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Within-trial and across-trials habituation mechanisms to irrelevant visual transients

Matteo Valsecchi[1] and Massimo Turatto[2]

[1] Department of Psychology, University of Bologna

[2] Center for Mind/Brain Sciences, University of Trento

Author Note:

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Correspondence concerning this article should be addressed to:

Matteo Valsecchi

Universitá di Bologna, Dipartimento di Psicologia

Viale Carlo Berti Pichat 5, 40127 Bologna (Italy)

Email: matteo.valsecchi@unibo.it

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Abstract

Observers can learn to resist distraction in visual search when feature singletons or luminance transients are repeatedly presented across trials at a given location. In this study, we investigated whether the same repetition benefit would be observed when luminance transients are repeatedly shown at the same location within the same trial, and how this effect relates to across-trials habituation of attentional capture. The results showed that interference was reduced when four luminance transients were presented at the same location before target appearance, compared to when a single transient was presented, replicating the feature singleton findings. Furthermore, the magnitude of this repetition effect did not depend on the local and global across-trials probability of repeated and single transients, supporting the hypothesis that two relatively independent within-trial and across-trials habituation mechanisms coexist. Finally, in Experiment 4, we demonstrated that the repetition effect was largely reduced when the first three transients appeared at a different location, ruling out the possibility that the repetition benefit was simply due to a warning effect and/or the spatial predictability of the last visual transient.

Keywords

Attention; Visual Search; Distraction; Habituation; Time scale

Public Significance Statement

This study shows that when visual transients, i.e. flashes, appear in relatively rapid sequence within a trial at a given location, the associated cost for responding to a following target is reduced as compared to the case when a single flash is shown. This repetition effect is independent of the local and global frequency of occurrence of trials with transients, indicating that multiple independent habituation mechanisms exist, operating at different time scales.

Introduction

Our visual system is highly sensitive to visual transients—sudden luminance changes in the environment that often signal important events, such as the appearance of a new object or the movement of an existing one. The visual system typically responds to visual transients, like onsets or rapid flashes (onset-offset), by rapidly and automatically orienting attention to the corresponding locations (Jonides, 1981). This sensitivity to visual transients and the associated attentional orienting response are hard-wired features of our visual brain, likely because detecting luminance transients is pivotal for survival, allowing us to notice and react to sudden changes in the environment (Sokolov, 1960, 1963).

In line with this view, visual attention research over the past fifty years has provided abundant evidence that visual transients, typically in the form of either onset or flash stimuli, attract attention in a stimulus-driven fashion. For example, based on the functional and physiological organization of the visual system into sustained and transient channels, Breitmeyer and Ganz (1976) proposed that luminance changes are rapidly detected through neuronal activity in the latter type of channel. This activity triggers a fast alignment of attention with the transient's location, followed by relatively slower processing in the sustained channel, which deals with stimulus identification. Subsequently, other classic studies—whether using the spatial cueing paradigm or the visual search paradigm—confirmed that target processing is faster and more accurate at the transient location. This is taken as evidence that attention is attracted to the same location (Jonides, 1981; Jonides & Yantis, 1988; Posner & Cohen, 1984; Yantis & Jonides, 1984).

If the fast and automatic orienting of attention triggered by visual transients generally has an obvious adaptive value—since these events may signal the presence of a potentially relevant stimulus—the brain must also be capable of mitigating such automatic responses when unnecessary. This is the case when, based on past experience, a visual transient has been classified as irrelevant to the organism's current goal. In such situations, further orienting would become disadvantageous, as the unintended capture of attention could interfere with task performance. This is particularly true when an observer knows that any visual transient presented before a pre-specified target will never spatially coincide with it, meaning the transient will never serve as a spatial cue to improve target processing. Hence, in this condition, the transient acts as a distractor that interferes with target processing, and ideally, the brain should disregard it to limit its negative impact on performance.

The results of a series of studies we conducted have shown that human observers are indeed capable of learning to ignore an irrelevant visual transient that briefly appears before the target (e.g., De Tommaso & Turatto, 2023; Turatto, Bonetti, & Pascucci, 2018; Turatto, Bonetti, Pascucci, et al., 2018; Turatto et al., 2019; Turatto & Pascucci, 2016). Specifically, we found that the lengthening of response times (RTs) for target discrimination caused by the presence of a visual transient just before the target, reliably decreases as participants are progressively exposed to the irrelevant abrupt luminance change. Crucially, we also demonstrated that this decrement in attentional capture conforms to certain characteristics of the general phenomenon of habituation. For instance, the irrelevant transient is better ignored (showing stronger habituation) when its frequency of presentation is higher, either in general (e.g. Turatto & Pascucci, 2016) or at a specific location (Valsecchi & Turatto, 2023). Furthermore, if, after habituation, the visual transient is omitted for some trials and then reintroduced, attentional capture re-emerges (Turatto & Pascucci, 2016).

In addition, as predicted by Sokolov's model, habituation of capture depends on how much the irrelevant visual transient is expected to occur, rather than on its absolute number of presentations (Turatto & Valsecchi, 2023). In other words, evidence suggests that irrelevant visual transients are more effectively ignored at higher presentation rates compared to lower rates. This indicates that the habituation of attentional capture depends on the expectation of the occurrence of the visual transient, which develops across trials. Indeed, Folk and Remington (2015) reported that only unexpected visual onsets interfere with target detection even when observers are set to respond to a color target, and they interpreted their findings in light of Sokolov's habituation model (Sokolov, 1963). Other studies with feature-singleton distractors (e.g. Ferrante et al., 2018; Sauter et al., 2019; Wang & Theeuwes, 2018) also consistently showed distractors appearing at expected locations produce less interference.

Although the major component of onset capture habituation appears to be the rate of irrelevant visual transients across trials (Turatto & Pascucci, 2016; Turatto & Valsecchi, 2023), a study by Pascucci and Turatto (2015) provided preliminary evidence for another habituation mechanism that operates on a faster timescale. This mechanism relies on the number of visual transients presented in quick succession within the same trial, specifically before the target appears. The authors manipulated the number of peripheral transients, which varied randomly between one and five on each trial, that preceded the presentation of a central target (a tilted Gabor patch) appearing at fixation. The results showed that the peripheral visual transients interfered with the identification of the central target (resulting in lower accuracy) when either one or two transients appeared before the target. However, this detrimental effect on performance progressively decreased when the sequence consisted of three, four, or five transients. These findings suggest the existence of a fast within-trial habituation mechanism that rapidly attenuates transients' interference when these are encountered repeatedly before the target. Notice that Betteto and colleagues (2024) recently demonstrated that a fast, within-trial repetition effect can also be observed with color singleton distractors. They employed a modified additional singleton paradigm in which each trial consisted of four discrete displays. The irrelevant color singleton, when present, could appear starting from the first display, or appear only in the last one together with the target.

So, the previous research seems to suggest that a fast repetition effect co-exists with a slower learning process that modulates attentional capture based on the local, i.e. restricted to one spatial location, and global, i.e. generalized across spatial locations, probability of distractor occurrence. In the present study, we specifically investigate the relationship between the within-trial repetition effect and the effects of the probability of occurrence of both single and repeated visual transients. We devised an experimental paradigm in which either four repeated transients, a single transient, or no transient could precede the target. Across experiments, we independently manipulated the probability of occurrence of single and repeated transients. To anticipate our results, we found that although the interference produced by single and repeated transients was reduced when their frequency increased, thus confirming that they both contributed to across-trials habituation, neither the frequency of repeated transients across trials nor the frequency of single transients across trials modulated the advantage associated with repeated transients. This supports the hypothesis that two independent habituation mechanisms, operating on different timescales, reduce the impact of irrelevant visual transients, one based on stimulus repetition and the other on stimulus frequency.

