets, while both being luminance transients, were represented on different dimension maps, such as size, line brightness and thickness, shape, and straight vs. curved lines (the distractor being a large bright circle, whereas the target a small letter T consisting of vertical and horizontal lines), which might have allowed observers to selectively suppress the distractor location in a distractor-specific map. Generally speaking, a number of details that varied between the paradigms might explain why the target-location effect emerged in variations of the additional-singleton paradigm and not in our study with luminance-transient distractors. However, another more intriguing possibility is that the lack of the target-location effect observed with luminance-transient distractors reveals that different mechanisms are responsible for handling this form of salient events as compared to feature-singleton distractors. Indeed, evidence for more dissociations between the effects of feature-singleton

and luminance-transient distractors exists in the literature. For instance, Adams and colleagues (2022) reported that within the context of a feature search paradigm, i.e. a search paradigm where the target is a pre-defined stimulus whose color and shape are constant across trials, observers were able to effectively resist distraction by color singletons while they were still captured by luminance transients.

The aim of the present study was thus to confirm the lack of the target-location effect that we previously found with luminance transients, and if this was the case, to try to understand the reasons for this finding. Note that the difference between luminance-transient and feature-singleton distractors with respect to the target-location effect, which might suggest different ways to handle the corresponding distraction, holds true irrespective of whether one assumes that the observed capture is genuinely stimulus driven or is instead modulated by top-down factors, as proposed by the contingent-capture hypothesis (Folk et al., 1992).

To anticipate our results, we confirmed that the distractor-location effect can be observed with both luminance-transient and color-singleton distractors, whereas the target-location effect only occurred with color-singleton distractors. Contrary to previous studies, which used different paradigms with different numbers of trials, we used exactly the same experimental design with both luminance-transient and color-singleton distractors, including the same number of stimuli and local probabilities. We excluded the co-location of the target and the distractor, while ensuring that the frequency of the target occurrence was balanced at all locations. Furthermore, in an attempt to understand the reason for such a difference, we conducted a series of experiments to evaluate whether specific differences between the stimuli and paradigms being used might explain the dissociation. After consistently finding a distractor-location effect but no target-location effect with luminance transients, we further

excluded the possibility that the dissociation could be ascribed to the fact that luminance-transient distractors and targets were represented in different dimension maps. Given the large set of experiments, we provide an overall summary of the experiments and results in Table 1.

In order to create a general paradigm that allowed to both exclude the co-location of targets and distractors within a trial, and to have unbalanced local distractor probabilities while also having balanced local target probabilities, we opted for a region-based design. Targets and distractors could thus occur in two regions, one in the left and one in the right hemifield (Goschy et al., 2014; Zhang et al., 2019). This design also allowed us to evaluate the effect of the spatial relationship between targets and distractors, and specifically whether having the two elements within the same hemifield/region improves or worsens performance. This might have important consequences for the interpretation of the source of distractor interference costs, and whether such costs emerge because of competition between targets and distractors or because of the need to re-orient attention towards the target after it has been captured by the distractor (Mathôt et al., 2010). Notice that although opting for a region-based design implies that the local distractor probability is reduced compared to a design where a single position is assigned to high distractor probability, this is unlikely to have determined our failure to detect the target-location effect with luminance transient distractors. First of all, the target-location effect in region-based designs has been observed before (e.g., Allenmark et al., 2019) and was replicated in our color-singleton distractor experiments. Secondly, we previously reported the absence of a target-location effect with luminance-transient distractors even when a single location was associated with high distractor probability (Valsecchi & Turatto, 2023, Experiment 3).

Experiment	Distractor	Target	Non Targets	Target-Location Effect	Congruency Effect
1	Color Singleton	Horizontal T Inside Shape Singleton	Horizontal Ts Inside Shape Nonsingletons	Yes	Cost
2	Flashed Circle	Horizontal T	None	N.S.	Advantage
3	Flashed Circle	Horizontal T	Ls	N.S.	Advantage
4	Brief Color Singleton	Horizontal T Inside Shape Singleton	Horizontal Ts Inside Shape Nonsingletons	Yes	Cost
5	Synchronous Flashed Circle	Horizontal T	None	N.S.	N.S.
6	Color Singleton	Horizontal T Inside Shape Singleton	Vertical Ts Inside Shape Nonsingletons	Yes	Cost
7	Flashed Circle	Flashed Circle With Gap	None	N.S.	Advantage

Table 1. Summary of experiments and main results. Experiments involving color singleton distractors are marked in gray. Notice that in general color-singleton distractors were associated with a significant target-location effect and with congruency costs, i.e., slower RTs when distractor and target were in the same region. Luminance transient distractors were associated with not significant target-location effects and congruency advantages, i.e. faster RTs for congruent trials. N.S.: Not Significant.

General Methods

Participants

Participants were recruited online through the Prolific service (Prolific Academic Ltd, Oxford, UK). We required participants to be between 18 and 50 years old, to be native English speakers, to have normal or corrected-to-normal vision, and to run the experiment on a desktop computer. Datasets were rejected and re-run if participants failed to reach an overall accuracy rate of at least 80%. Participants were compensated with 4.5 GBP in Experiments 1, 3, 4 and 6 (which lasted under 36 min) and 3.75 GBP in Experiments 2, 5 and 7 (which lasted under 30 min), and were informed about the general aim of the experiment, their task, and data handling procedures in the Prolific interface. They gave their consent by agreeing to be directed to the experiment url. All the experiments of the present study 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, Approval nr. 2022-065, Title of study: "Studio dell'abituazione della cattura dell'attenzione da parte di stimoli salienti").

The most crucial results that we base our conclusions on is the target-location effect, i.e., the difference in RTs between when the target appears at the high-probability and low-probability locations in distractor-absent trials. After collecting 24 participants in the basic replication of the target-location effect with color-singleton distractors within our current paradigm (Experiment 1), we used G*Power 3.1.9.7 (Faul et al., 2007) to estimate the N necessary required to reproduce the effect. Given the measured effect size d_z = 0.546, the procedure yielded an estimate of N = 29 in order to achieve 80% power. Due to the need to balance the left-right hemifield of the high frequency region across participants, we tested 30 participants in all experiments.

Constraints on Generality

We did not impose limitations on gender, ethnicity or age outside of the 18-50 years range because we did not have a priori hypotheses concerning the role of age, gender or ethnicity in determining the results of the present study. The request of being native speakers of English was related to the fact that the instructions were administered in English through the Pavlovia server. Since, however, we do not expect language to have an influence on the phenomena that we investigated, we predict that our results will generalize to the whole adult population.

Transparency and Openness

The experiments were created using the PsychoPy3 version 2022.2.4 software (Peirce et al., 2019), and run online using the Pavlovia web hosting service (Open Science Tools

Limited, Nottingham, UK). Data analysis was performed using Matlab (Mathworks, Natick, MA, USA) and Jasp 0.16.4 (JASP Team, 2023). All experimental scripts, experimental data and analysis scripts are made available to the reviewers at the following link: "https://www.dropbox.com/s/y9pmhpfjjcyqnvy/ZenodoOnsetVsFeatureS.zip?dl=0". The final version will be made publicly available through the Zenodo repository at the following DOI: 10.5281/zenodo.8220999. This study's design and its analysis were not pre-registered.

Setup, general stimuli and procedure

In all the experiments conducted in this study, participants were asked to fixate a point at the center of the screen, and stimuli were presented at eight locations arranged around the fixation point (see Figure 1). Participants were asked to place themselves at a distance three times the length of a segment (84% of screen width) presented on the screen at the beginning of the experiment. Assuming the instructed viewing distance the stimuli were centered at an eccentricity of 4.54° of visual angle. Out of the eight locations, the three locations on the left and on the right were assigned to the Low and High Distractor Probability regions, counterbalanced across participants, whereas the up and down locations were not assigned to any region and were never used to present targets and distractors. The fixation point was a white circle (0.23° diameter). Except in the case of Experiment 7, the task was always to discriminate the letter T (mid gray, 0.91° across, line width 2 pixels), rotated either clockwise or counterclockwise. The letter T served both as probe and target when it appeared as onset in luminance-transient distractor experiments, and as probe in feature-singleton distractor experiments, where the target was defined by the shape singleton. Participants were required to press the G or H key on their keyboard, as quickly and as accurately as possible, to report whether the T was rotated counterclockwise or clockwise, respectively. The letter T remained on the screen until response or for a maximum of 2500 ms in the experiments where the

target character appeared together with other nontarget characters (Experiments 1, 3, 4 and 6). In all other cases (Experiments 2, 5 and 7), it was flashed for 150 ms. If participants failed to respond within 2500 ms from the target onset, or if they pressed the wrong key, a warning ("TOO SLOW" or "WRONG!", respectively) appeared on the screen during the inter-trial interval.

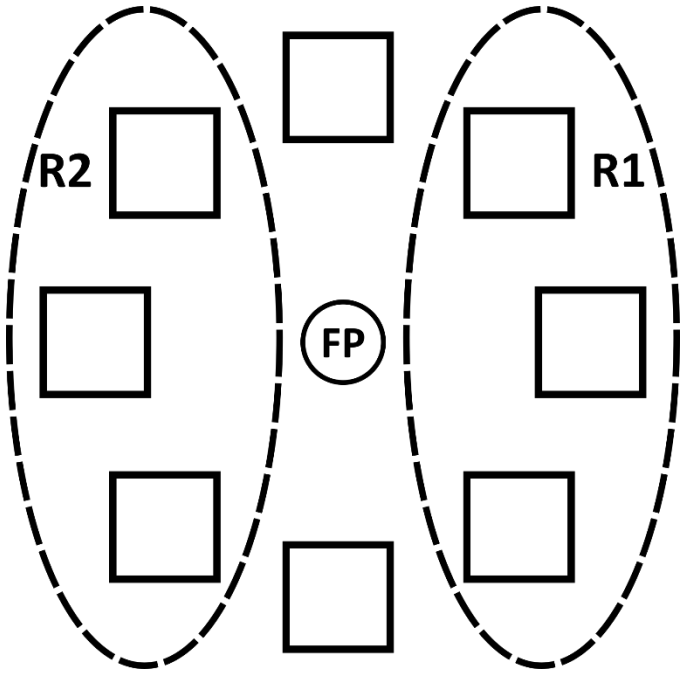

Figure 1. Definition of regions. In every experiment, stimuli were presented at each of 8 positions surrounding the fixation point. The target and the distractor stimulus (when present) appeared in either one of the three locations on the right (here identified as R1) or in the three locations on the left (here identified as R2). Targets and distractors never appeared in the top and bottom locations. For each participant, either R1 or R2 was assigned to be the High Probability Region, where the distractor appeared with a 8-1 probability compared to the other region.

Study Design

While the specific stimuli and task varied, all the experiments conducted in the present study were based on the same experimental design and on the same contingency of local target and distractor occurrence. Targets and distractors, when present, appeared in two regions as depicted in Figure 1. The ratio of presentation of distractors in the high- and low-

probability regions was 8 to 1 (Lin et al., 2021). Within each region, distractors occurred the same number of times at each of the three locations. Targets appeared the same number of times in each region. In each trial the position of the target was selected randomly within the region, with the only limitation that if one location was occupied by the distractor, the target occupied one of the two other locations, again chosen randomly.

Each experiment consisted of three blocks of trials, with each block featuring 168 trials. Out of the 168 trials in each block, distractors appeared 12 times in the low-probability region, 96 times in the high-probability region, and were absent in the remaining 60 trials. Hence, distractors occurred globally in 64.3% of trials, 57.1% in the high-probability region, and 7.1% in the low-probability region. The distractor occurrence probability at each location was 1/3 of the total distractor probability in that region.

Before the experimental session, participants underwent 18 practice trials, with targets presented equally likely in each region and with distractors presented in 12 trials, twice at each possible location.

Data analysis

All of the data analyses were conducted using Matlab R2021a (The Mathworks, Natick MA). In all of the analyses, outlier rejection was performed based on the median absolute deviation (MAD; Leys et al., 2013), setting the threshold to 5 MADs. We further discarded RTs lower than 150 ms. RTs longer than 2500 ms were not admitted during data collection.

For each experiment we performed the same two sets of analyses. The first set of analyses concerns the distractor-location effect (i.e. the difference in RTs and error rates between trials where a distractor occurred in the high- and in the low-distractor probability region), the target-location effect (i.e. the effect of the region where the target occurred on RTS and error rates, limited to distractor-absent trials), and the distractor interference effect

(i.e. the difference in RTs and error rates between trials where distractors were present, separately for the two regions, and the average RTs and error rates in distractor-absent trials). All these effects were tested by means of paired-sample t-tests. For target-location effects we also computed Bayes factors using the bayesFactor Toolbox Version 1.1 for Matlab (https://klabhub.github.io/bayesFactor/). For each of the experiments involving luminance transient distractors (2,3,5 and 7), we also performed between-observer t-tests comparing the target-location effect with the one we had measured in Experiment 1, i.e. in the replication of the target-location effect with feature-singleton distractors.

The second set of analyses concerns what we call the *congruency effect*, i.e., the effect of congruency between the target region and the distractor region. To this aim we split distractor-present trials depending on whether the distractor was in the high- or low-probability region and on whether the target was in the same or different region as the distractor. The results (RTs and error rates) were submitted to 2x2 repeated-measure ANOVAs with Congruency (congruent vs. incongruent) and Distractor Probability (high vs. low) as factors. The main effect of Distractor Probability is equivalent to the distractor-location effect in the previous set of analyses and is not reported. Summary tables containing the mean RTs (Table S1), the mean normalized RT effects (Table S2), and the mean Error Rates (Table S3), for all experiments and all with corresponding 95% Confidence Intervals, are provided as supplementary materials.

Notice that while we present both RTs and error rates data and analyses, we draw our conclusions only based on the RT results, since accuracies were relatively high in this paradigm, and even the distractor-location effect, which we invariably replicated in RTs, can fail to reach significance in the basic additional-singleton paradigm (see Results of Experiment 1).

We further performed a Bayesian repeated-measure ANOVA combining the target-location effect data from the experiments involving luminance-transient distractors (2, 3, 5 and 7). This was performed using Jasp 0.16.4 (JASP Team, 2023).

In all figures error bars represent between-participants standard error of the mean.

Experiment 1: color-singleton distractor

The aim of Experiment 1 was to reproduce the emergence of the target-location effect due to the learning of the distractor spatial statistics in an additional-singleton paradigm, similar to the one used by Wang and Theeuwes (2018b), but with a region-wise manipulation of distractor occurrence (Goschy et al., 2014). The region-wise manipulation of the distractor probability allows for the likelihood of target occurrence to be equal at the distractor high- and low-probability locations, and is equivalent to matching target occurrence probability in distractor-present trials (Zhang et al., 2019).

Methods

Participants

The datasets from 9 participants were rejected for failing to reach the required minimal overall accuracy level of 80%. Out of the 30 participants whose data were analyzed, 11 were female and 19 were male. The mean age was 33.6 years.