Experiment 1

Here, we aimed to test whether transient interference, or cost, is attenuated when the transient is presented iteratively in rapid succession before the target within the same trial. We examined this by comparing the effect of repeated transients to that of a single transient appearing at the same location—what we define as the repetition effect. The emergence of a repetition effect would indicate the existence of a rapid habituation mechanism for rejecting irrelevant visual transients on a short, within-trial timescale, as originally suggested by Pascucci and Turatto (2015). Furthermore, the location of repeated trials was fixed throughout the experiment for each participant, which allowed us to compare the effect of a single transient at the location where repeated transients were presented (single-at-repeated) with that of a single transient appearing at the opposite location (single-at-opposite)—what we define as the location effect. This comparison will help determine the extent to which repeated transients contribute to the well-established development of local habituation across trials (Turatto & Valsecchi, 2023). Compared to single trials, repeated trials could produce more, equal, or less long-term local habituation, depending on whether the between-trial habituation mechanism: (1) treats each individual transient in a repeated trial as a driver of habituation, (2) treats repeated transients as a single transient, or (3) ignores repeated transients altogether. Understanding how repeated transients influence long-term habituation will contribute to the broader goal of this study, that is to clarify the relationship between short-term and long-term rejection mechanisms.

Notice that, when designing the stimuli for the current study, we opted to have the visual transient to precede the target with a Stimulus Onset Asynchrony (SOA) of 150 ms. This likely reduces the interference produced by the visual transient compared to a simultaneous presentation (See the comparison between Experiments 2 and 5 in Valsecchi & Turatto, 2024), although the existing literature shows that also with an asynchronous onset interference is reliable (e.g. Ruthruff et al., 2019). Our motivation for using asynchronous visual transients was to align with the standard paradigm employed in our previous works (Turatto & Valsecchi, 2023; Valsecchi & Turatto, 2023, 2024). The SOA was initially introduced to mitigate the potential for masking or crowding effects when the visual transient and target were co-located—i.e., when the visual transient could act as a valid exogenous cue.

Methods

Participants

The sample consisted of forty participants (mean age = 36 years, 16 females) 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 new participants were recruited when participants failed to reach an overall accuracy rate of at least 80%. This required rejecting the data of 4 participants. Participants were compensated with 4.4 GBP for an expected duration of the experiment under 35 minutes 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"). Data included in the present work were collected between January and June 2024.

To estimate the appropriate sample size for our study, we identified the difference in RTs when the irrelevant transient, in a given trial, appeared four times or only once at the same location as the most crucial test (later referred to as the repetition effect). This effect has not been tested before with irrelevant visual transients, but we know that habituation can lead to strong reductions of interference. Specifically, the size of the Distractor Location effect in the Experiment 2 of Valsecchi and Turatto (2024), which used comparable stimuli and procedure, was large (dz = 0.883). Since we could not directly estimate the expected size of the repetition effect in the current study, we decided to be conservative and picked a sample size of 40, which a priori would allow us to detect medium-sized effects. A sensitivity analysis performed with G*Power 3.1.9.7 (Faul et al., 2007) indicated that we could expect to have 80% power for effects with dz as small as 0.454, at a two-tailed significance level of .05.

Constraints on Generality

In this and the following experiments, 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. We cannot exclude that cultural differences outside of English speaking communities might have an impact on the phenomena that we investigated, i.e. attentional orienting and learning.

Transparency and Openness

All 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, Release 2021a) and JASP v. 0.18.3 (JASP Team, 2024). All experimental scripts, experimental data and analysis scripts are publicly available through the Zenodo repository at the following url: https://doi.org/10.5281/zenodo.15097570.

The design of the study and the analyses were not pre-registered.

During the preparation of this work, the authors used ChatGPT (OpenAI, Inc., https://openai.com/) to improve readability and language. After using this tool, the authors reviewed and edited the content as needed and took full responsibility for the content of the publication.

Stimuli, design and procedure

At the beginning of the experiment, participants were asked to set themselves at a viewing distance equal to three times the length of a segment presented on the screen (70% of screen height). All stimulus sizes and eccentricities in degrees of visual angle are computed assuming the instructed viewing distance.

Each trial started with the presentation of a circular display consisting of a central fixation point (white, 0.27° width), surrounded by eight gray circular placeholders (dark gray, psychopy RGB -0.7336; diameter 2.4°, line width 3 pixels), arranged along an imaginary circumference (10° radius) centered on the fixation point. All stimuli appeared on a black background. After that 2150 ms were elapsed from the display onset, the target appeared for 150 ms in one of the four placeholders located on the diagonal axes. It consisted of the "U" character (mid gray, horizontal and vertical size 1.01°, line width 4 pixels) clockwise or counterclockwise rotated by 90°, and participants were instructed to report as quickly and accurate as possible its orientation by pressing the G or the H key to respectively. If participants pressed the wrong key, or if no response was recorded within 2500 ms, a warning

message (i.e., “Wrong!” or “Too slow!”), appeared in red for 300 ms in the center of the screen 500 ms after the offset of the placeholder display. The placeholder array remained on the screen until participants responded or for a maximum of 2500 ms after the target onset. Participants were also informed that on some trials either one or four irrelevant visual transients, each consisting in a brief flash (onset-offset), could briefly appear on the display prior to the target appearance, and were encouraged to ignore such stimuli. The transient was caused by a white ring (diameter 3.54°, line width 12 pixels) appearing for 150 ms around one of the four placeholders located on the vertical and horizontal axes (up, down, left or right). Notice that the position where targets and the irrelevant transients appeared were completely segregated.

Depending on the presence vs absence of the irrelevant transient and on its repetition in the trial, there were four experimental conditions: *absent*, *repeated*, *single-at-repeated*, and *single-at-opposite*. In the repeated and single-at-repeated condition the transient appeared at the same location (repeated location), whereas in the single-at-opposite condition the transient appeared at the location opposite to the repeated one (opposite location). The specific location of the repeated and opposite conditions along either the vertical or horizontal axes in the array were counterbalanced across participants. In the repeated condition, four luminance transients, each lasting 150 ms, were presented at the same location starting 500 ms after display onset and with an SOA between transients of 500 ms. This caused the fourth transient to appear 150 ms before the target onset, as in the two single conditions (see Figure 1). In the two single conditions a single transient was presented for 150 ms at the corresponding location 150 ms before the target onset. The inter-trial interval was set to 2 seconds.

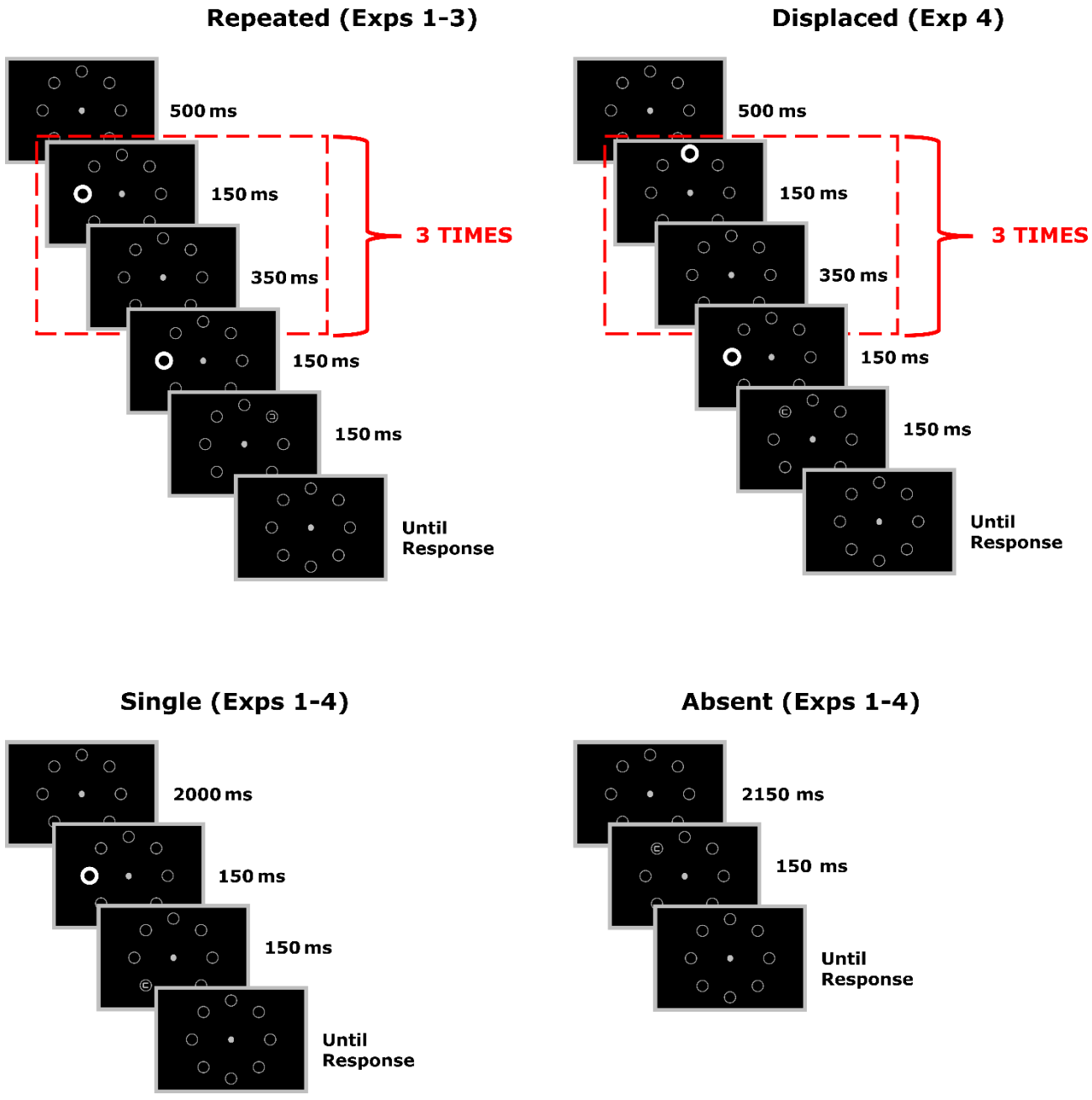

Figure 1. Trial events in each of the experimental conditions

In all conditions participants reported the orientation of the rotated U character, randomly located in one of the oblique positions, which in all trial types appeared 2150 ms after the onset of the display. In all transient-present trials (repeated, single-at-repeated, single-at-opposite conditions) the target was preceded by a luminance transient flashed for 150 ms around either the up, down, left or right placeholder. In the repeated condition the transient was preceded by other three identical flashes appearing in sequence every 500 ms at the same

location. The displaced condition (see Experiment 4) was identical to the repeated condition, except that the first three transients happened at the placeholder located 90° counterclockwise relative to final transient. For a given observer the repeated transients (Experiments 1-3) or the final transient in displaced trials (Experiment 4) were presented at one location throughout the experiment (left in the example), whereas single trials could appear either at the same location or at the opposite location (right in the example). The Repeated/Displaced location (up, down, left or right) was balanced between observers.

The experiment started with 12 practice trials, followed by three blocks of 108 trials each, for a total of 324 experimental trials, with breaks between blocks. In each block the overall irrelevant transient rate was 33%, as it appeared in 36 out of 108 trials. Specifically, there were 18 transient-present trials at the repeated location: 9 trials (8.3% of all trials) in the repeated condition, 9 trials (8.3% of all trials) in the single-at-repeated condition; in addition, there were also 18 trials (16.6% of all trials) in the single-at-opposite condition. This means that overall, in each block there were 18 transient-present trials at both locations (repeated and opposite).

Results and Discussion

In this and the following experiments data analyses were conducted using Matlab R2021a (The Mathworks, Natick MA), except for Bayes Factor calculations, which were performed in Jasp 0.18.3 (JASP Team, 2024). RTs outlier rejection was 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 considered failures to respond during data collection and were counted as errors in the data analyses. In the present

experiment the application of the outlier rejection method led to the removal of 1.8% of the data.

The impact of an irrelevant visual transients on target discrimination, if any, was defined as *visual transient cost*, and was computed for both RTs and error rates, and calculated as the difference between transient-present trials and transient-absent trials (present minus absent). A positive transient cost value would indicate a negative impact of the irrelevant visual transient on performance, typically due to an involuntary capture of attention. Hence, the analyses were performed directly on the transient cost in the different conditions.

Performing the analyses directly on the transient costs has the advantage of discounting inter-participant differences in RTs and error rates, and was justified by the fact that on transient-absent trials both RTs and error rates did not change significantly between experiments (see Supplementary Analysis and Figure S1). Average RTs and error rates for all experiments, along with RT and error rate transient costs are reported in the Supplementary Tables 1 and 2.

Transient costs for RTs and error rates in the different conditions of Experiment 1 are plotted in Figure 2. As a first step we tested the repetition effect by performing a paired-sample *t* test comparing the transient costs in the repeated condition and in the single-at-repeated condition, which revealed a significant difference, $t(39) = 2.241$, $p = .031$, $d_z = 0.354$, mean difference = 15.2 ms, 95% CI = [29 1.5]. However, despite the within-trial transient repetitions largely attenuated its impact on performance, the transient still produced a reliable RT cost, $t(39) = 4.416$, $p < .001$, $d_z = 0.698$, mean = 19.3 ms, 95% CI = [10.4 28.1]. The transient cost did not significantly differ between the single-at-repeated condition and the single-at-opposite condition, i.e. there was no significant location effect, $t(39) = 1.267$, $p = .213$, $d_z = 0.2$, mean difference = -6.2 ms, 95% CI = [-3.7 16].

Error rates were 4.5% overall. Error rate visual transient cost is shown in Figure 2b. The pattern of results is like the one of RTs. The repetition effect was again significant, $t(39) = 3.171$, $p = .003$, $d_z = 0.501$, mean difference = -3.4%, 95% CI = [-5.6 -1.2], whereas the location effect was not significant, $t(39) = 0.395$, $p = .695$, $d_z = 0.062$, mean difference = -0.4%, 95% CI = [-2.3 1.5]. However, in the case of error rates the transient cost in the repeated condition did not significantly differ from 0, $t(39) = 1.926$, $p = .061$, $d_z = 0.305$, mean = -1.6%, 95% CI = [-3.3 0.1].

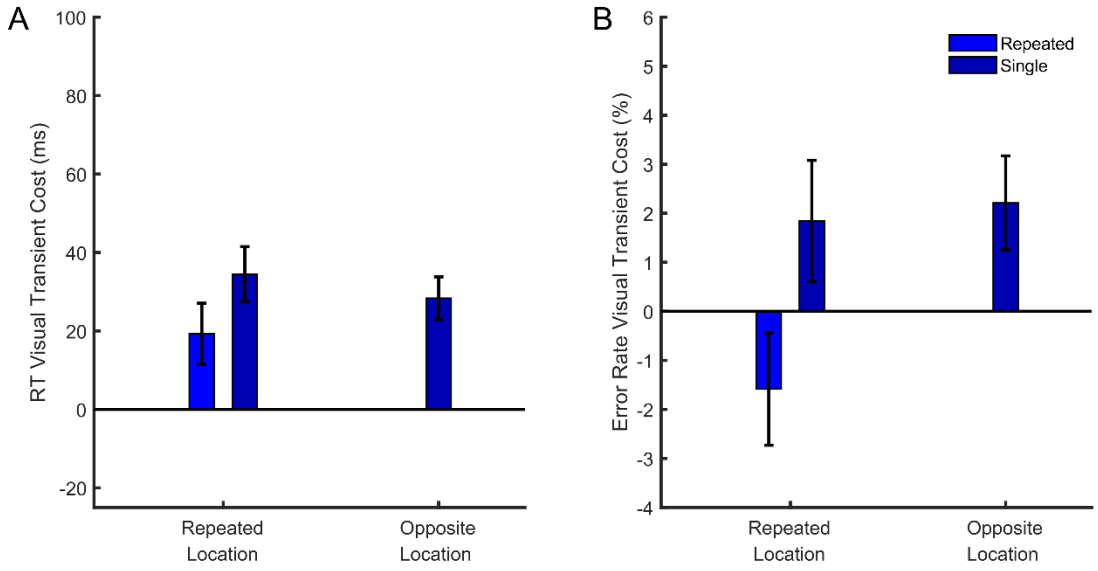

Figure 2. Experiment 1 results

Transient costs for RTs (A) and error rates (B) in Experiment 1, as a function of conditions. Error bars are 95% within-observer Confidence Intervals.