Stimuli and procedure

Each trial began with the presentation of the central fixation point. After 1 second the search display appeared (Figure 2A), which consisted of eight shapes (approximately 2.3° across, line width 4 pixels): either seven circles and one pentagon or one pentagon and seven circles, randomly chosen for each trial. Each shape contained a letter T, randomly rotated

clockwise or counterclockwise. The color of the shapes was either red or green, and in distractor-present trials one of the shapes (never coincident with the shape singleton) differed in color from the others. The task was to report the orientation of the T contained in the shape singleton (the target), while ignoring the color of the stimuli. The search display and the fixation point disappeared after the response was emitted or 2500 ms after the display onset. The inter-trial interval was set to 1 second.

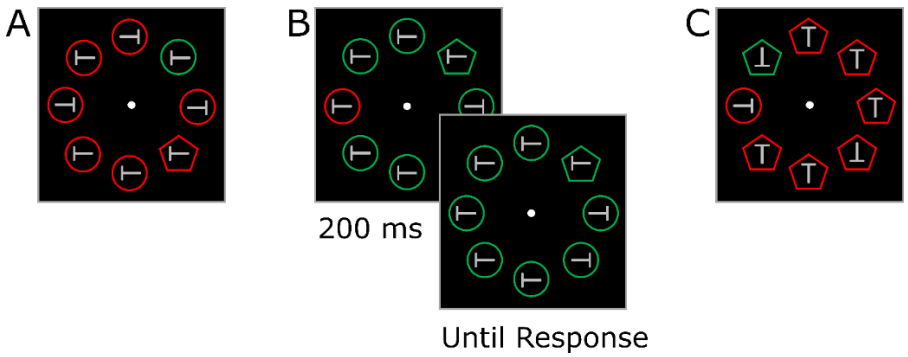

Figure 2. Stimuli used in experiments with color-singleton distractors. A: Experiment 1, participants reported the orientation (left vs right) of the letter T inside the shape singleton (here the red pentagon) while ignoring the color singleton (here green circle). B: Experiment 4, in this example the target was the green pentagon. The color singleton (in this example the red circle) was presented only for 200 ms, then its color became the same of the other stimuli. C: Experiment 6, the target was the red circle. Non-target stimuli (here the pentagons) contained upright or upside-down Ts. In all experiments color and shape of the target and the distractor changed randomly from trial to trial.

Results and discussion

Overall, 0.42% of RTs were rejected as outliers. The overall error rate was 5.4%.

Distractor-location, target-location and distractor interference effects

Mean RTs and error rates, plotted as a function of distractor region in distractor-present trials and as a function of target region in distractor-absent trials are presented in Figure 3. As expected, the RT results indicated the presence of both a distractor-location effect, $t(29) = 3.211$, $p = .003$, $d_z = 0.586$, RT difference = -53.5 ms. 95% CI [-87.7000 -19.4] ms, and of a target-location effect, $t(29) = 2.85$, $p = .008$, $d_z = 0.52$, RT difference = 33.8 ms. 95% CI [9.5 58] ms, $BF_{01} = 0.183$. Again, as expected, there was a significant distractor interference both for distractors presented in the high-probability region, $t(29) = 11.884$, $p < .001$, $d_z = 2.17$, RT difference = 118.6 ms, 95% CI [98.2 139] ms, and for distractors presented in the low-probability region, $t(29) = 7.955$, $p < .001$, $d_z = 1.452$ ms, RT difference = 172.2 ms, 95% CI [127.9 216.4] ms.

Numerically the error rate pattern matched the RT pattern. Statistically however only the distractor interference effect reached significance, both for distractors appearing in the high-probability region, $t(29) = 4.728$, $p < .001$, $d_z = 0.863$, error rate difference = 2.8%, 95% CI [1.6 3.9] %, and in the low-probability region, $t(29) = 3.883$, $p = .001$, $d_z = 0.709$, error rate difference = 4.9%, 95% CI [2.3 7.4] %. The distractor-location effect, $t(29) = 2.027$, $p = .052$, $d_z = 0.37$, error rate difference = -2.1%, 95% CI [-4.2 0] %, and the target-location effect, $t(29) = 1.103$, $p = .279$, $d_z = 0.201$, error rate difference = 0.6%, 95% CI [-0.5 1.7] %, $BF_{01} = 2.958$,

were not significant.

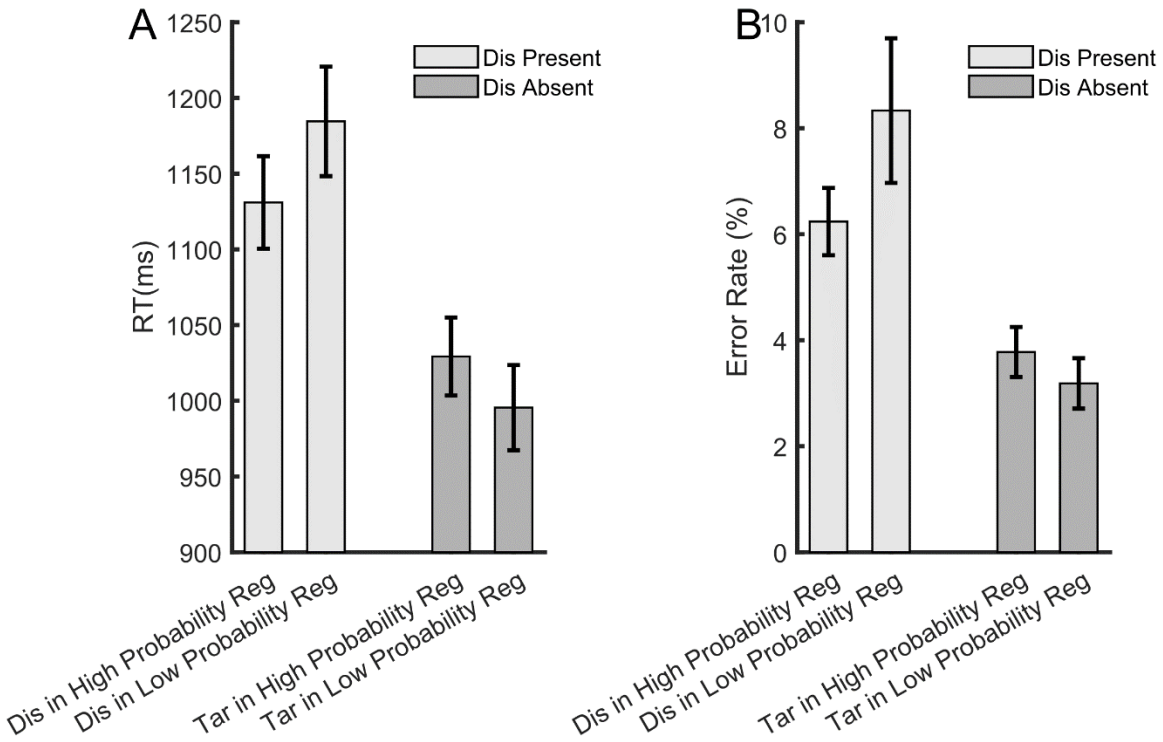

Figure 3. Mean RTs (A) and error rates (B) in Experiment 1, in distractor-present and distractor-absent trials, as a function of distractor and target region, respectively.

Congruency effect

RTs from distractor-present trials, split as function of the region where the distractor appeared and of the congruency between distractor and target region are presented in Figure 4. The results show a congruency cost, i.e., participants were slower when target and distractors appear in the same region. This was confirmed by the ANOVA results, which yielded a significant main effect of Congruency, $F(1,29) = 45.577$, $p < .001$, $\eta_p^2 = .611$, and a significant Congruency x Distractor Probability interaction, $F(1,29) = 8.305$, $p = .007$, $\eta_p^2 = .223$. The interaction indicates that the congruency effect was larger when the distractor appeared in the high-probability region. Part of this interaction might be explained by the

target-location effect adding to the congruency effect. With distractors in the high-probability region, congruent targets were also in the high-probability region, which was generally associated with slower RTs. In contrast, incongruent targets were in the low-probability region, which could contribute to the general trend of slower RTs for congruent trials. The opposite was true for distractors appearing in the low-probability region.

The analysis of error rates yielded a significant main effect of Congruency $F(1,29) = 16.714$, $p < .001$, $\eta_p^2 = .366$, and a significant two-way interaction, $F(1,29) = 6.348$, $p = .017$, $\eta_p^2 = .18$. Notice that the interaction in the case of error rates is opposite to the one that was observed for RTs, since congruency had a larger effect on error rates when distractors appeared at the low-probability region.

The results from Experiment 1 fully replicated two key findings in the literature: the target-location effect and the congruency cost. When observers learn to resist distraction from a color singleton at a likely location, they pay a cost in terms of increased RTs when a target appears at that location (Valsecchi & Turatto, 2021; Wang & Theeuwes, 2018b, 2018a). When the distractor appears spatially close to the target there was a cost in terms of RTs compared to the situation where the distractor appears in the opposite location, coherent with the results of other studies that implemented variations of the additional-singleton paradigm (Barras & Kerzel, 2016; Caputo & Guerra, 1998; Kiss et al., 2012; Turatto & Galfano, 2001). In Experiment 2 we investigated whether the same holds true when luminance transients act as distractors.

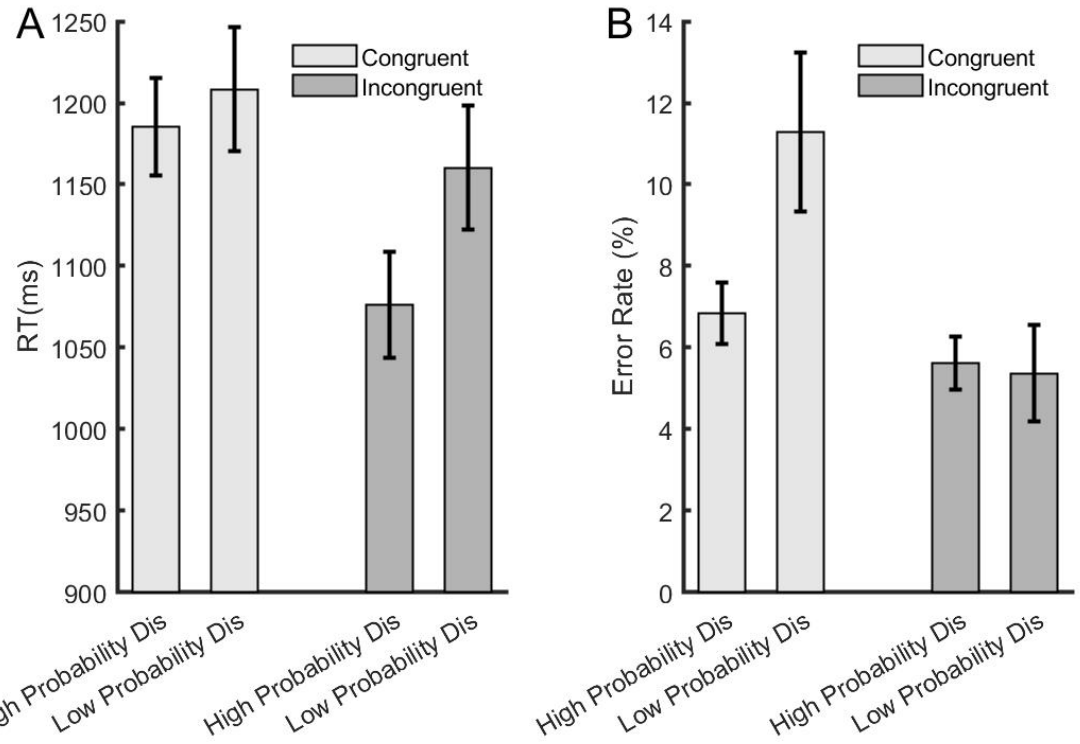

Figure 4. RTs (A) and error rates (B) in the distractor-present trials of Experiment 1, plotted as a function of the distractor probability at the region where the distractor appeared and of the congruency between the distractor and target regions.

Experiment 2: luminance-transient distractor

Experiment 2 was an attempt to replicate the target-location effect in a paradigm where distractors are luminance-transients, similar to the ones used in our previous studies (Turatto & Valsecchi, 2023; Valsecchi & Turatto, 2023). In those studies, the target-location effect was either not tested because targets and distractors always occurred at separate locations (Turatto & Valsecchi, 2023), or it was tested allowing targets to co-occur at the same location during a trial (Valsecchi & Turatto, 2023, Experiment 3). Here, we used the same region-wise approach, as in Experiment 1, where targets and distractors appeared at different locations during a trial, but the probability of target occurrence at each location was equalized across trials.

Methods

Participants

The datasets from 3 participants were rejected for failing to reach the minimum required overall accuracy of 80%. Out of the 30 participants whose data were analyzed, 11 were female and 19 were male. The mean age was 33.3 years.

Stimuli and procedure

The stimuli used in Experiment 2 are depicted in Figure 5A. Each trial began with the presentation of the central fixation point surrounded by 8 circular placeholders (gray, line width 2 pixels). In distractor-present trials, after 850 ms, one of the circles flashed (increased in line width to 10 pixels and brightness to white) for 150 ms. Simultaneously with the offset of the flash, or 1000 ms after fixation onset in distractor-absent trials, the target (a rotated T) was presented for 150 ms. The task was to report the orientation of the T, while ignoring the flashed circle. The fixation point and the placeholders remained on the screen until the response was emitted or until 2500 ms were elapsed after the target onset. The inter-trial interval was set to 1 second.

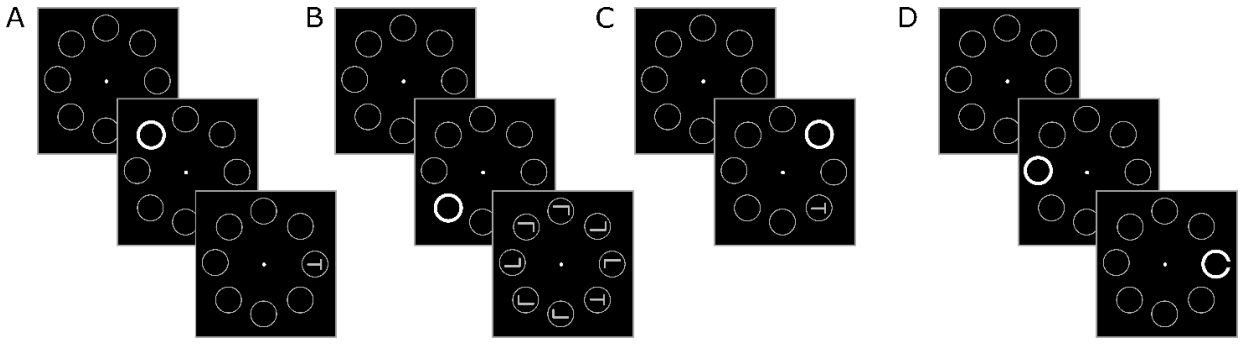

Figure 5. Stimuli used in distractor-present trials in experiments with luminance-transient distractors. Panel A, Experiment 2. Panel B, Experiment 3. Panel C, Experiment 5. Panel D, Experiment 7. In panel A, B and C participants reported the orientation of the letter T while ignoring the flashed circle. In panel D participants

reported the side of the gap in the second flashed circle while ignoring the flashed circle without the gap. In panel A, C and D targets and flashed circles were presented for 150 ms, in panel B the search array containing the target was displayed until response.