Overall, Experiment 1 yielded two key findings: first, a series of repeated transients in close temporal proximity within the same trial showed a reduced impact on target discrimination compared to the presentation of a single transient at the same location. Notice that Betteto, De Tommaso, and Turatto (2024) report a similar within-trial repetition effect

with color singleton distractors. In the Discussion section, we will propose some hypotheses regarding the mechanism underlying the benefit observed in the repeated condition. For now, we can only conclude that this benefit is distinct from the classical across-trials habituation mechanism observed in previous studies (Pascucci & Turatto, 2015; Turatto & Valsecchi, 2023), as that would have also affected performance in the single-at-repeated trials. Instead, the results suggest the existence of a faster habituation mechanism operating on a shorter (within-trial) timescale, which does not operate solely on the basis across-trials transient repetitions.

But does the presence of within-trial repeated transients have no effect on across-trials habituation of attentional capture? To answer this question, the location effect (i.e., the difference between single-at-repeated and single-at-opposite) is crucial. Several scenarios are possible. In one scenario, each repeated visual transient contributes not only to the within-trial repetition effect but also to local across-trials habituation of attentional capture. In this case, since visual transients are more than twice as likely to occur at the repeated location than at the opposite location (5:2 ratio), we would expect a location effect, with reduced transient cost in the single-at-repeated condition compared to the single-at-opposite condition. In contrast, in another scenario repeated and single transients are treated as entirely different events, governed by separate habituation mechanisms. In this case, repeated transients would not contribute to across-trials habituation. This scenario predicts the opposite location effect: since the probability of a single-at-repeated trial (8.3% of all trials) is half that of a single-at-opposite trial (16.6% of all trials), habituation—mainly determined by local irrelevant transient probability (Turatto & Valsecchi, 2023) — would result in an advantage for the single-at-opposite condition.

However, the results showed no significant location effect (opposite vs. repeated). This suggests the interim conclusion that repeated transients are just as effective in producing

across-trials local habituation as single transients. Experiments 2 and 3 will further investigate how the presence of repeated trials contributes to and is affected by across-trials habituation, by evaluating how the probability of repeated and single trials impacts performance across trials and locations.

Experiment 2

In Experiment 1, the rate of visual transients in the single-at-opposite condition (16.6% of all trials) was equivalent to the combined rate of visual transients at the repeated location, namely in the repeated (8.3% of all trials) and single-at-repeated conditions (8.3% of all trials). The absence of a location effect—meaning that attentional capture was equivalent for both single conditions—supports the conclusion that repeated trials are as effective as single trials in determining the local level of habituation across trials. If this were not the case, performance would have been substantially worse in the single-at-repeated trials, given that their frequency was half that of the single-at-opposite trials.

Hence, to quantify the level of transient rejection that would have been expected if single-at-repeated trials occurred in the absence of the repeated trials, in Experiment 2 all three conditions had the same rate of occurrence (8.3% of all trials). Assuming that the transient cost in single trials had not reached a ceiling level, we expected such cost for single-at-opposite trials to rise substantially, becoming larger than in single-at-repeated trials.

Methods

Participants

Since we planned to conduct analyses involving a direct comparison of the results of Experiments 1 and 2, in order to avoid having unbalanced samples we decided to collect the

same number of participants as in Experiment 1. The sample consisted of forty participants (mean age = 36.2 years, 23 females), recruited online through the Prolific service (Prolific Academic Ltd, Oxford, UK). 5 datasets were discarded for failing to reach 80% accuracy. New participants were recruited to reach the intended sample size. When it comes to within-observer t-tests, i.e. the Repetition and Location effects, the sample size of 40 a priori warrants the possibility to detect medium-sized effects with *dz* as small as 0.454, with 80% power at a two-tailed significance level of .05, as from the sensitivity analysis computed with G*Power 3.1.9.7 (Faul et al., 2007). Moreover, for the ANOVAs comparing the Location or Repetition effects between experiments, given the 2 x 2 mixed within-between participants design and the sample size of 40 + 40 observers, we expected a priori to be able to detect 2 x 2 interactions with effect sizes of at least η^2_p=0.094, i.e. medium to large, with 80% power, as from the sensitivity analysis computed with MorePower 6.0.4 (Campbell & Thompson, 2012).

Stimuli, design and procedure

As in Experiment 1, with the following exception: as anticipated the transient rate was the same (8.3% of all trials) in each condition, leading to an overall irrelevant transient rate of 25%.

Results and Discussion

In the present experiment, the outlier rejection method removed 1.5% of the data.

Transient costs for RTs and error rates in the different conditions, alongside with those from Experiment 1, are plotted in Figure 3. The repetition effect was replicated in Experiment 2, as the RT transient cost was larger in the single-at-repeated condition than in the repeated condition, $t(39) = 4.245$, $p < .001$, $d_z = 0.671$, mean difference = 32.3 ms, 95% CI = [47.7 16.9].

As in Experiment 1, the repeated transients still produced a reliable RT cost, $t(39) = 4.29$, $p < .001$, $d_z = 0.678$, mean = 19 ms, 95% CI = [10 27.9]. Crucially, contrary to Experiment 1, a significant location effect emerged, as RTs were longer in the single-at-opposite condition compared to the single-at-repeated condition, $t(39) = 2.054$, $p = .047$, $d_z = 0.325$, mean difference = -16.7 ms, 95% CI = [-33.2 -0.3].

To verify whether the halving of the probability of single-at-opposite trials in Experiment 2 significantly modulated the repetition and the location effects relative to Experiment 1, we performed two mixed ANOVAs comparing transient costs in the two Experiments. In the case of the location effect, the ANOVA on RT transient costs with Experiment (1 vs. 2) as a between-participant factor, and Location (single-at-repeated vs. single-at-opposite) as within-participant factor yielded a significant interaction, $F(1,78) = 5.82$, $p = .018$, $\eta^2_p = .069$, indicating that the location effect was indeed stronger in Experiment 2, a significant main effect of Experiment, $F(1,78) = 7.867$, $p = .006$, $\eta^2_p = .092$, and no significant main effect of Location, $F(1,78) = 1.239$, $p = .269$, $\eta^2_p = .016$. To test whether the main effect of Experiment involved larger transient costs at both locations, we directly compared RT transient costs for single trials at the repeated location between Experiments 1 and 2. The independent-sample *t* test was not significant, $t(78) = 1.739$, $p = .086$, $d_z = 0.389$, Mean = 16.8 ms, 95% CI = [-2.4 36]. In the case of the repetition effect, the ANOVA on RT transient costs with Experiment (1 vs. 2) as a between-participant factor, and Repetition (repeated vs. single-at-repeated) as within-participant factor, yielded a significant effect of Repetition, $F(1,78) = 21.705$, $p < .001$, $\eta^2_p = .218$, but no significant main effect of Experiment, $F(1,78) = 1.705$, $p = .196$, $\eta^2_p = .021$ and no significant interaction, $F(1,78) = 2.804$, $p = .098$, $\eta^2_p = .035$. The corresponding Bayesian ANOVA yielded a $BF_{excl} = 1.165$ for the interaction, i.e. undecided.

The analysis of error rates in Experiment 2 produced a significant repetition effect, $t(39) = 3.074$, $p = .004$, $d_z = 0.486$, mean difference = -3.2%, 95% CI = [-5.4 -1.1], and the advantage for repeated trials as compared to absent trials was not significant, $t(39) = 1.616$, $p = .114$, $d_z = 0.256$, Mean = -1%, 95% CI = [-2.2 0.2]. The location effect was not significant, $t(39) = 1.181$, $p = .245$, $d_z = 0.187$, mean difference = 1.3%, 95% CI = [-0.9 3.5]. The ANOVA comparing the location effect between Experiment 1 and 2 did not produce any significant result (all ps > .252). The ANOVA comparing the repetition effect in Experiment 1 and 2 yielded a significant main effect of Repetition, $F(1,78) = 19.504$, $p < .001$, $\eta^2_p = .2$, no significant main effect of Experiment, $F(1,78) = 0.24$, $p = .626$, $\eta^2_p = .003$, and no significant interaction, $F(1,78) = .015$, $p = .903$, $\eta^2_p < .001$.

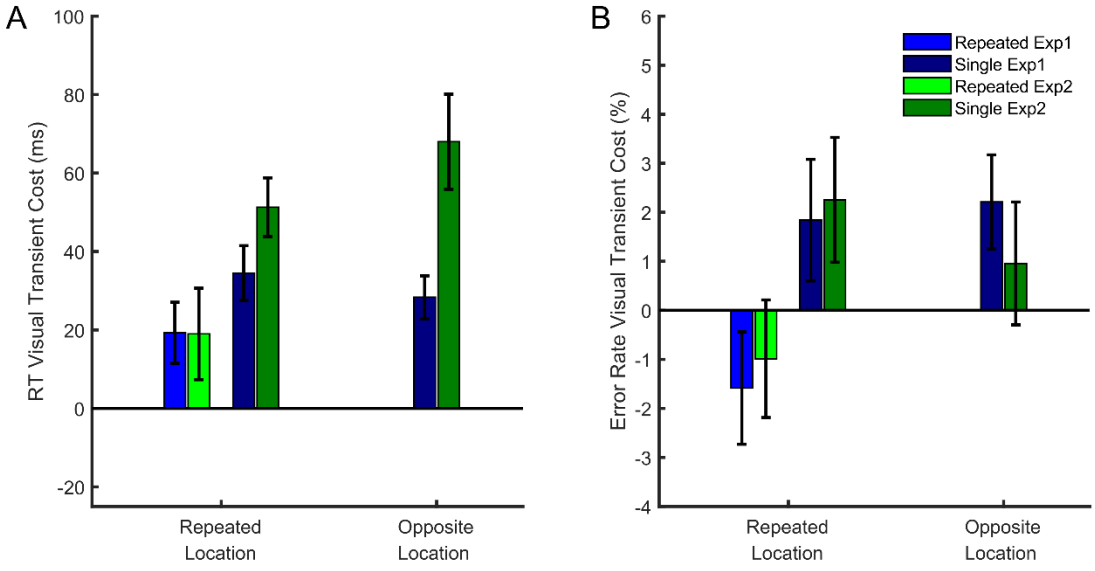

Figure 3. Results of Experiment 1 and 2

Transient costs for RTs (A) and error rates (B) in Experiment 1 and 2, as a function of conditions. As compared to Experiment 1, the transient rate in the single-at-opposite location was reduced by 50%, which produced a large increase in RT transient costs in this condition. Error bars are 95% within-observer Confidence Intervals.

Overall, the results confirmed those of Experiment 1, showing a significant reduction in the cost associated with the irrelevant transient in the repeated condition compared to the single-at-repeated condition. Thus, repeated within-trial transient presentations significantly reduced interference compared to a single transient presented at the same location. This finding supports the existence of a within-trial habituation mechanism operating on a shorter timescale, which co-exists with the across-trials habituation mechanism typically studied in previous studies (e.g., Turatto & Pascucci, 2016). If this short-term repetition mechanism did not exist, repeated transients could only contribute to long-term habituation and no advantage for repeated transients compared to single ones would occur.

Crucially, as predicted, when the rate of transients in the single-at-opposite location was halved compared to Experiment 1 (from 16.6% to 8.3% of all trials), a significant location effect emerged, with RTs selectively increased in single-at-opposite trials. This increase in transient costs with the decreased probability of transients demonstrates that trials with repeated transients do contribute to local habituation across trials, and they do so with an efficiency comparable to that of single trials. If this were not the case, RT costs in Experiment 1 should have been larger for single-at-repeated trials compared to single-at-opposite trials, given that the probability of single-at-repeated trials was half that of single-at-opposite trials.

Overall, the results of Experiments 1 and 2 suggest that the mechanism responsible for reduced costs in response to repeated transients within a trial is insensitive to across-trials learning, as the overall transient rate did not influence the repetition effect. Experiment 3 directly tested this hypothesis.

Experiment 3

The aim of Experiment 3 was to evaluate whether the within-trial habituation mechanism that reduced the transient salience in the repetition condition would interact with the habituation mechanism based on transient expectation across trials (Turatto & Valsecchi, 2023). To this end, the number of trials in the repeated condition was doubled compared to Experiment 2. Several scenarios are possible. First, if the within-trial habituation mechanism is insensitive to across-trials habituation, the magnitude of the repetition effect should remain unchanged as repeated trials become more frequent. Conversely, if the within-trial habituation mechanism benefits from across-trials habituation—perhaps because participants learn to expect that a fourth transient will follow the first three in the same position—then increasing the frequency of repeated trials might enhance the repetition effect. Additionally, doubling the probability of repeated trials might influence across-trials levels of habituation, both at the local and global spatial scale. The latter hypothesis is based on the finding by De Tommaso and Turatto (2023) that distraction by luminance transients is affected both by the across trials probability of transients at a specific location and by the across trials probability of transients across all possible locations, supporting the conclusion that both local and global habituation mechanisms modulate capture.

Methods

Participants

Since we planned to conduct analyses involving a direct comparison of the results of Experiments 2 and 3, in order to avoid having unbalanced samples we decided to collect the same number of participants as in Experiment 2. The sample consisted of forty participants (mean age = 33.7 years, 18 females), recruited online through the Prolific service (Prolific

Academic Ltd, Oxford, UK). 13 datasets were discarded for failing to reach 80% accuracy. A further dataset was removed because the RTs were on average 1703 ms, which seemed incompatible with the instruction of responding "as quick as possible", considering that the other participants had average RTs of 601 ms. New participants were tested to reach the planned sample size. As with the previous experiments, when it comes to within-observer t-tests, i.e. the Repetition and Location effects, the sample size of 40 a priori warrants the possibility to detect medium-sized effects with *dz* as small as 0.454, with 80% power at a two-tailed significance level of .05, as from the sensitivity analysis computed with G*Power 3.1.9.7 (Faul et al., 2007). Moreover, for the ANOVAs comparing the Location or Repetition effects between experiments, given the 2 x 2 mixed within-between participants design and the sample size of 40 + 40 observers, we expected a priori to be able to detect 2 x 2 interactions with effect sizes of at least η^2_p = .094, i.e. medium to large, with 80% power, as from the sensitivity analysis computed with MorePower 6.0.4 (Campbell & Thompson, 2012).

Stimuli, design and procedure

As in Experiment 2, with the following exception: repeated trials constituted 16.6% of all trials, single-at-opposite trials were 8.3% of all trials and single-at-repeated trials were 8.3% of all trials, leading to an overall rate of trials with transients of 33%.

Results and Discussion

In the present experiment the outlier rejection method removed 1.5% of the data.

Transient costs for RTs and error rates in the different conditions are plotted in Figure 4, alongside with those from Experiment 2. The analysis of RTs showed that, as in Experiment 2, the repetition effect was significant, $t(39) = 3.967$, $p < .001$, $d_z = 0.627$, mean difference = -24.5 ms, 95% CI = [-37 -12]. One-sample *t* tests showed that contrary to Experiments 1 and 2,

the RT transient cost for repeated trials was not significant, $t(39) = 1.647$, $p = .108$, $d_z = 0.26$, mean = -9 ms, 95% CI = [-20.1 2.1]. Coherently with the results of Experiment 2, RTs showed a significant main effect of Location, $t(39) = 4.061$, $p < .001$, $d_z = 0.642$, mean difference = -21.3 ms, 95% CI = [-31.9 -10.7].

To test whether doubling the probability of repeated trials in Experiment 3 compared to Experiment 2 significantly modulated the repetition and the location effects, we performed mixed ANOVAS comparing transient costs in the two Experiments. In the case of the repetition effect, the ANOVA performed on RT transient cost with Experiment (2 vs. 3) as a between-participants factor, and Repetition (repeated vs. single-at-repeated) as within-participant factor, yielded a significant effect of Repetition, $F(1,78) = 33.6$, $p < .001$, $\eta^2_p = .301$, a significant main effect of Experiment, $F(1,78) = 21.69$, $p < .001$, $\eta^2_p = .218$, and no significant interaction, $F(1,78) = 0.628$, $p = .431$, $\eta^2_p = .008$. The corresponding Bayesian ANOVA yielded a $BF_{excl} = 3.672$ against inclusion of the interaction to model the data.