Results and discussion

Overall, 1.31 % of RTs were rejected as outliers. The overall error rate was 3.15%

Distractor-location, target-location and distractor interference effects

Mean RTs and error rates, plotted as a function of distractor region in distractor-present trials and as a function of target region in distractor-absent trials are presented in Figure 6. As expected, we found a distractor-location effect, RTs were on average 14.5 ms faster, 95% CI [-20.7 -8.4] ms, when distractors appeared in the high-probability region as compared to the low-probability region, $t(29) = 4.838$, $p < .001$, $d_z = 0.883$. In contrast, no significant target-location effect emerged, $t(29) = 0.197$, $p = .845$, $d_z = 0.036$, RT difference = -0.5 ms, 95% CI [-5.8 4.8] ms, $BF_{01} = 5.053$. The target-location effect was significantly different in Experiment 2 compared to Experiment 1 , $t(58) = 2.827$, $p = .006$, $d = 0.73$, difference = 34.3 ms, 95% CI [10 58.6] ms. Distractor interference was limited to distractors appearing in the low-probability region $t(29) = 2.734$, $p = .011$, $d_z = 0.499$, RT difference = 12.4 ms, 95% CI [3.1 21.7] ms, whereas distractors presented in the high-probability region did not produce a significant cost in terms of RTs, $t(29) = 0.795$, $p = .433$, $d_z = 0.145$, RT difference = -2.1 ms, 95% CI [-7.6 3.4] ms.

The analysis of error rates revealed no significant distractor-location effect, $t(29) = 1.353$, $p = .186$, $d_z = 0.247$, error rate difference = -0.7%, 95% CI [-1.7 0.3] %. The target-location effect was significant, $t(29) = 2.053$, $p = .049$, $d_z = 0.375$, error rate difference = -0.9%, 95% CI [-1.7 0] %, $BF_{01} = 0.826$. Notice that albeit relatively small, the direction of the effect

was opposite to the one expected based on the hypothesis of enhanced inhibition in the high-probability region, given that more errors occurred when targets were presented in the high-probability region. The target-location effect was significantly different in Experiment 2 compared to Experiment 1 , $t(58) = 2.128$, $p = .038$, $d = 0.549$, difference = 1.4 %, 95% CI [0.1 2.8] %. The distractor interference effect was significant when distractors appeared in the-high probability region, $t(29) = 2.32$, $p = .028$, $d_z = 0.424$, error rate difference = 0.9%, 95% CI [0.1 1.7] %, and when they appeared in the low-probability region $t(29) = 2.597$, $p = .015$, $d_z = 0.474$, error rate difference = 1.5%, 95% CI [0.3 2.7] %.

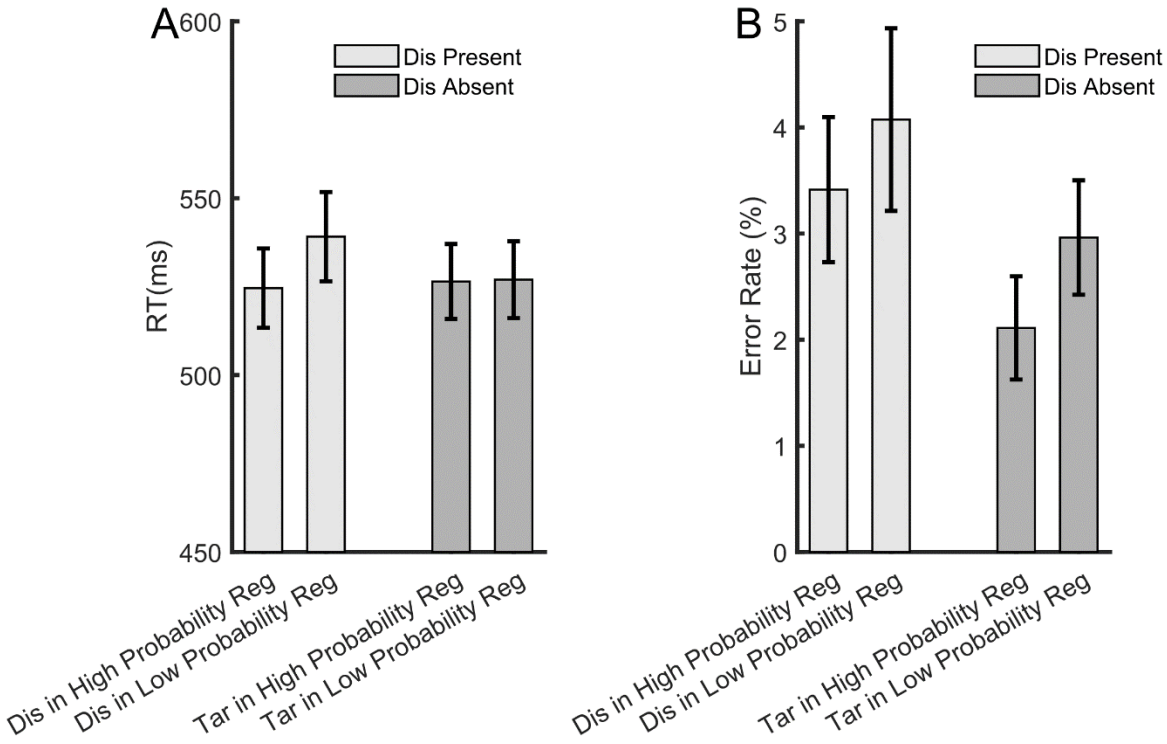

Figure 6. Mean RTs (A) and error rates (B) in Experiment 2, in distractor-present and distractor-absent trials, as a function of distractor and target region, respectively.

Congruency effect

RTs from distractor-present trials, split as function of the region where the distractor appeared and of the congruency between distractor and target region are depicted in Figure 7. Contrary to the finding from Experiment 1, here RTs showed a congruency advantage, i.e. participants were faster when the target appeared in the same region of the distractor, as evidenced by a significant main effect of the factor Congruency, $F(1,29) = 5.208$, $p = .03$, $\eta_p^2 = .152$. This effect was not modulated by the distractor region, as evidenced by the lack of a significant Congruency x Distractor Probability interaction, $F(1,29) = 0.202$, $p = .656$, $\eta_p^2 = .007$.

The analysis of error rates revealed a significant main effect of the factor Congruency, $F(1,29) = 6.164$, $p = .019$, $\eta_p^2 = .175$, and no significant Congruency x Distractor Probability interaction, $F(1,29) = 1.838$, $p = .186$, $\eta_p^2 = .06$. The lower error rate in congruent trials is consistent with the observation that participants were also faster in this condition.

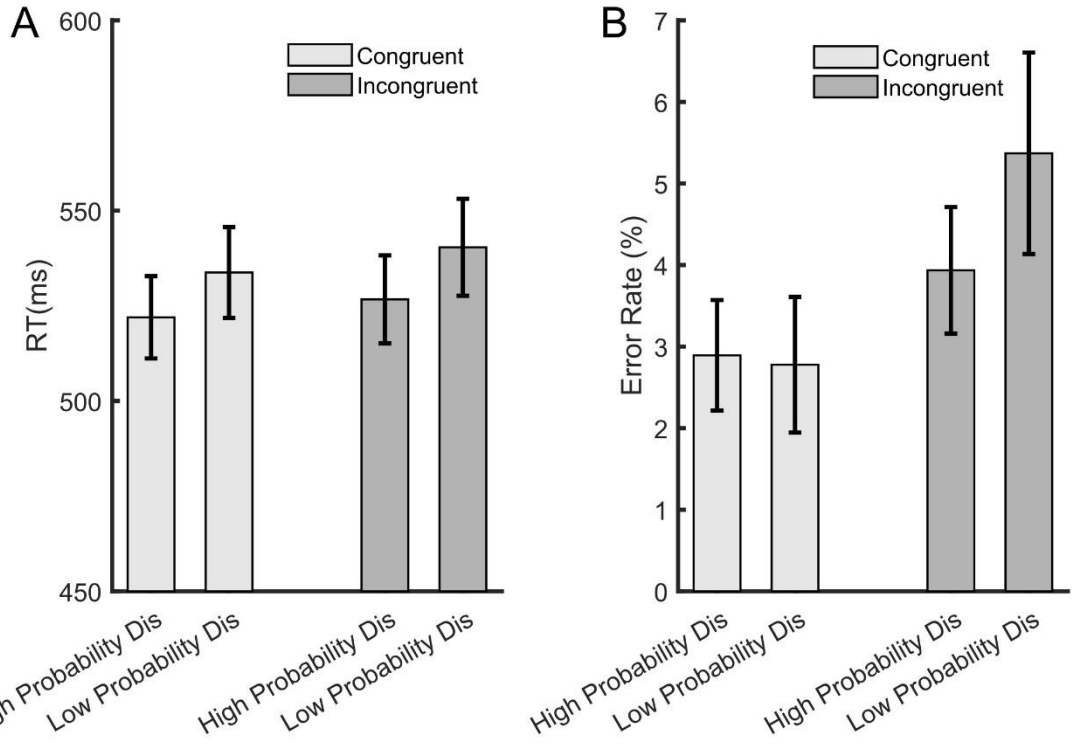

Figure 7. RTs (A) and error rates (B) in the distractor-present trials of Experiment 2, plotted as a function of the distractor probability at the region where the distractor appeared and of the congruency between the distractor and target regions.

The results from Experiment 2 indicate that the general distractor interference, particularly at high-probability locations, seems to be weaker in the case of luminance transients. This might partially be explained by a more efficient attentional guidance towards the luminance-transient target T in Experiment 2, as compared to a slower orienting toward the shape-singleton target in Experiment 1 (also see, Gaspelin et al., 2016). However, what is crucial is the fact that while the distractor-location effect was observed irrespective of the distractor type, the target-location effect emerged only with color-singleton distractors, as described in multiple previous studies (e.g., Valsecchi & Turatto, 2021; Wang & Theeuwes, 2018a, 2018b; Zhang et al., 2019), but not with luminance-transient distractors, thus confirming the results from our previous study (Valsecchi & Turatto, 2023). When comparing the pattern of results from the color-singleton and the luminance-transient distractor, we also found another qualitative difference between the two conditions. In Experiment 1, when the color-singleton distractor and the shape-singleton target were located in the same region, i.e., both to the right or to the left of the fixation point, we observed an increase in RTs compared to when the target and the distractor were in opposite hemifields. Conversely, in Experiment 2, when the luminance-transient distractor preceded the luminance-transient target in the same region, participants were faster compared to when the two stimuli were in different regions. This is consistent with the fact that luminance-transient distractors, captured attention to a location near the target when in the same region, thus acting like a congruent cue, and to a location away from the target when in a different region, thus acting like an incongruent cue, similarly to what has been shown with onset distractors preceding feature-singleton targets (Mathôt et al., 2010).

Comparison of Experiments 1 and 2

The first two experiments investigated the consequences of having spatially unbalanced occurrence probabilities of either a color-singleton distractor (Experiment 1) or a luminance-transient distractor (Experiment 2). Besides the intrinsic aspect of the two types of distractors, an abrupt luminance increment in the case of luminance-transients, and a stimulus that differs in color from other otherwise homogeneous stimuli in the case of color singletons, there are other aspects that differ between the two paradigms used to present color-singleton and luminance-transient distractors, which might be relevant to explain the different results.

The first aspect concerns the search efficiency in the two paradigms. In addition to the lack of the target-location effect with luminance transients and the reversal of the congruency effect with color singletons, another macroscopic difference emerged from the two experiments: RTs were almost halved in Experiment 2 as compared to Experiment 1. This is not surprising, because in Experiment 2 the target T was also a luminance-transient item appearing in isolation, whereas in Experiment 1 the target was a shape singleton. The faster search with a luminance-transient target might imply a smaller potential for interference by the luminance-transient distractor (Gaspelin et al., 2016), and therefore a smaller need for distractor inhibition, which would explain the weaker or absent target-location effect.

The second aspect concerns the stimulation temporal dynamics. By definition a transient is a dynamic discontinuity, namely an event whose interference on the target search is temporarily very limited, engaging attention for a limited time. On the contrary, the color-singleton distractor is a static discontinuity that remains present in the search array, and continues to create interference, until the target is found and the search process is terminated.

The third aspect concerns the temporal order of appearance of the target and the distractor. In Experiment 2 the transient distractor preceded the target by 150 ms, whereas in

Experiment 1 the color-singleton distractor and the shape-singleton target appeared simultaneously, as commonly happens in the additional-singleton paradigm. As previously suggested (Mathôt et al., 2010), when targets and distractors are simultaneous, or if the distractor trails the target, the origin of the distractor interference might shift from the need to re-orient attention from the distractor to the target, to a possible competition among stimuli for attracting attention.

The fourth aspect worth considering is that in our luminance-transient distractor paradigm the target was the only stimulus associated with the task response. In the additional-singleton paradigm, instead, each stimulus in the search array, including the distractor, contained an element (in our case, the letter T) that could evoke a response congruent or incongruent (depending on its orientation) with the probe element inside the shape-singleton target. Hence, when the color-singleton distractor is erroneously selected, the embedded element is also likely processed, and its identity might potentially interfere with the generation of the response associated with the probe inside the target, to the point of priming an erroneous response (Becker, 2007; Feldmann-Wüstefeld et al., 2021; Folk & Remington, 2006; Theeuwes et al., 2000), which in turn might increase the need for suppressing the distractor.

Finally, in Experiment 1, namely with the additional-singleton paradigm, participants could not predict before the beginning of the trial the shape and color of both the target and the distractor. In our luminance-transient paradigm instead, the distractor was invariably a flashed circle and the target a flashed letter, and this might be a crucial determinant for the emergence of a target-location effect. Indeed, following the dimension-weighting account (Liesefeld et al., 2019; Liesefeld & Müller, 2019), if participants can predict the dimension defining the distractor, and if that dimension differs from the one defining the target, they can

potentially selectively apply spatial suppression within the map representing the distractor feature, instead of suppressing the distractor location at the saliency map level. This would prevent the emergence of costs for the processing of the target appearing at locations associated with distractor suppression (Zhang et al., 2019).

In the following we present a set of experiments specifically aimed at evaluating whether these differences could explain the discrepant pattern of results that we observed between Experiments 1 and 2, and particularly the lack of the target-location effect when a transient distractor is used.

Experiment 3: luminance-transient distractors and search difficulty

The aim of Experiment 3 was to evaluate whether increasing the target search difficulty could boost the capture by the luminance-transient distractor, thereby increasing the need for distractor inhibition, potentially leading to the emergence of a target-location effect. To this end, we used a modified version of the luminance-transient distractor paradigm from Experiment 2. Instead of appearing alone, the target T was presented together with an array of rotated Ls serving as non-target elements, which appeared inside the placeholders.

Methods

Participants

The datasets from 7 participants were rejected for failing to reach the required overall accuracy of 80%. Out of the 30 participants whose data were analyzed, 15 were female and 15 were male. The mean age was 33.5 years.

Stimuli and procedure

The stimuli and procedure used Experiment 3 were identical to the those of Experiment 2, with the following two exceptions. First, a rotated L was presented in each non-

target placeholder at the same time as the rotated target T (Figure 5B). The two segments constituting the Ls were identical to the those forming the T, with the difference that the horizontal segment was randomly shifted up or down. The vertical segment was also shifted randomly left or right. Second, the search array remained on the screen until response or for the maximum allowed response time of 2500 ms.

Results and discussion

Overall, 0.19% of RTs were rejected as outliers. The overall error rate was 3.56%

Distractor-location, target-location and distractor interference effects

Mean RTs and error rates, plotted as a function of distractor region in distractor-present trials and as a function of target region in distractor-absent trials are presented in Figure 8. The first result that emerges clearly is that on average RTs were above 1000 ms, confirming that finding a rotated T among rotated Ls is a serial and inefficient search (e.g., Wolfe, 1998). Furthermore, we observed a significant distractor-location effect, $t(29) = 2.387$, $p = .024$, $d_z = 0.436$, RT difference = -29.3 ms, 95% CI [-54.3 -4.2] ms, and a significant interference effect for distractors appearing both at the high-probability location, $t(29) = 2.682$, $p = .012$, $d_z = 0.49$, RT difference = 23.8 ms, 95% CI [5.6 41.9] ms, and at the low-probability location, $t(29) = 3.536$, $p = .001$, $d_z = 0.645$, RT difference = 53 ms, 95% CI [22.4 83.7] ms. The finding of a reliable distractor interference effect is consistent with the suggestion that interference by luminance transients is larger when search is difficult (Gaspelin et al., 2016). Crucially, as in Experiment 2, the target-location effect was not significant, $t(29) = 0.107$, $p = .916$, $d_z = 0.02$, RT difference = -3.3 ms, 95% CI [-65.6 59.1] ms, $BF_{01} = 5.117$. Notice that increasing the difficulty of the search task produced an increase in the between-observer variability of the target effect, hence, the CI associated with the effect is quite large, so that the CI does not allow us to exclude the possibility of even a relatively large

effect. Having this caution in mind, even under conditions where a luminance transient exerts a significant disturbance on the search process, we did not find evidence that using the statistics of the transient's spatial occurrence to reduce distraction comes at a cost for processing targets. Notice that although the difference between the target-location effect in Experiments 3 and 1 (37 ms, CI [-28.5 102.5]) was numerically larger than the one observed between Experiments 2 and 1, it was not significant, $t(58) = 1.132$, $p = .262$, $d = 0.292$, which again might be explained by the increased RTs variability associated with a more difficult search.

The analysis of error rates revealed no significant effects. Distractor-location effect, $t(29) = 0.892$, $p = .38$, $d_z = 0.163$, error rates difference = -0.5%, 95% CI [-1.5 0.6] %. Target-location effect, $t(29) = 1.963$, $p = .059$, $d_z = 0.358$, error rates difference = 1.1%, 95% CI [0 2.2] %, $BF_{01} = 0.957$. Target-location effect comparison between Experiment 3 and Experiment 2, $t(58) = 0.628$, $p = .533$, $d = 0.162$, difference = -0.5%, 95% CI [-2 1.1] %. Distractor interference in the high probability region, $t(29) = 0.609$, $p = .547$, $d_z = 0.111$, error rates difference = -0.2%, 95% CI [-1.5 0.6] %. Distractor interference in the low probability region $t(29) = 0.455$, $p = .652$, $d_z = 0.083$, error rates difference = 0.2%, 95% CI [-0.7 1.1] %.

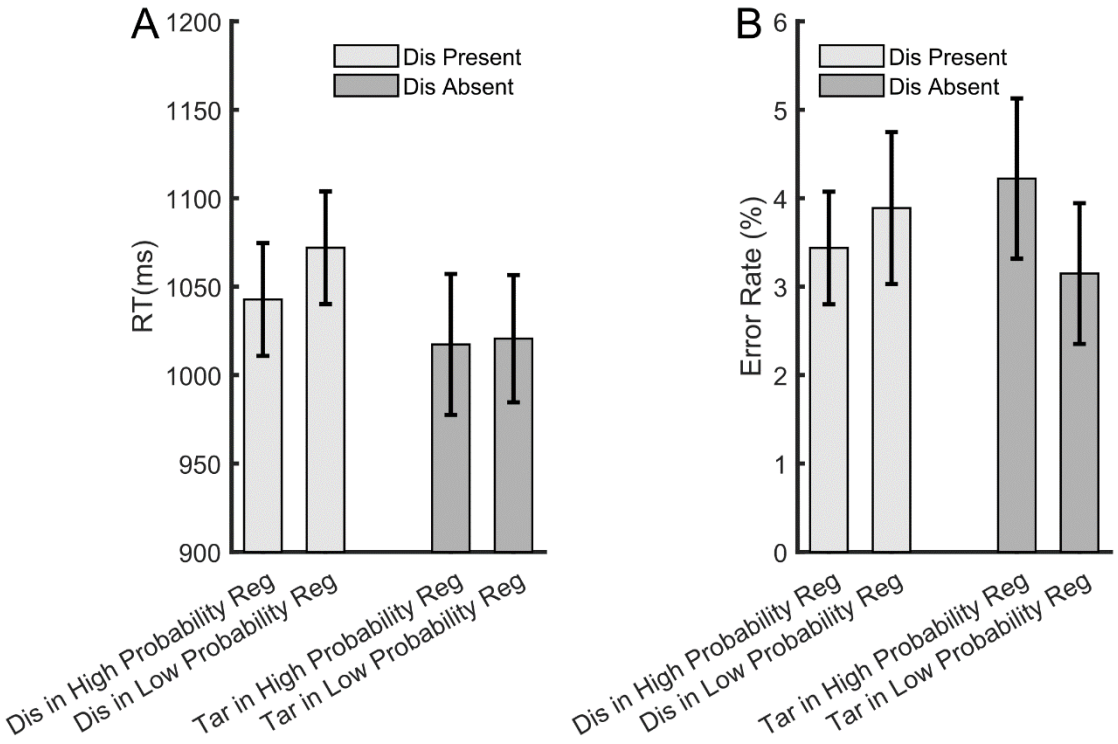

Figure 8. Mean RTs (A) and error rates (B) in Experiment 3, in distractor-present and distractor-absent trials, as a function of the distractor and target region, respectively.

Congruency effect

RTs from distractor-present trials, split as function of the region where the distractor appeared and of the congruency between target and distractor regions are presented in Figure 9. The results show a congruency advantage, in line with Experiment 2. The ANOVA results yielded a significant main effect of Congruency, $F(1,29) = 32.488$, $p < .001$, $\eta_p^2 = .528$, and a significant Congruency x Distractor Probability interaction, $F(1,29) = 0.472$, $p = .498$, $\eta_p^2 = .016$. The ANOVA performed on error rates failed to yield any significant effect. Main effect of Congruency, $F(1,29) = 0.034$, $p = .856$, $\eta_p^2 = .001$. Congruency x Distractor Probability interaction, $F(1,29) = 0.014$, $p = .905$, $\eta_p^2 < .001$.

One crucial aspect of the results of Experiment 3 is that the longer RTs to far distractors were observed also when the target itself did not appear in isolation. In principle

an apparent motion signal due to the rapid succession of distractor and target might have driven attentional capture in Experiment 2. A stronger apparent motion signal when target and distractor appeared in the same hemifield might have explained the congruency advantage. However, in Experiment 3 we observed the congruency advantage although the target did not appear in isolation, excluding a possible role of apparent motion.

In general, the finding of a worse performance when distractors appear far from the target can be interpreted as a sign of costs emerging from the need to re-orient attention towards the target once it has been captured by the distractor (Mathôt et al., 2010), a common finding in all of the experiments involving luminance-transient distractors included in the present study. Evidently, however, participants were able to reduce such re-orienting costs for distractors appearing in likely locations without necessarily having to pay a price for orienting towards the target, even when the target was difficult to find. This excludes search difficulty as the reason for the different pattern of results between Experiments 1 and 2. In the following experiment, we tested the possible role of the different temporal dynamics of stimulation.

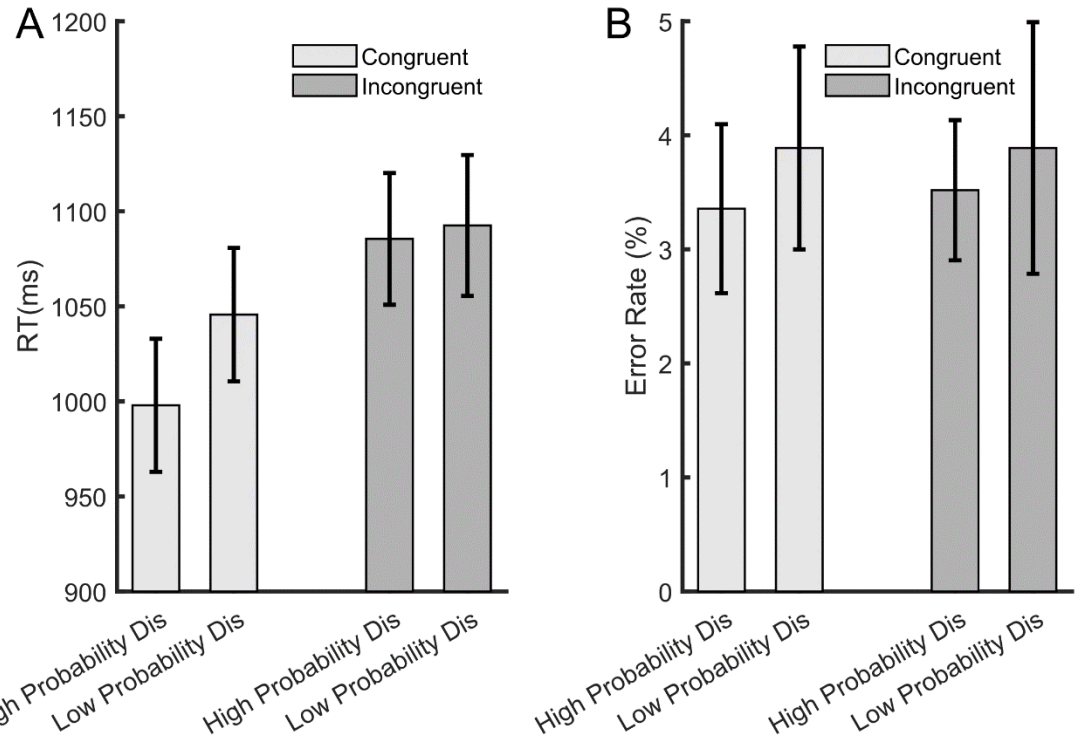

Figure 9. RTs (A) and error rates (B) in the distractor-present trials of Experiment 3, plotted as a function of the distractor probability at the region where the distractor appeared and of the congruency between target and distractor regions

Experiment 4: transient color-singleton distractors

The aim of Experiment 4 was to test whether the presence of the distractor element throughout the search process, likely requiring sustained inhibition of the distractor location, is the determinant of the emergence of the target-location effect. Note that the transient nature of the interference produced by abrupt-onset distractors has been proposed as a possible explanation for the finding that the introduction of an auditory dual task differentially affects attentional capture by onsets and feature singletons (Boot et al., 2005). To answer this question, we slightly modified the additional-singleton paradigm used in Experiment 1 by reducing the duration of the color-singleton distractor to 200 ms. In this way, the target and distractor endurances were made comparable to that of the corresponding events in Experiment 2, where transients were used.

Methods

Participants

The datasets from 8 participants were rejected for failing to reach the required overall accuracy of 80%. Out of the 30 participants whose data were analyzed, 14 were female and 16 were male. The mean age was 34.5 years.

Stimuli and procedure

The stimuli and procedure used Experiment 4 were identical to those of Experiment 1, with the exception that, when present, the color-singleton distractor remained visible only for 200 ms from the display onset, after which its color became the same of the other stimuli (Figure 2B).

Results and discussion

Overall, 0.61% of RTs were rejected as outliers. The overall error rate was 4.49%

Distractor-location, target-location and distractor interference effects

Mean RTs and error rates, plotted as a function of distractor region in distractor-present trials and as a function of target region in distractor-absent trials are presented in Figure 10. The pattern of results was similar to the that observed in Experiment 1. The distractor-location effect was close to significance, $t(29) = 1.871$, $p = .071$, $d_z = 0.342$, RT difference = -20.9 ms, 95% CI [-43.7 1.9] ms, but crucially the target-location effect was significant, $t(29) = 2.399$, $p = .023$, $d_z = 0.438$, RT difference = 36 ms, 95% CI [5.3 66.8] ms, $BF_{01} = 0.447$. The interference effect was significant for distractors appearing both at the high-probability location, $t(29) = 8.116$, $p < .001$, $d_z = 1.482$, RT difference = 73.8 ms, 95% CI [55.2 92.4] ms, and at the low-probability location $t(29) = 6.718$, $p < .001$, $d_z = 1.227$, RT difference = 94.7 ms, 95% CI [65.9 123.5] ms.

The analysis of error rates revealed no significant effects. Distractor-location effect, $t(29) = 1.916$, $p = .065$, $d_z = 0.35$, error rates difference = -1.6%, 95% CI [-3.3 0.1] %. Target-location effect, $t(29) = 0.589$, $p = .56$, $d_z = 0.108$, error rates difference = 0.4%, 95% CI [-1 1.8] %, $BF_{01} = 4.383$. Distractor interference in the high-probability region, $t(29) = 0.886$, $p = .383$, $d_z = 0.162$, error rates difference = 0.4%, 95% CI [-0.5 1.3] %. Distractor interference in the low-probability region, $t(29) = 1.891$, $p = .069$, $d_z = 0.345$, error rates difference = 2%, 95% CI [-0.2 4.1] %.

The results ruled out the hypothesis that the static vs. transient nature of the distractor was responsible for the emergence of a target-location effect with color singletons and not with luminance transients. When participants were presented with a color singleton only in the very early phase of the search process, we still observed a robust target-location effect, even if the distractor-location effect itself was statistically weaker. Note however, that there cannot be a target-location effect without a distractor-location effect.