In the case of the location effect, the ANOVA on RT transient costs with Experiment (2 vs. 3) as a between-participants factor, and Location (single-at-repeated vs. single-at-opposite) as within-participant factor yielded no significant interaction, $F(1,78) = 0.228$, $p = .635$, $\eta^2_p = .003$, with a corresponding $BF_{excl} = 4.141$, indicating that the magnitude of the location effect was not modulated by the change in repeated trial probability, a significant main effect of Experiment, $F(1,78) = 10.193$, $p = .002$, $\eta^2_p = .116$, and a significant main effect of Location $F(1,78) = 15.426$, $p < .001$, $\eta^2_p = .165$.

The analysis of error rates in Experiment 3 (4.6% overall) yielded no significant repetition effect, $t(39) = 1.229$, $p = .227$, $d_z = 0.194$, mean difference = -1.3%, 95% CI = [-3.3 0.8], there were no significant transient costs in repeated trials, $t(39) = 0.102$, $p = .919$, $d_z = 0.016$, Mean = -0.1%, 95% CI = [-1.4 1.3]. The location effect was also not significant, $t(39) = 0.129$, $p = .898$, $d_z = 0.02$, mean difference = 0.1%, 95% CI = [-1.4 1.5]. The ANOVA comparing

the repetition effect in Experiments 2 and 3 yielded a significant effect of Repetition, $F(1,78) = 9.397$, $p = .003$, $\eta^2_p = .108$, no significant main effect of Experiment, $F(1,78) = 0.007$, $p = .933$, $\eta^2_p < .001$, and no significant interaction, $F(1,78) = 1.847$, $p = .178$, $\eta^2_p = .023$. The ANOVA comparing the location effect in Experiments 1 and 2 did not yield any significant results (all ps > .293).

Overall, the results indicated that the repetition effect was not influenced by doubling the frequency of the repeated trials, suggesting that the within-trial facilitation mechanism is largely insensitive to learning that occurs across trials. However, inspection of Figure 4 reveals another important finding, which was confirmed by the statistical analyses. Doubling the probability of repeated trials did reduce transient costs across trials, but this reduction was observed at a global level, meaning that transient costs were decreased to a similar extent in all conditions, including the single ones.

Experiments 1 and 2 demonstrated that the transient cost in the repeated condition was smaller than in the single-at-repeated condition, even though the transient rate across trials was the same in both conditions, and both types of trials occurred at the same location. This led us to hypothesize that the attenuation of transient cost or capture observed in the repeated condition was controlled by a within-trial habituation mechanism, which does not overlap with the habituation mechanism operating at the across-trials level. The evidence suggests that these two mechanisms are independent, and their effects appear to be additive. In Experiment 3, the combined influence of within-trial and across-trials habituation led to the complete abolition of transient cost in the repeated condition. Crucially, the specificity of the two habituation mechanisms was preserved, as evidenced by the fact that the difference in transient cost between the repeated and single-at-repeated conditions remained unchanged even though observers were exposed to repeated trials more frequently.

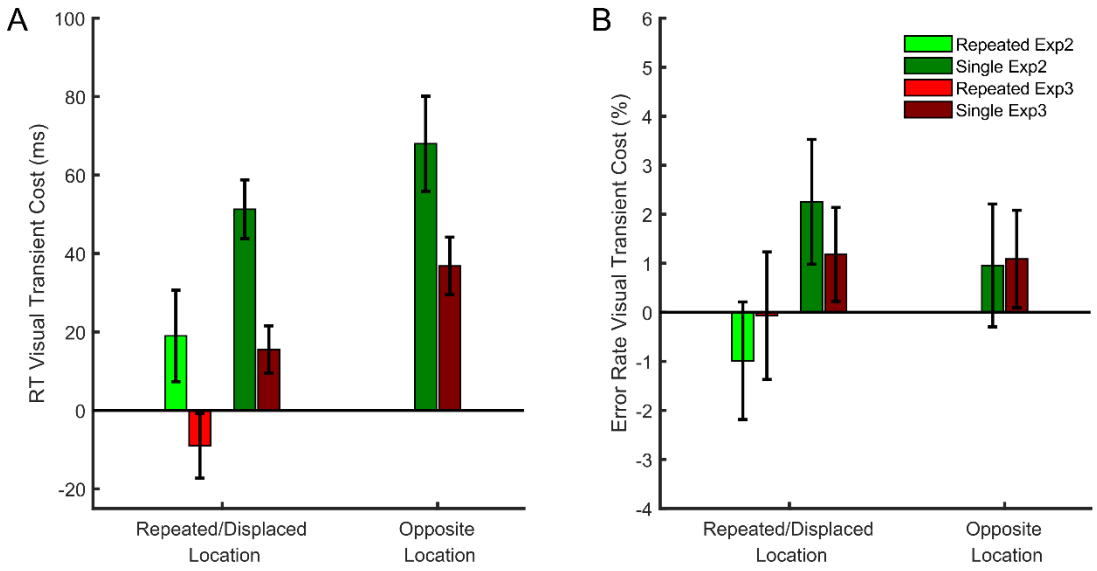

Figure 4. Results of Experiment 2 and 3

Transient costs for RTs (A) and error rates (B) in Experiment 2 and 3, as a function of conditions. The increase in transient rate in the repeated condition produced a lack of transient cost in this condition, and general reduction in transient cost, but the magnitude of the repetition effect was largely unchanged. Error bars are 95% within-observer Confidence Intervals.

Experiment 4

While we have interpreted the reduction in transient cost in the repeated condition as evidence for a within-trial habituation mechanism, an alternative explanation is that this finding reflects a warning effect (Weinbach & Henik, 2012). Specifically, when a stimulus regularly precedes the imperative one, it can help prepare participants to respond more effectively to the latter (Posner & Boies, 1971). In this view, the four repeated transients may have better prepared participants to respond to the subsequent target compared to a single

transient, as seen in the single-at-repeated and single-at-opposite conditions. The clear prediction of this warning signal hypothesis is that a general preparatory benefit associated with the repetition condition should become evident regardless of where the warning signals, i.e. the visual transients anticipating the target, are presented in the display.

In contrast, if the transient repetitions engaged a within-trial habituation mechanism, this effect should be mostly location-specific, as observed in Experiments 1-3 and in previous studies investigating habituation to onsets across trials (De Tommaso & Turatto, 2023; Turatto & Valsecchi, 2023). To distinguish between these possibilities, the present experiment displaced the first three transients in the sequence to a different location compared to the last one preceding the target. If the advantage of the repeated condition were merely due to a warning effect, we would still expect a reduced transient cost in this condition compared to the two single visual transient conditions. Conversely, if the reduction in transient cost observed in the repeated condition is due to local within-trial habituation, it should largely disappear when the first three transients are presented in a different location compared to the last one. In the previous experiment, all repeated transients occurred in the same position within a trial, making the initial transients a 100% valid spatial cue for the position of the last transient before the target. Similarly, in the present experiment, the location of the last transient in displaced trials was made completely predictable by consistently displacing it 90° counterclockwise relative to the first three. This approach ensures that any spatial cueing effect in this and the previous experiments is comparable.

Methods

Participants

Since we planned to conduct analyses involving a direct comparison of the results of Experiments 2 and 4, to avoid having unbalanced samples we decided to collect the same number of participants as in Experiment 2. The sample consisted of forty participants (mean age = 32.8 years, 19 females), recruited online through the Prolific service (Prolific Academic Ltd, Oxford, UK). 4 datasets were discarded for failing to reach 80% accuracy and new participants were tested. As with the previous experiments, when it comes to within-observer t-tests, i.e. the Repetition and Location effects, the sample size of 40 a priori warrants the possibility to detect medium-sized effects with *dz* as small as 0.454, with 80% power at a two-tailed significance level of .05, as from the sensitivity analysis computed with G*Power 3.1.9.7 (Faul et al., 2007). Moreover, for the ANOVAs comparing the Location or Repetition effects between experiments, given the 2 x 2 mixed within-between participants design and the sample size of 40 + 40 observers, we expected a priori to be able to detect 2 x 2 interactions with effect sizes of at least η^2_p=0.094, i.e. medium to large, with 80% power, as from the sensitivity analysis computed with MorePower 6.0.4 (Campbell & Thompson, 2012).