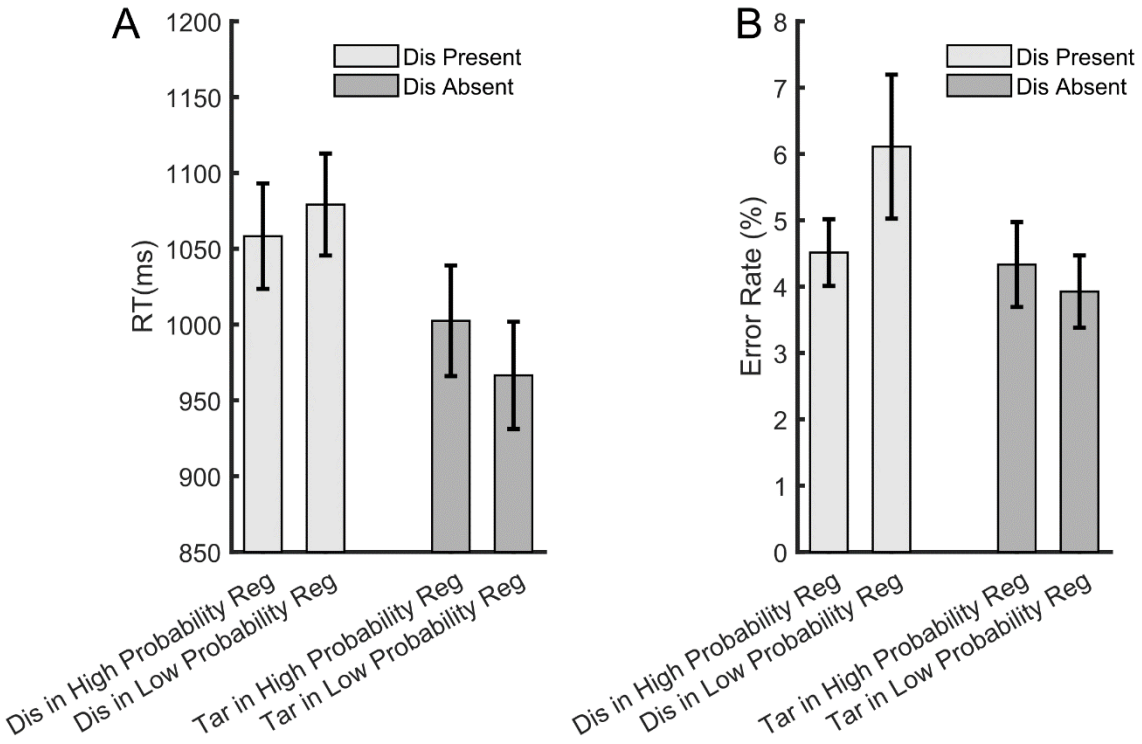

Figure 10. Mean RTs (A) and error rates (B) in Experiment 4, in distractor-present and distractor-absent trials, as a function of the target and distractor regions, respectively.

Congruency effect

RTs from distractor-present trials, split as function of the region where the distractor appeared and of the congruency between distractor and target regions are presented in Figure 11. Again, the results were in line with those from Experiment 1. This was confirmed by the ANOVA results, which yielded a significant main effect of Congruency, $F(1,29) = 11.847$, $p = .002$, $\eta_p^2 = .29$, and a significant Congruency x Distractor Probability interaction, $F(1,29) = 4.655$, $p = .039$, $\eta_p^2 = .138$. As in Experiment 1, the interaction was associated with a larger congruency effect for distractors appearing in the high-probability region and might in part be explained by the target-location effect adding to the congruency effect. The ANOVA performed on error rates failed to yield any significant effect. Main effect of Congruency, $F(1,29) = 3.672$,

p = .065, η_p^2 = .112. Congruency x Distractor Probability interaction, $F(1,29)$ = 0.005, p = .944, η_p^2 < .001.

The observed discrepancy in the direction of the congruency effect between Experiments 1 and 2 does not seem to arise from the sustained nature of color-singleton distractors compared to luminance-transient distractors. When the duration of a color-singleton distractor was reduced, so that it could only interfere with the early phases of the search process, a congruency cost was still observed.

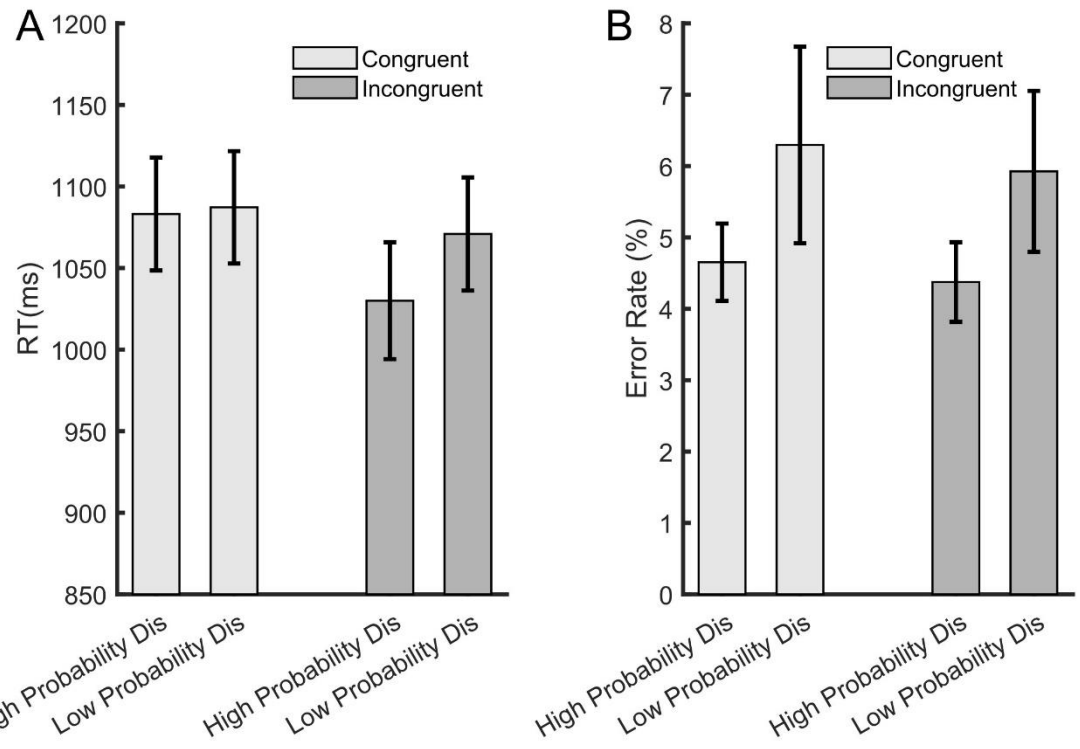

Figure 11. RTs (A) and error rates (B) in the distractor-present trials of Experiment 4, plotted as a function of the distractor probability at the region where the distractor appeared and of the congruency between the target and distractor regions.

Experiment 5: luminance-transient distractor simultaneous with the target

Experiment 4 showed that by reducing the color-singleton distractor duration so that it became a sort of transient event similar to the flashed-circle distractor, the target-location effect still emerged. However, there is another aspect in the timing of the stimuli that differed between Experiments 1 and 2, and that might be relevant to producing the discrepant results as far as the target-location effect is concerned. Indeed, whereas in Experiment 1 the color-singleton distractor appeared simultaneously with the target, in Experiment 2 the luminance transient preceded the target by 150 ms. Thus, the nature of the processes leading to distractor rejection might change depending on the asynchrony between the onset of the distractor and the search array (Mathôt et al., 2010). To address this, the luminance-transient paradigm that we used in Experiment 2 was modified so that the distractor appeared concurrently with the target, similar to what happens with color-singleton distractors in the additional-singleton paradigm.

Methods

Participants

The datasets from 3 participants were rejected for failing to reach the required overall accuracy of 80%. Out of the 30 participants whose data were analyzed, 11 were female and 19 were male. The mean age was 35.7 years.

Stimuli and procedure

The stimuli and procedure used Experiment 5 were identical to the ones of Experiment 2, with the exception that, when present, the luminance transient appeared 1000 ms after the

onset of the fixation and the placeholders, and remained on the screen for 150 ms, in other words it appeared and disappeared simultaneously with the target (Figure 5C).

Results and discussion

Overall, 0.89% of RTs were rejected as outliers. The overall error rate was 4.91%

Distractor-location, target-location and distractor interference effects

Mean RTs and error rates, plotted as a function of distractor region in distractor-present trials and as a function of target region in distractor-absent trials are presented in Figure 12. The pattern of RT results was consistent with the that of Experiment 2, except for the fact that the transient distractor interference was slightly more pronounced. Whereas the distractor-location effect was significant, $t(29) = 4.522$, $p < .001$, $d_z = 0.826$, RT difference = -12.6 ms, 95% CI [-18.3 -6.9] ms, no significant target-location effect emerged, $t(29) = 0.161$, $p = . 873$, $d_z = 0.029$, RT difference = -0.5 ms, 95% CI [-7.5 6.4] ms, $BF_{01} = 5.083$. The target-location effect was significantly smaller in Experiment 5 compared to Experiment 1, $t(58) = 2.785$, $p = .007$, $d = 0.719$, difference = 34.3 ms, 95% CI [9.6 59] ms. The general distractor interference was significant both for distractors appearing in the high-probability region, $t(29) = 5.972$, $p < .001$, $d_z = 1.09$, RT difference = 11.2 ms, 95% CI [7.4 15.1] ms, and in the low-probability region, $t(29) = 7.768$, $p < .001$, $d_z = 1.418$, RT difference = 23.8 ms, 95% CI [17.6 30.1] ms.

The analysis of error rates revealed no significant effects. Distractor-location effect, $t(29) = 1.464$, $p = .154$, $d_z = 0.267$, error rates difference = 1%, 95% CI [-0.4 2.4] %. Target-location effect, $t(29) = 0.327$, $p = .746$, $d_z = 0.06$, error rates difference = -0.2%, 95% CI [-1.3 1] %, $BF_{01} = 4.896$. Comparison of Target-location effects in Experiments 5 and 1, $t(58) = 0.996$, $p = .323$, $d = 0.257$, difference = 0.8%, 95% CI [-0.8 2.3] %. Distractor interference effect when distractors appeared in the high-probability region, $t(29) = 0.173$, $p = .864$, $d_z = 0.032$, error

rates difference = 0.1%, 95% CI [-0.6 0.7] %. Interference effect with distractors in the low-probability region, $t(29) = 1.308$, $p = .201$, $d_z = 0.239$, error rates difference = -1%, 95% CI [-2.5 0.5] %.

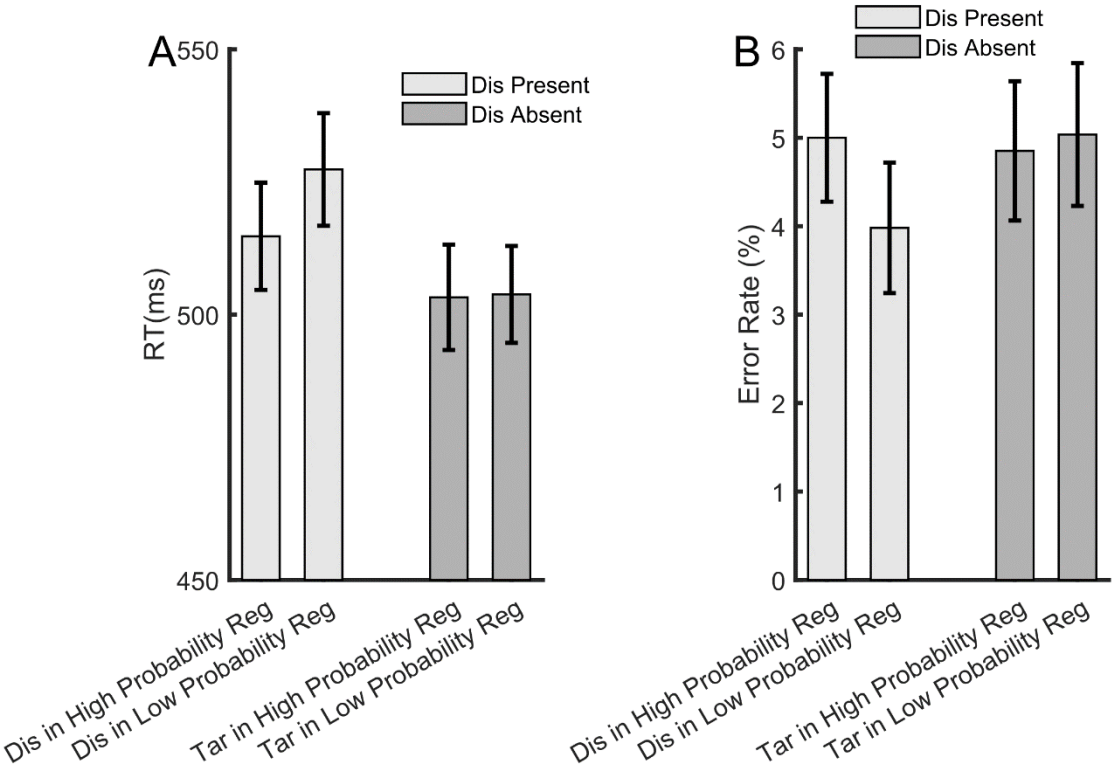

Figure 12. Mean RTs (A) and error rates (B) in Experiment 5, in distractor-present and distractor-absent trials, as a function of the target and distractor regions, respectively.

Congruency effect

RTs from distractor-present trials, split as function of the region where the distractor appeared and of the congruency between the target and distractor regions are presented in Figure 13. Considering the RT data, it appears that making the transient distractor appearing simultaneously with the target largely reduced the congruency effect. Neither the main effect of Congruency, $F(1,29) = 0.484$, $p = .492$, $\eta_p^2 = .016$, nor the Congruency x Distractor Probability interaction, $F(1,29) = 1.179$, $p = .287$, $\eta_p^2 = .039$, were significant. On the contrary, the main effect of Congruency was significant in the analysis of error rates, $F(1,29) = 11.409$, p

= .002, η_p^2 = .282. The Congruency x Distractor Probability interaction was not significant, $F(1,29) = 1.43$, $p = .241$, $\eta_p^2 = .047$.

Mathôt and colleagues (2010) showed that when transient distractors appear simultaneously with color-singleton targets, congruency effects are reversed relative to the case when the distractor appears before the target. When the two stimuli were simultaneous, a distractor in the same hemifield as the target produced a larger cost relative to a distractor in the opposite hemifield, which was interpreted as a consequence of increased competition between the two items. When the distractor anticipated the target, RTs were longer when it appeared in the opposite hemifield compared to the target, which was attributed to the need to re-orient attention over a larger distance. In our data, making the target and distractor simultaneous failed to reverse the congruency effect, which was largely reduced for RTs but still showed a congruency advantage in error rates. This contrasts with the results of Experiments 1 and 4, where the congruency advantage with a color-singleton distractor was quite robust. Our results were only partially consistent with those of Mathôt and colleagues (2010), in the sense that the congruency advantage was still present, albeit reduced, indicating re-orienting costs. The reason for this discrepancy with the study of Mathôt and colleagues is unclear. One possibility is that in our paradigm the luminance-transient distractor was much more salient than the target, so that it captured attention even when it appeared simultaneously with the target in a far location, leading to larger re-orienting costs in incongruent trials. Crucially, however, we can exclude that making distractors and targets simultaneous is the key manipulation that determines the emergence of the target-location effect, which was still absent in the present experiment as well as in Experiment 2.

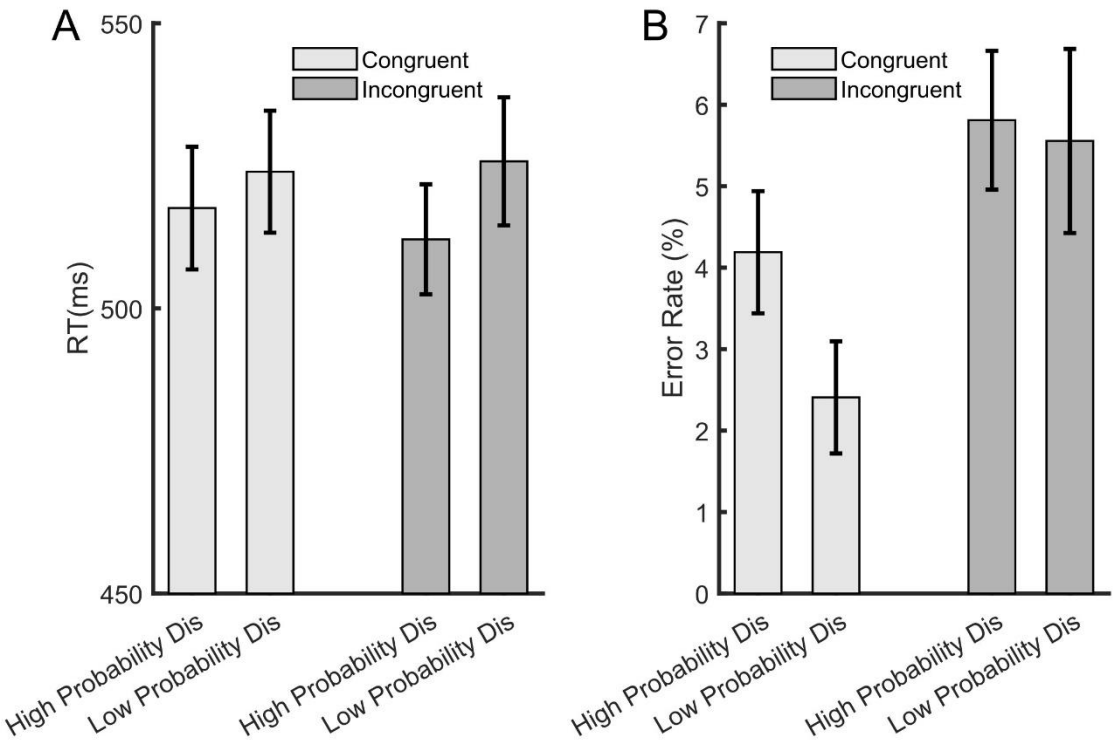

Figure 13. RTs (A) and error rates (B) in the distractor-present trials of Experiment 5, plotted as a function of the distractor probability at the region where the distractor appeared and of the congruency between the target and distractor regions.

Experiment 6: color singleton with no response competition

Another potentially key ingredient that differed between our luminance-transient distractor paradigm and our implementation of the additional-singleton paradigm, and the paradigm used by Mathôt and colleagues (2010), is that in the additional-singleton paradigm each element of the search array, including the distractor, contains a task-related stimulus (typically a vertical vs horizontal line, whereas in our Experiment 1 it was a rotated T) which may or may not be congruent with the probe element inside the target shape. In Experiment 6 we evaluated whether the lack of task-related elements, and particularly inside the distractor, was sufficient to abolish the target-location effect.

Methods

Participants

The datasets from 3 participants were rejected for failing to reach the required overall accuracy of 80%. Out of the 30 participants whose data were analyzed, 17 were female and 13 were male. The age data from one participant were not available. The mean age of the remaining participants was 37 years.

Stimuli and procedure

The stimuli and procedure from Experiment 6 were identical to the those of Experiment 1, with the exception that the non-target elements in the search display (including the distractor) contained either an upright or an upside-down letter T, whereas only the shape-singleton target contained the clockwise or counterclockwise T, which required the discriminative response (Figure 2C).

Results and discussion

Overall, 1.35% of RTs were rejected as outliers. The overall error rate was 4.66%

Distractor-location, target-location and distractor interference effects

Mean RTs and error rates, plotted as a function of distractor region in distractor-present trials and as a function of target region in distractor-absent trials are presented in Figure 14. The RT pattern resembled those from the other experiments that used the additional-singleton paradigm (Experiment 1 and 4). The distractor-location effect, $t(29) = 4.086$, $p < .001$, $d_z = 0.746$, RT difference = -53.5 ms, 95% CI [-80.3 -26.7] ms, as well as the target-location effect, $t(29) = 2.514$, $p = .018$, $d_z = 0.459$, RT difference = 33.7 ms, 95% CI [6.3 61.1] ms, $BF_{01} = 0.359$, were significant. The general distractor interference was significant for distractors appearing both in the high-probability region, $t(29) = 7.956$, $p < .001$, $d_z = 1.453$,

RT difference = 76.1 ms, 95% CI [56.6 95.7] ms, and in the low-probability region, $t(29)$ = 7.131, $p < .001$, $d_z = 1.302$, RT difference = 129.6 ms, 95% CI [92.5 166.8] ms.

The analysis of error rates only yielded a significant interference effect for distractors presented in the high-probability region, $t(29) = 2.073$, $p = .047$, $d_z = 0.379$, error rates difference = 1.6%, 95% CI [0 3.2] %. The interference effect for distractors in the low-probability region, $t(29) = 1.814$, $p = .08$, $d_z = 0.331$, Error Rate difference = 1.9%, 95% CI [-0.2 4] %, the distractor-location effect, $t(29) = 0.287$, $p = .776$, $d_z = 0.052$, Error Rate difference = -0.2%, 95% CI [-2 1.5] %, and the target-location effect, $t(29) = 0.313$, $p = .756$, $d_z = 0.057$, Error Rate difference = -0.1%, 95% CI [-1.1 0.8] %, $BF_{01} = 4.916$, were not significant.

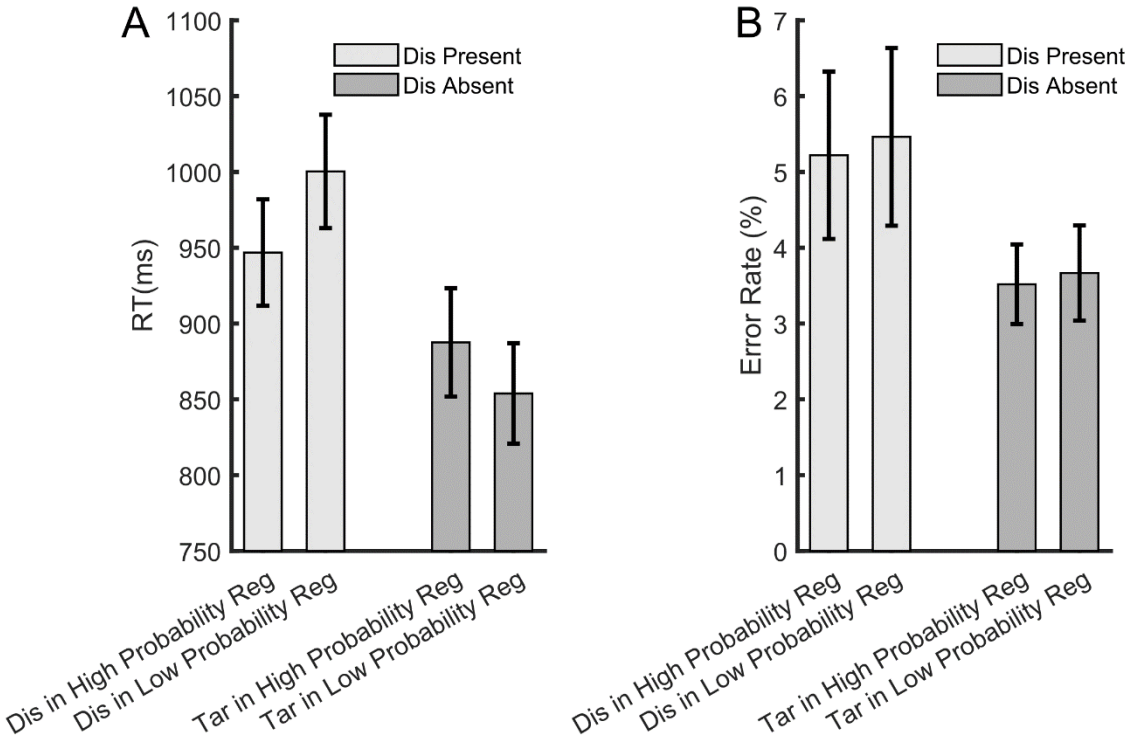

Figure 14. Mean RTs (A) and error rates (B) in Experiment 6, in distractor-present and distractor-absent trials, as a function of distractor and target region, respectively.

Congruency effect

RTs from distractor-present trials, split as function of the region where the distractor appeared and of the congruency between the target and distractor regions are presented in Figure 15. The results show a congruency cost, again in accordance with the findings from Experiments 1 and 4. The ANOVA on RTs yielded a significant main effect of Congruency, $F(1,29) = 16.064$, $p < .001$, $\eta_p^2 = .356$, and a significant Congruency x Distractor Probability interaction, $F(1,29) = 6.9$, $p = .014$, $\eta_p^2 = .192$. As in Experiments 1 and 2, the interaction was associated with a larger congruency effect for distractors appearing in the high-probability region and might in part be explained by the target-location effect adding to the congruency effect. The ANOVA on error rates failed to yield any significant results: Congruency main effect, $F(1,29) = 0.109$, $p = .744$, $\eta_p^2 = .003$, Congruency x Distractor Probability interaction, $F(1,29) = 0.277$, $p = .602$, $\eta_p^2 = .009$.

Although capture by an item containing a task-related stimulus can produce target-specific interference effects (Becker, 2007; Feldmann-Wüstefeld et al., 2021; Folk & Remington, 2006; Theeuwes et al., 2000), the results of Experiment 6 demonstrated that removing the task-relevant item from the color-singleton distractor does not in itself change the overall pattern of results: both the distractor and the target-location effects were still evident, and having a distractor close to the target made performance worse. Thus, we can exclude that the absence of a task-related stimulus inside the luminance-transient distractor used in Experiments 2 and 5 was the cause of the missing target-location effect. Moreover, we can also exclude, to a certain extent, that the absence of a pre-set target template is a crucial feature for the emergence of a target-location effect. In Experiments 2, 3 and 5, participants knew that their target was a T rotated clockwise or counterclockwise. By contrast, in Experiments 1 and 4, the target (i.e., the shape singleton) was determined in relation to the

non-target elements and defined only by its contrast along the shape dimension, making it impossible to search for it using a feature-based template analogous to the letter T.

In Experiment 6, only the target contained the T rotated clockwise or counterclockwise, so in principle, participants could have employed a template-based search strategy as in the transient distractor experiments, yet the results were still in accord with those of Experiments 1 and 4, namely, there was no evidence of a target-location effect. Admittedly, in our Experiment 6, guidance by the shape-based saliency of the target might have been more efficient than template-based search, and participants might still have relied on it to perform the task. However, a clear indication that template-based search is not, in itself, preventing the emergence of a target-location effect comes from the study by Ferrante and colleagues (2018), who found the effect in an additional color-singleton paradigm where participants were searching for a specific target configuration among non-target items that were not changing across trials.

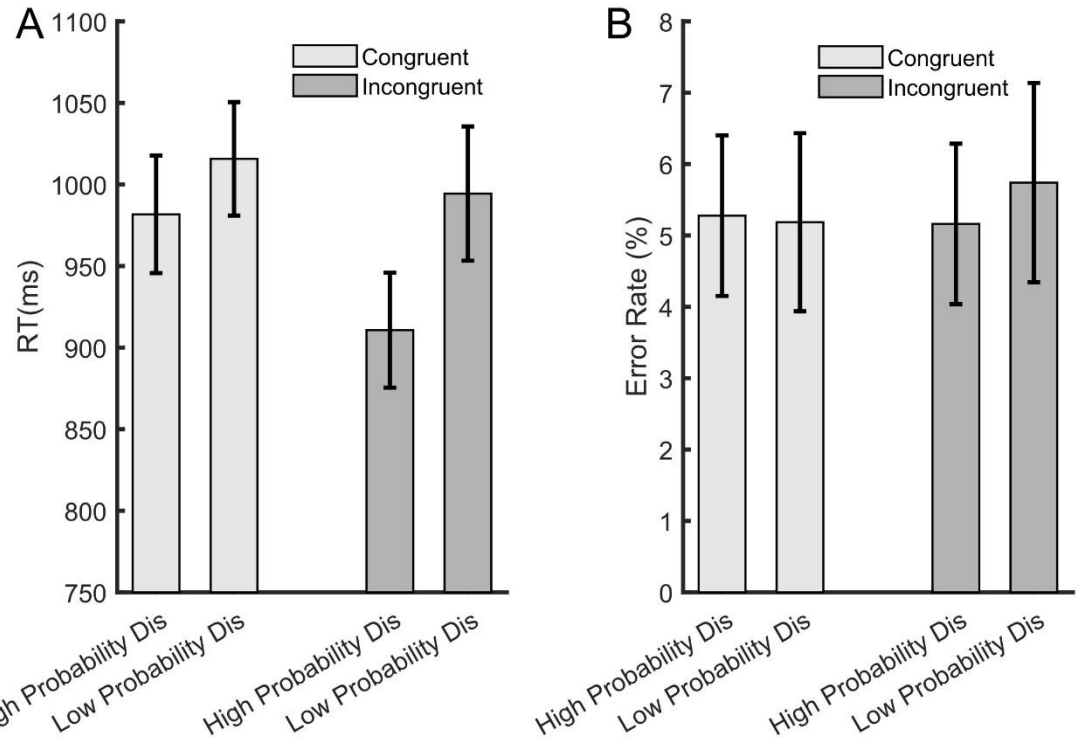

Figure 15. RTs (A) and error rates (B) in the distractor-present trials of Experiment 6, plotted as a function of the distractor probability at the region where the distractor appeared and of the congruency between the distractor and target regions.