Stimuli, design and procedure

As in Experiment 2, with the following exception: in the repeated condition, now called *displaced condition*, the first three transients in the sequence were displaced to a location 90° counterclockwise relative to the position of the last one (Figure 1). The rate of displaced, single-at-displaced and single-at-opposite condition was the same (each 8.3% of all trials), leading to an overall rate of 25% trials with transients.

Results and Discussion

In the present experiment the outlier rejection method removed 1.6% of the data.

Transient cost for RTs and error rates in the different conditions are plotted in Figure 5. The analysis of RTs showed that, contrary to all previous experiments, the repetition effect, here defined as the difference between transient costs in the displaced and single-at-displaced trials, was not significant, $t(39) = 0.492$, $p = .625$, $d_z = 0.078$, mean difference = -3.3 ms, 95% CI = [-17 10.4]. A one-sample *t* tests showed that the RT transient cost for displaced trials was significant, $t(39) = 5.01$, $p < .001$, $d_z = 0.792$, mean = 38.3 ms, 95% CI = [22.8 53.7]. The results showed no significant main effect of Location, $t(39) = 0.515$, $p = .61$, $d_z = 0.081$, mean difference = 3.3 ms, 95% CI = [-9.5 16.1].

To verify whether displacing the first three repeated transients in Experiment 4 significantly modulated the repetition and the location effects, we performed a mixed ANOVAs comparing the transient cost in Experiments 2 and 4. In the case of the repetition effect, the ANOVA performed on RT transient cost with Experiment (2 vs. 4) as a between-participant factor, and Repetition (repeated/displaced vs. single-at-repeated/displaced) as within-participant factor, yielded a significant effect of Repetition, $F(1,78) = 12.243$, $p < .001$, $\eta^2_p = .136$, no significant main effect of Experiment, $F(1,78) = 0.353$, $p = .554$, $\eta^2_p = .005$, and, crucially , a significant interaction, $F(1,78) = 8.092$, $p = .006$, $\eta^2_p = .094$, indicating that the repetition effect was indeed reduced in Experiment 4.

The RT results suggest that the repetition effect is primarily driven by a local, short-term process that attenuates distraction. The findings indicate that neither a warning effect nor the spatial predictability of the last transient (i.e., a potential cueing effect) was responsible for the repetition effect. This conclusion is supported by Experiment 4, where the timing and spatial predictability of the first three transients relative to the fourth were identical to those in Experiment 2, yet the repetition effect was significantly reduced.

In the case of the location effect, the ANOVA on the RT transient cost with Experiment (2 vs. 4) as a between-participants factor, and Location (single-at-repeated/displaced vs.

single-at-opposite) as within-participant factor did not yield a significant main effect of Location, $F(1,78) = 1.701$, $p = .196$, $\eta^2_p = .021$, no significant main effect of Experiment, $F(1,78) = 3.513$, $p = .065$, $\eta^2_p = .043$, and no significant interaction, $F(1,78) = 3.751$, $p = .056$, $\eta^2_p = .046$. The corresponding Bayesian ANOVA yielded a $BF_{incl} = 1.196$ for the interaction to model the data, i.e. substantially undecided.

In the present experiment, the overall transient rate at the displaced location was 16.6%, consisting of displaced trials (8.3% of all trials) and single-at-displaced trials (8.3% of all trials), i.e. twice as much as the rate at the opposite location (8.3% of all trials). It might seem puzzling that this did not produce shorter RTs at the displaced location, given the results of Experiment 2 and the established fact that transient interference at a given location depends on the transient rate at that location (De Tommaso & Turatto, 2023; Turatto & Valsecchi, 2023). However, it is important to note that in Experiment 4, transients appeared repetitively at an additional location, 90° away from the displaced and opposite locations. The increase in the number of locations from two to three compared to Experiments 1-3 may have shifted the habituation effect to be more influenced by the global rate of occurrence rather than the local rate (De Tommaso & Turatto, 2023). Nonetheless, caution is warranted in overinterpreting this result, as the statistical evidence—the Location by Experiment interaction representing the modulation of the location effect due to the displacement manipulation—is not conclusive.

The analysis of error rates in Experiment 4 (5% overall) yielded a significant repetition effect, $t(39) = 3.175$, $p = .003$, $d_z = 0.502$, mean difference = -2.9%, 95% CI = [-4.7 -1], there were no significant transient cost in displaced trials, $t(39) = 1.655$, $p = .106$, $d_z = 0.262$, Mean = -1.2%, 95% CI = [-2.6 0.3]. The location effect was also not significant, $t(39) = 0.557$, $p = .58$, $d_z = 0.088$, mean difference = 0.6%, 95% CI = [-1.7 3]. The ANOVA comparing the error rate repetition effect in Experiments 2 and 4 yielded a significant main effect of repetition, $F(1,78)$

= 19.362, $p < .001$, $\eta^2_p = .199$, no significant main effect of Experiment, $F(1,78) = 0.125$, $p = .725$, $\eta^2_p = .002$, and no significant interaction, $F(1,78) = 0.071$, $p = .79$, $\eta^2_p < .001$. The corresponding Bayesian repeated-measure ANOVA yielded a $BF_{excl} = 3.931$ against the inclusion of the interaction to model the data. The ANOVA comparing the location effect in Experiments 2 and 4 did not yield any significant results (all *p*s > .228).

The results revealed a dissociation between RTs and error rates regarding the effects of repetition on these measures. For RTs, transient repetitions primarily depend on a local habituation mechanism, as evidenced by the reduced magnitude of the effect from Experiment 2 to Experiment 4, where the first three transient repetitions in the sequence occurred at a different location. In contrast, when considering error rates, the benefits of repeating the transient before the target do not appear to be spatially selective. It is likely that the repeated transients help observers orient their temporal attention to the occurrence of the target, independently of the location-based transient habituation.

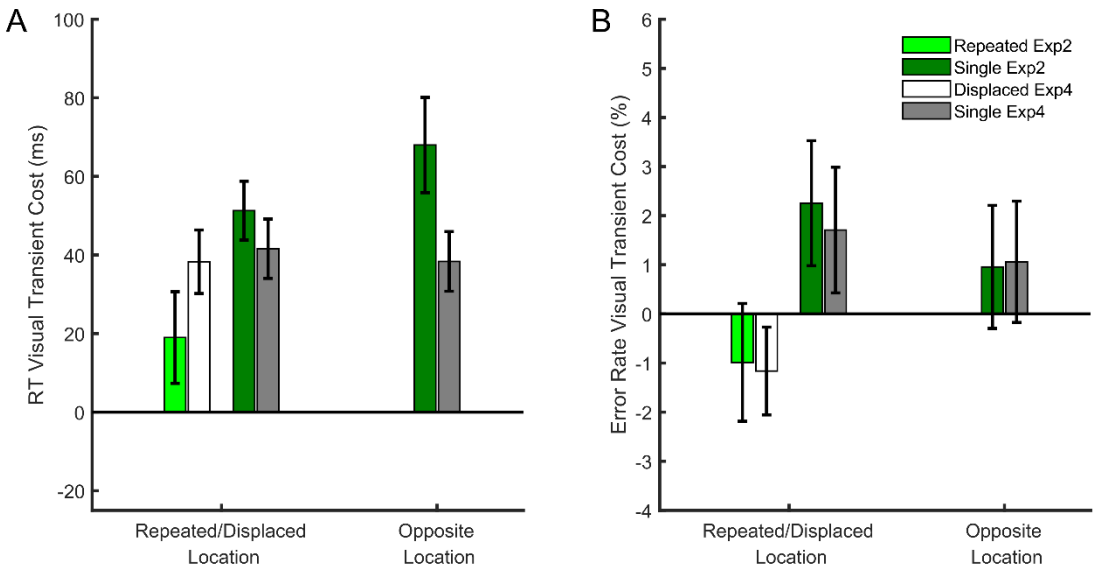

Figure 5. Results of Experiment 2 and 4

Transient costs for RTs (A) and error rates (B) in Experiment 2 and 4, as a function of conditions. In Experiment 4, the repeated trials were substituted by the displaced trials, in which the first three transients in the sequence appeared at a different location as compared to the last one preceding the target. Under these conditions, the advantage previously observed in the repeated condition disappeared. Error bars are 95% within-observer Confidence Intervals.