Experiment 7: transient targets and distractors

Before concluding that qualitatively different processes are involved in coping with luminance onset and color-singleton distractors based on their spatial occurrence distribution, we need to rule out a final possible interpretation of our results. One of the most prominent accounts of distraction in visual search is the dimension-weighting account (Liesefeld et al., 2019; Liesefeld & Müller, 2019). According to this account, suppression of distractors based on their regional occurrence probability only leads to an associated cost for processing targets appearing at the same location if the distractor suppression occurs at the level of the priority map, which is feature blind (Koch & Ullman, 1985). When targets and distractors are represented in separate dimension maps, and observers know in advance the feature defining the distractors, they can selectively downweight the corresponding salience activity in the specific map, which means that no suppression activity is exerted in the saliency map, avoiding incurring any target processing costs (Liesefeld & Müller, 2021; Zhang et al., 2019). Hence, the aim of Experiment 7 was to test whether the target-location effect can be reinstated with a luminance-transient distractor by making the target and distractor as similar as possible, thus eliminating or reducing the likelihood that they can be represented in separate dimension maps. Under these conditions, any suppressive activity exerted to filter the distractor must manifest itself in the target-location effect, if any.

Methods

Participants

The datasets from 5 participants were rejected for failing to reach the required overall accuracy of 80%. Out of the 30 participants whose data were analyzed, 17 were female and 13 were male. The mean age of the remaining participants was 36.1 years.

Stimuli and procedure

The stimuli used in Experiment 7 were identical to the those of Experiment 2, with the exception that the target stimulus, was a flashed circle instead of being the usual letter T as in the previous experiments. The flashed target was itself identical to the luminance-transient distractor circle (white, 10 pixels line thickness, 150 ms duration), with the exception of a small aperture (0.22° width), either on the left or right side (Figure 5D). Participants reported the side of the gap by pressing either the G (left) or H (right) key, and they were informed that on some trials two circles would have been flashed in rapid succession, in which case only the circle with the gap, always appearing second, would have been task relevant.

Results and discussion

Overall, 1.53% of RTs were rejected as outliers. The overall error rate was 4.23%

Distractor-location, target-location and distractor interference effects

Mean RTs and error rates, plotted as a function of distractor region in distractor-present trials and as a function of target region in distractor-absent trials are presented in Figure 16. The pattern of RT results was consistent with the that found in Experiment 2. The distractor-location effect was significant, $t(29) = 3.063$, $p = .005$, $d_z = 0.559$, RT difference = -14.6 ms, 95% CI [-24.3 -4.8] ms. On the contrary, no significant target-location effect emerged, $t(29) = 0.495$, $p = .624$, $d_z = 0.09$, RT difference = -1.8 ms, 95% CI [-9.3 5.7] ms, $BF_{01} = 4.594$. The target-location effect was significantly smaller in Experiment 7 compared to Experiment 1, $t(58) = 2.869$, $p = .006$, $d = 0.741$, difference = 35.6 ms, 95% CI [10.8 60.4] ms. The general

distractor interference was close to significance for distractors appearing both in the low-probability region $t(29) = 2.042$, $p = .05$, $d_z = 0.373$, RT difference = 11.5 ms, 95% CI [0 23.1] ms, and in the high-probability region $t(29) = 0.866$, $p = .393$, $d_z = 0.158$, RT difference = -3 ms, 95% CI [-10.2 4.1] ms.

The analysis of error rates showed a relatively prominent interference effect both for distractors presented in the high-probability region, $t(29) = 3.479$, $p = .002$, $d_z = 0.635$, error rates difference = 1.8%, 95% CI [0.7 2.8] %, and in the low-probability region, $t(29) = 2.252$, $p = .032$, $d_z = 0.411$, error rates difference = 1.6%, 95% CI [0.1 3.1] %. The distractor-location effect, $t(29) = 0.222$, $p = .826$, $d_z = 0.04$, error rates difference = 0.1%, 95% CI [-1.1 1.4] %, and the target-location effect, $t(29) = 0.724$, $p = .475$, $d_z = 0.132$, error rates difference = 0.4%, 95% CI [-0.7 1.4] %, $BF_{01} = 4.043$, were not significant, nor was the comparison of the target-location effect in Experiments 7 and 1, $t(58) = 0.299$, $p = .766$, $d = 0.077$, difference = 0.2%, 95% CI [-1.3 1.7] %.

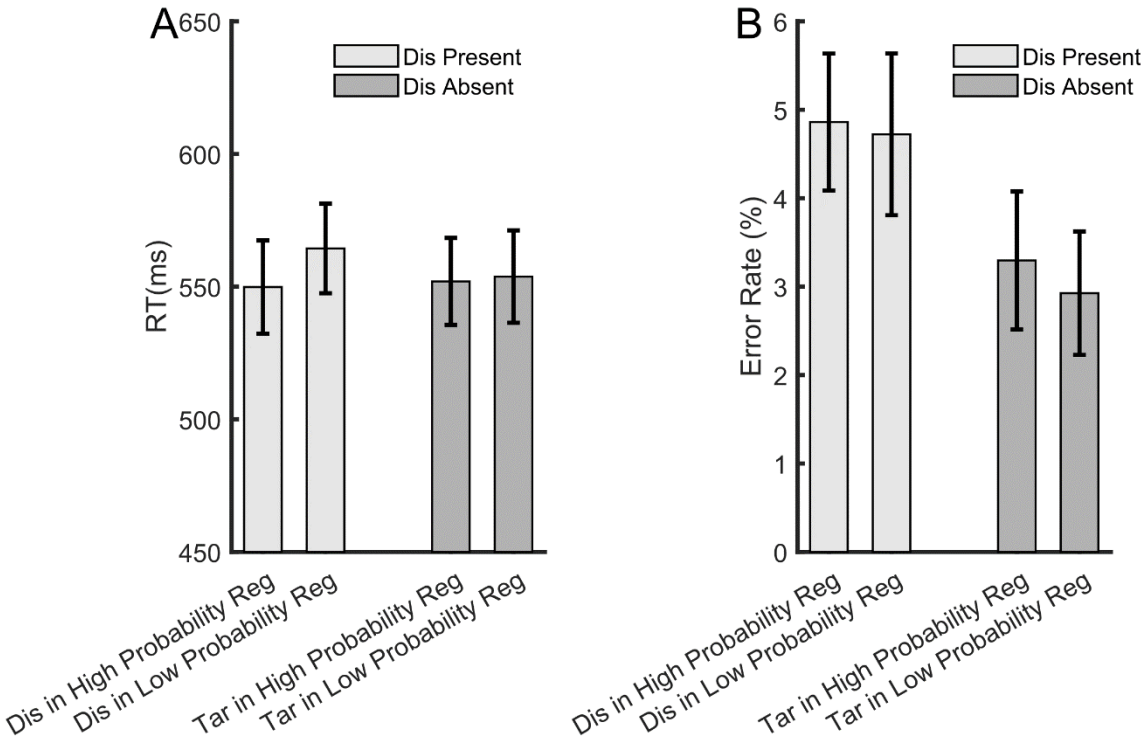

Figure 16 Mean RTs (A) and error rates (B) in Experiment 7, in distractor-present and distractor-absent trials, as a function of distractor and target region, respectively.

Congruency effect

RTs from distractor-present trials, split as function of the region where the distractor appeared and of the congruency between the target and distractor regions are presented in Figure 17. The RT results were again in accordance with the findings from Experiments 2, i.e. there was a congruency advantage. The ANOVA on RTs yielded a significant main effect of Congruency, $F(1,29) = 50.714$, $p < .001$, $\eta_p^2 = .636$, and no significant Congruency x Distractor Probability interaction, $F(1,29) = 0.014$, $p = .906$, $\eta_p^2 < .001$. The ANOVA on error rates again yielded a significant Congruency effect, $F(1,29) = 14.307$, $p < .001$, $\eta_p^2 = .33$, and no significant Congruency x Distractor Probability interaction, $F(1,29) = 0.449$, $p = .508$, $\eta_p^2 = .015$. The effect of congruency on error rates was in accordance with that observed with RTs, i.e., they both pointed to a worse performance when the target and the distractor were in opposite

hemifields. As we discussed previously, this pattern of results is suggestive of additional time needed to re-orient attention from the distractor location to the target location across hemifields in incongruent trials (Mathôt et al., 2010).

Despite the fact that the target and the distractor were basically identical, no sign of a target-location effect emerged. This indicates that suppressing the locations associated with the distractor did not impair the processing of the target when it appeared at the same locations. The results of the present experiment also allow us to exclude the possibility that in Experiments 1, 3, and 5 (also see, Valsecchi & Turatto, 2023), the target-location effect was missing because participants enacted dimension-specific mechanisms to selectively resist distraction without incurring target processing costs (Liesefeld & Müller, 2021; Zhang et al., 2019).

Notice that the paradigm adopted in Experiment 7 presented distractors and targets that are distinct in the time domain. In principle, one could run the same experiment with the two stimuli occurring simultaneously, as we did in Experiment 5. However, we believe that this would dramatically change the nature of the task. In Experiment 5, the distractor still captured attention due to its higher saliency relative to the target. If the distractor and target had the same saliency (same size, same luminance), the search process would become serial, and the RT increase in the presence of the distractor rather than being an index of attentional capture could reflect a degree of uncertainty about the target location. One might still observe a distractor-location effect if observers strategically initiate the search starting from the low distractor-probability region, where each stimulus has a higher probability of being the target. If a nontarget has a higher probability of being attended in a serial search, it will have a larger impact on the search process. As for the target-location effect, it is hard to make predictions.

We can speculate that, faced with a single stimulus, in distractor-absent trials observers would have no uncertainty about the target location and might not rely on the a priori probabilities.

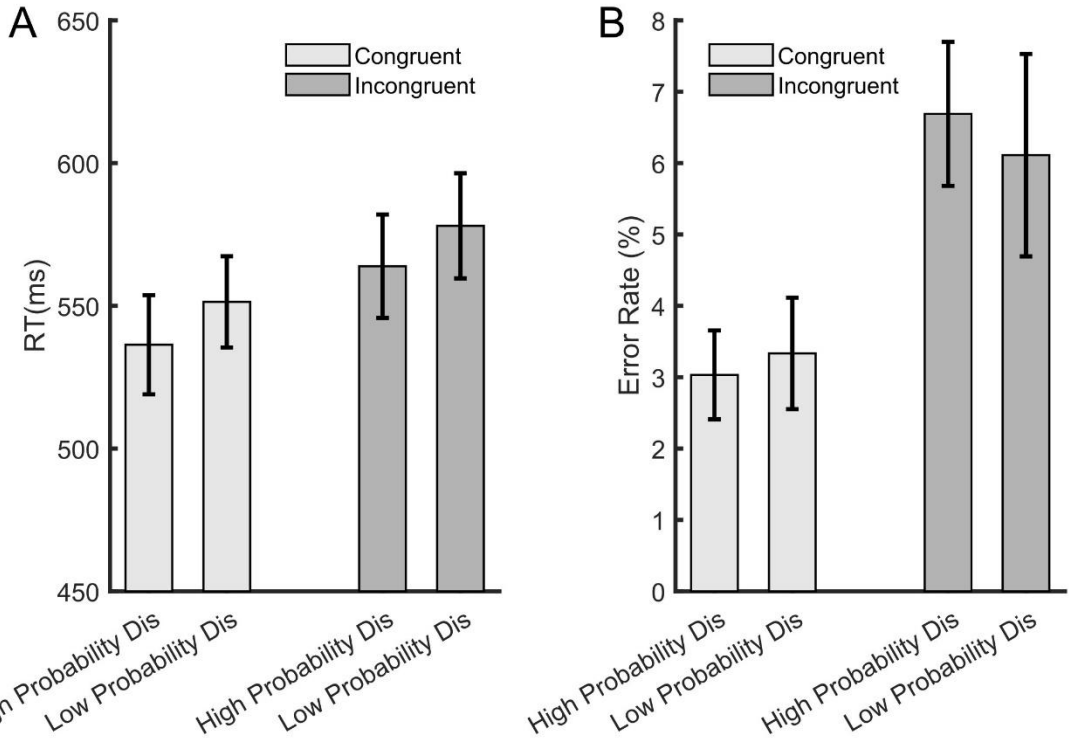

Figure 17. RTs (A) and error rates (B) in the distractor-present trials of Experiment 7, plotted as a function of the distractor probability at the region where the distractor appeared, and of the congruency between the target and distractor regions.

Combined analysis of target-location effect in Experiments 2, 3, 5 and 7

As a final step, to assess the accumulated evidence against the emergence of a target-location effect with luminance-transient distractors, we combined the distractor-absent data from Experiment 2, 3, 5, and 7 and performed a Bayesian repeated-measures ANOVA with Region (high vs. low probability) as a within-participant factor and Experiment (2, 3, 5, and 7) as a between-participant factor. The analysis provided evidence against the inclusion of the factor Region in the model, $BF_{excl} = 7.178$, against the inclusion of the two-way interaction, BF_{excl}

= 22.216, and in favor of the inclusion of the factor Experiment, $BF_{excl} < .001$. Thus, despite the obvious difference in RTs between the experiments, particularly due to the expected slowing of RTs in the T/L search task of Experiment 3, we confirm that the combined evidence is against the existence of a target-location effect with luminance-transient distractors.

General Discussion

The focus of this study was on the processes that enable human beings to use environmental statistics to resist distraction in the presence of two different types of distracting stimuli, namely color singletons and luminance transients.

The starting point of our research was the notion that observers can learn where to expect feature-singleton and luminance-transient distractors, and use this statistical information to attenuate visual distraction, a result known as the distractor-location effect (Goschy et al., 2014; Valsecchi & Turatto, 2023; Wang & Theeuwes, 2018a). In addition, since the results from feature-singleton distractor studies indicated that target processing is particularly impaired where the distractor is more likely to occur (known as the target-location effect), it has been proposed that the target-location effect is diagnostic of the fact that distractor filtering is achieved by means of a spatial suppression applied to the distractor location, with stronger suppression where the distractor is more frequent (Chelazzi et al., 2019; Ferrante et al., 2018; Liesefeld & Müller, 2019, 2021; Luck et al., 2021; Sauter et al., 2019; Wang & Theeuwes, 2018a; Zhang et al., 2019). The finding that observers can learn to resist distractors based on the local statistics of their occurrence is not limited to the additional-singleton paradigm, but was shown to extend to the case where colored cues that matched or did not match the instructed target color preceded the search array (Kerzel & Huynh Cong, 2021). As is commonly found in contingent capture paradigms (Folk et al., 1992), only the cues that matched the target color captured attention, while non-matching cues were mostly

ignored. Limited to the case where cues matched the target color, Kerzel and Huynh Cong (2021) found both the counterpart of a distractor-location effect, i.e., RTs were longer when an invalid cue was presented at a low-frequency location, and the counterpart of a target-location effect, i.e., in invalid trials, participants were slower if the target was presented at a location that was frequently associated with the cue, suggesting that the locations associated with the distractor were suppressed in the map corresponding to the task-relevant color, whereas the representation of the irrelevant colors was suppressed altogether.

In contrast with this coherent set of findings, our previous study with luminance-transient distractors (Valsecchi & Turatto, 2023) provided preliminary evidence that when dealing with this type of salient events, observers seem capable of reducing the interference at the distractor location without incurring costs for target processing. This suggests the possibility that rejection of salient stimuli has different effects depending on whether saliency arises from competitive interactions among the different stimuli in the display (Koch & Ullman, 1985), or is defined by a local transient activity, possibly largely coded in the magnocellular system (Breitmeyer & Ganz, 1976).

To replicate and further explore this potentially intriguing difference, we conducted seven experiments, which all used the same experimental design but different stimuli and paradigms so as to identify whether factors other than the use of color singletons vs. luminance transients explained the different patterns of results. We point the reader to Table 1 for a summary of the stimuli employed and the most relevant results. In general, the pattern of results systematically confirmed that the target-location effect was only found in the case of color-singleton distractor, and it indicated that color-singleton distractors are associated with congruency costs, namley color singleton distractors interfere more with target processing

when they are in the same region, whereas luminance transient distractors interfere more when they are in the opposite hemifield.

What could explain the different results? A promising and reasonable starting point is to note the different ways in which color singletons (and feature singletons in general) and luminance transients are detected in the visual attention system. In primates, these two classes of stimuli are analyzed by separate, magnocellular (M) and parvocellular (P) neuronal pathways, which originate in the retina and project to separate M- and P-dedicated layers in the lateral geniculate nucleus (LGN) (Livingstone & Hubel, 1988). The two neural pathways then remain largely segregated also in the visual cortex, thus giving rise to the dorsal and ventral pathways respectively (Ungerleider & Mishkin, 1982), with the former dedicated to the analysis of transient stimuli, whereas the latter is specialized for objects recognition and the related visual features.

With regard to this, since the original model proposed by Koch and Ullman (1985), feature singletons, and specifically color singletons in our experiments, are believed to be initially detected and then attended through the activity in a series of topographic maps of the visual world. Each map codes a specific stimulus feature (e.g., color, orientation, etc.), and their computations then converge on a saliency map that provides a "biased" view of the environment by signaling the salient locations. Importantly, the saliency of a given element, at a given location, is determined by mechanisms that detect feature contrasts in each map, which depends on how different an element is from the surrounding elements. Therefore, a red item among green items is isolated as a salient feature singleton because it largely differs from the surrounding elements in the color map. This peak of activation is then transmitted to the final saliency map, which is used to control the allocation of attention. Since this functional

architecture relies on detailed color and shape discriminations, it is very likely to involve activity in the P system, primarily located in the ventral stream.

According to the Koch and Ullman (1985) model, attention is attracted by the highest peak of activation. If this peak is generated by a distractor, the corresponding location is suppressed via top-down inhibitory signals, and attention is shifted to the next most salient location until the target is found. If several instances of suppression accumulate more at a given location, this will induce relatively long-lasting plastic changes in the saliency map (Turatto & Valsecchi, 2022). This mechanism would be consistent with the target-location effect found with color-singleton distractors, as reported here and in other previous studies (Ferrante et al., 2018; Valsecchi & Turatto, 2021; Wang & Theeuwes, 2018a, 2018b). However, the model explicitly predicts that the time necessary to shift from one salient element to the next one depends on their spatial separation. Thus, the time to select the target should increase as the distance from the distractor, which initially captured attention, increases. By contrast, we observed the opposite pattern, with the color singleton interfering more when it was closer (i.e., in the same hemifield) than when it was more distant (i.e., in the opposite hemifield) from the target. As a matter of fact, other previous studies have already reliably demonstrated that a color-singleton distractor causes greater interference when it is closer to the target. For instance, Caputo and Guerra (1998) found a significant reduction in target discriminability in the presence of a color-singleton distractor, and this effect intensified as the distractor approached the target (also see, Barras & Kerzel, 2016; Kiss et al., 2012; Turatto & Galfano, 2001). The authors proposed that when the salient distractor is mistakenly selected because it is the most salient element in the display, it generates an inhibitory surround, leading to impaired target selection and discrimination in nearby locations. This proposed mechanism would be consistent with the inverse-distance effect observed with color-singleton distractors

in our set of experiments. Considering the target-location effect and the inverse-distance effect, it appears that two forms of suppression exist in the presence of a color-singleton distractor. One form attenuates the saliency of the distractor at its location, a suppression likely triggered by the selection of an irrelevant element, and which accounts for the distractor-location effect and, crucially, the target-location effect. The second form of suppression is automatically implemented whenever an element is selected in the saliency map, regardless of it being a target or a distractor. Its goal is to attenuate the interference from the surrounding non-selected elements (Caputo & Guerra, 1998). This would explain the inverse-distance effect, as the selection and processing of the target would be hindered more by the suppressive surround generated by the preceding erroneous distractor selection.

Now let's shift our focus to luminance-transient distractors. As we have discussed, these types of events are processed in the M system, with its main cortical projections forming the dorsal stream. It is important to note that the salience of luminance transients is not computed relative to the surrounding elements, as is the case with feature singletons. Luminance transients, whether in the form of onsets, offsets, or sudden variations in luminance of an existing element, can capture attention even in a blank field. Accordingly, studies have demonstrated that attentional capture triggered by visual transients is controlled by the M system (Steinman et al., 1997). Furthermore, since the influential work of Posner and his colleagues (e.g., Posner, 1980; Posner & Cohen, 1984), it has been established that the time required to reorient spatial attention from one position to another increases with distance when attention has been initially attracted by a luminance transient (e.g., Rizzolatti et al., 1987). Previous studies have also shown that with practice, attentional capture is attenuated by habituation mechanisms (e.g., Turatto, Bonetti, & Pascucci, 2018; Turatto & Pascucci, 2016), and habituation is more effective at the more likely distractor location (Turatto & Valsecchi,

2023), a result that we have replicated here. However, the distractor-location effect was not accompanied by a target-location effect, indicating that no suppression was exerted at the luminance-transient distractor location to reduce its interference (also see, Valsecchi & Turatto, 2023). In other words, luminance transients were simply filtered out by preventing attention from orienting toward the corresponding location, which is something that is consistent with the habituation hypothesis (De Tommaso & Turatto, 2023; Turatto, Bonetti, & Pascucci, 2018; Turatto & Pascucci, 2016; Turatto & Valsecchi, 2023; Valsecchi & Turatto, 2023). Within this framework, the neural model of the target might be isolated from that of the distractor based on different parameters, including, for example, the temporal order. However, when habituation was not fully established and spatial capture occurred, which was more likely to happen at the less frequent distractor location, the interference from the distractor was greater when the target and distractor were in opposite hemifields. This could be attributed to the fact that attention had to traverse a longer distance from the distractor to the target location. In other words, with luminance-transient distractors, interference primarily arose from the need to reorient attention towards the target after it had been captured by the irrelevant luminance transient. This was evident from the larger costs associated with a distractor that was farther away. Our first hypothesis is thus that the P pathway implements saliency computations based on local contrast in feature maps, which produces higher interference for distractors near targets. Local suppression in the map produces both the distractor location and the target location effects. The M system instead detects transients irrespective of the surrounding stimuli, so that there are larger (re-orienting) costs when distractor and target are far, and statistical learning of distractor location reduces interference as a result of habituation, i.e. by implementing a predictive model of the likely distractor, hence reducing capture by the distractors at the frequent location without affecting target processing.

The observation of larger costs for transient distractors that appear far from the target suggests a possible partially independent explanation for the results of the current study. The habituation account assumes that learning to resist distraction by visual transients involves a reduction in capture by distractors appearing at likely locations and that the lack of a target effect is due to the fact that a separate template is used to identify targets and distractors. Alternatively, one could assume that learning to resist distraction does not involve a reduction in the probability of capture but rather more efficient disengagement of attention from the distractors appearing at the most likely location. Within this framework, the absence of a target-location effect would derive from the fact that when the target appears in isolation, no need for attentional disengagement ensues, and thus any post-capture effect of spatial learning would have no observable effect.

Support for the idea that learning the statistics of distractor spatial occurrence could affect the ease of disengaging attention from the distractor comes from studies on overt orienting. Statistical learning leads to both reduced oculomotor capture by feature-singleton distractors at expected locations. However, when the distractor at expected locations is fixated, the latency for disengaging fixation from the distractor is shorter (Kim & Anderson, 2022; Sauter et al., 2021; Wang et al., 2019). Specifically, in the case of onset distractors, it has been suggested that oculomotor capture and disengagement are differentially influenced by top-down aspects, such as the similarity of the distractor to the instructed target (Born et al., 2011), although this has been challenged (Becker et al., 2017). Selectively biasing the re-orienting of attention from a distractor in a frequent location might offer observers the possibility to reduce distraction costs without paying any cost for processing the target at that location. The present data do not allow us to establish whether learning to ignore luminance-transient distractors

involves a reduction in capture, an improvement in post-capture attentional re-orienting or a combination of both.

Independently of the exact mechanisms involved, the assumption that learning to resist distraction by color singletons and luminance transients might have different effects in the visual system could also provide an alternative explanation for the results of a recent study (Chang et al., 2023). In that study, it was observed that learning to suppress feature-singleton distractors at one location does not produce a target-location effect when tested with a transient probe. The authors interpreted this finding as a lack of proactive suppression at the most likely distractor location. However, it is possible that suppressing a location to avoid distraction by feature singletons does not necessarily impair attentional orienting towards transient stimuli. Such a dissociation is also supported by results from previous studies investigating distractor filtering during passive viewing. When participants are passively exposed to luminance-transient distractors, the degree of capture habituation is the same as when the same distractor is presented during a task that requires target discrimination (Turatto, Bonetti, Pascucci, et al., 2018). In contrast, the attenuation of capture triggered by a color-singleton distractor appears much weaker when participants do not have to find and select a shape-singleton target compared to when the same shape singleton is the target of the search (Duncan & Theeuwes, 2020), or when colored distractors in general are used (Geng et al., 2019; Won & Geng, 2020). Moreover, when observers search for a target defined by a specific color, color-singleton distractors exert much less interference than abrupt-onset distractors (Adams et al., 2022). It has been suggested that if an abrupt-onset distractor is consistently associated with a given feature, such as a nontarget color, it does not induce additional suppression of that specific color (Burgess et al., 2022). These findings, along with the pattern of results reported here, further support the idea that learning to reject color

singletons and luminance transients might not be equivalent for the visual system (Valsecchi & Turatto, 2023), and might not lead to the same perceptual and attentional consequences.

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Supplementary Tables

Condition	Region Probability		Exp 1	Exp 2	Exp 3	Exp 4	Exp 5	Exp 6	Exp 7
Distractor Present	High	Mean	1130.99	524.58	1042.74	1058.31	514.77	946.84	549.84
		95% CI ±	62.5	22.92	65.24	71.15	20.67	71.82	35.96
	Low	Mean	1184.53	539.12	1072	1079.17	527.36	1000.35	564.41
		95% CI ±	73.94	25.82	65.11	68.8	21.71	76.51	34.54
Distractor Absent	High	Mean	1029.25	526.46	1017.33	1002.5	503.27	887.55	551.98
		95% CI ±	52.65	21.66	81.52	74.66	20.3	73.09	33.53
	Low	Mean	995.47	526.96	1020.59	966.46	503.81	853.88	553.8
		95% CI ±	57.51	22.21	73.6	72.33	18.67	67.79	35.6
Congruent	High	Mean	1185.47	521.98	997.94	1083.13	517.59	981.71	536.37
		95% CI ±	61.19	22.11	71.59	70.77	22	73.7	35.53
	Low	Mean	1208.45	533.75	1045.66	1087.23	523.97	1015.71	551.39
		95% CI ±	77.4	24.41	71.81	70.43	21.88	71.17	32.67
Incongruent	High	Mean	1076.17	526.69	1085.5	1030	512.12	910.7	563.87
		95% CI ±	66.68	23.65	70.87	73.23	19.72	72.06	37.05
	Low	Mean	1160.29	540.38	1092.57	1070.89	525.79	994.42	578.03
		95% CI ±	77.96	26.05	75.84	70.91	22.96	84.14	37.66

Table S1: mean RTs and 95% between-observer confidence intervals as a function of Condition. Region Probability and Experiment.

Effect		Exp 1	Exp 2	Exp 3	Exp 4	Exp 5	Exp 6	Exp 7
Distractor Region	Mean	-5.47	-2.7	-3.32	-2.48	-2.5	-6.59	-2.84
	95% CI ±	3.22	1.09	2.44	2.35	1.12	2.94	1.87
Target Region	Mean	3.86	-0.03	0.69	4.17	-0.11	4.09	-0.13
	95% CI ±	2.45	1.01	6.26	3.22	1.32	3.34	1.33
Congruency	Mean	8.3	-0.99	-6.96	3.98	0.32	6.16	-4.84
	95% CI ±	2.75	0.96	2.64	2.36	1.07	2.85	1.39

Table S2: normalized Distractor-Location. Target-Location and Congruency effects (relative to the mean RT for each observer in the distractor absent/low frequency trials) and 95% between-observer confidence intervals. for each experiment.

Condition	Region Probability		Exp 1	Exp 2	Exp 3	Exp 4	Exp 5	Exp 6	Exp 7
Distractor Present	High	Mean	6.24	3.41	3.44	4.51	5	5.22	4.86
		95% CI ±	1.3	1.4	1.3	1.03	1.48	2.26	1.58
	Low	Mean	8.33	4.07	3.89	6.11	3.98	5.46	4.72
		95% CI ±	2.79	1.76	1.76	2.22	1.51	2.4	1.87
Distractor Absent	High	Mean	3.78	2.11	4.22	4.33	4.85	3.52	3.3
		95% CI ±	0.97	0.99	1.85	1.31	1.61	1.07	1.6
	Low	Mean	3.19	2.96	3.15	3.93	5.04	3.67	2.93
		95% CI ±	0.97	1.1	1.63	1.12	1.65	1.29	1.43
Congruent	High	Mean	6.85	2.89	3.36	4.65	4.19	5.28	3.03
		95% CI ±	1.54	1.39	1.52	1.11	1.53	2.3	1.27
	Low	Mean	11.3	2.78	3.89	6.3	2.41	5.19	3.33
		95% CI ±	3.98	1.7	1.82	2.82	1.41	2.55	1.6
Incongruent	High	Mean	5.63	3.94	3.52	4.37	5.81	5.16	6.69
		95% CI ±	1.33	1.59	1.26	1.14	1.74	2.3	2.06
	Low	Mean	5.37	5.37	3.89	5.93	5.56	5.74	6.11
		95% CI ±	2.4	2.53	2.26	2.31	2.31	2.86	2.9

Table S3: mean Error Rates and 95% between-observer confidence intervals as a function of Condition. Region Probability and Experiment.