General Discussion

Previous studies have consistently shown that visual transients anticipating the target by appearing at a different location, typically in the form of rapid brief onsets, act as visual distractors, negatively impacting observers' identification performance by producing longer RTs compared to when no transients are present (Jonides & Yantis, 1988; Lamy & Egeth, 2003; Posner & Cohen, 1984; Yantis & Jonides, 1984). However, this form of capture is subject to habituation, which largely depends on the local and global transient rates (De Tommaso & Turatto, 2023). In this respect, we have demonstrated that habituation of onset capture is based on the degree of expectation, built across trials, concerning the occurrence of the irrelevant visual transients (Turatto & Valsecchi, 2023).

Here, in addition to manipulating the rate of irrelevant visual transients across trials, we also crucially varied the number of visual transients presented within the same trial, which were either one (single conditions) or four (repeated condition). The results from the various experiments led to four main findings. First, we consistently found that the repetition of four luminance transients within a trial, in close temporal proximity and at the same location, produced weaker interference on target discrimination than a single luminance transient, or three transients appearing, before the last one, at a different location. Second, the magnitude of this repetition effect was insensitive to inter-trial learning, namely it did not change based on the frequency of repeated trials or single trials. Third, the presence of repeated transients did not seem to influence the local habituation of attentional capture. Repeated trials, even though they exposed observers to a larger number of transients, appeared to be as effective in generating local across-trial habituation of capture as single trials. Fourth, while repeated transients did not contribute to local across-trials habituation, they produced a global across-trials habituation of capture that extended beyond the location where they were presented.

Repetition Effect

In discussing this set of findings, we will first consider the repetition effect, namely the fact that the transient interference was reduced when the transient was repeated four times in the same trial, as opposed to just once. The data suggest that this effect results from a rejection mechanism that operates within a restricted range of space and time. This conclusion is supported by the observation that the effect disappeared when the first three transients in the sequence were presented at a different location compared to the last one, and by the fact that the presence of repeated transients did not, by itself, increase the level of local habituation across trials.

Repetition effect as habituation on a short time scale

What could explain the stronger attenuation of onsets interference observed in the repetition condition? As suggested by Pascucci and Turatto (2015), we propose that this capture reduction reflects the operation of a fast within-trial habituation mechanism, which attenuates the transient's salience by quickly making the event expected due to its repetitions within the trial. In other words, the last onset in the sequence, which is the one that competes most for attention with the immediately subsequent target, is much less unexpected or surprising when preceded by its repeated occurrences, compared to when it appears as a single transient, as in the two single conditions, in which expectation arises from across-trials statistics. Probably, within-trial expectation is different from across-trial expectation, but in any case this view aligns with the notion that attention is captured by surprising events (Itti & Baldi, 2009), or that attention is drawn to stimuli that are unexpected based on the past history of stimulation (Sokolov, 1963). These mechanisms may operate over a longer across-trials timescale or a shorter within-trial timescale, as demonstrated in the present study (see also Betteto et al., 2024).

765 *Repetition effect and inhibition of return*

766 Alternatively, the reduced cost associated with visual transients observed in the
767 repeated condition could be related to the well-known phenomenon of Inhibition of Return
768 (IOR). IOR is defined as a delay in responding to stimuli which appear at a location that was
769 previously occupied by a peripheral visual cue consisting of a visual transient, especially when
770 the task does not require maintaining attention at the cue location (Klein, 2000; Posner &
771 Cohen, 1984). IOR typically manifests as a reversal of the exogenous cueing effect as the
772 SOA between cue and target increases. Various theories about the nature of IOR have been
773 proposed, focusing on sensory, attentional, and motor aspects of the phenomenon (e.g.
774 Berlucchi, 2006; Lupiáñez et al., 2006). In general, if the IOR reduces the readiness to orient
775 towards a stimulus that follows a peripheral visual transient, this should apply both when the
776 second stimulus is a target and when it is irrelevant. There is indeed some
777 evidence supporting this. Theeuwes and Godijn (2004) studied oculomotor IOR in a repeated
778 saccade task and showed that when an irrelevant peripheral onset was presented at a location
779 where another onset had been presented 1300 ms earlier, it produced less oculomotor
780 interference compared to when it appeared at a new location. It can be assumed that the same
781 processes that reduce the sensory/attentional strength of onsets recurring at the same
782 location in IOR paradigms would also act upon the repeated transients in our paradigm,
783 contributing to the within-trial habituation observed in repeated trials.

784 However, it is worth noting that IOR itself has been interpreted as a form of
785 habituation. Dukewich (2009) argued that IOR should be reconceptualized as a form of
786 habituation because the two phenomena share the same functional role, i.e. to avoid orienting
787 towards irrelevant stimuli, and exhibit several common characteristics. For instance, the time
788 course of IOR, with an initial suppression of orienting followed by a recovery, is reminiscent of
789 the buildup-spontaneous recovery temporal profile of habituation. Dukewich (2009)

further highlighted that at least some components of IOR cannot be explained solely by sensory adaptation and must be interpreted as habituation, as IOR is object- rather than space-based (Tipper et al., 1991). The idea that IOR results from a habituation process has also been incorporated into the computational model by Ibáñez-Gijón and Jacobs (2012). In their model, a habituation field interacts with two other activation fields, one representing the sensory input and the other representing the orienting decision process as implemented in the intermediate layer of the superior colliculus, to generate the IOR effect.

Repetition effect and inter-trial priming

In addition to research on IOR, another line of research has explored the potential beneficial effects, specifically, reduced costs, of local repetition of visual onsets in close temporal proximity, focusing on inter-trial sequence effects. At least in the case of feature singleton distractors, it has been shown that repeating their location in subsequent trials reduces distraction (Goschy et al., 2014), although this effect can be less reliable than the effect of local distractor probability (Wang & Theeuwes, 2018), and the advantage is largely reduced when the distractors that are repeated at the same location are not defined in the same visual dimension (Sauter et al., 2018). Perhaps more crucially when it comes to the present study, this repetition effect can be dissociated from the statistical learning of local distractor probability across trials, as the repetition advantage occurs even when overall local distractor probability is equal at all locations, and learning of overall local probability can occur even when inter-trial repetitions are prevented (Goschy et al., 2014). The fact that both distractor location repetition and statistical learning contribute to mitigating distraction might also explain why the exposure to an imbalance in distractor probability produces an advantage for color-singleton distractors at high-probability locations that emerges extremely rapidly, but at the same time is also resistant to extinction (Valsecchi & Turatto, 2021). The excess of local distractor repetitions might contribute to rapidly instate the relative advantage

for the high distractor probability location, whereas habituation (or statistical learning) that builds up over multiple trials might produce a form of learning that is more resilient to sudden changes in the statistics of the stimulation. There is at least one study which tested distraction induced by visual onsets and reported that habituation to onset stimuli repeating at the same location can be established extremely fast (Kelley & Yantis, 2009). The paradigm in the Kelley and Yantis (2009) study differed from the present one in multiple ways; for instance, observers did not have to search for the target, which consistently appeared at the center of the screen, and the visual transient shared the task-relevant feature (red-green color mixture) with the target. Nonetheless, the finding of rapidly occurring habituation, although across trials, suggests that a fast repetition-based process may also play a role in reducing distraction by visual transients.

Dedicated investigations will be needed to evaluate the extent to which IOR and inter-trial repetition effects are related to the within-trial repetition effect we report here. These studies will likely involve a parametric manipulation of inter-trial repetition and inter-trial timing. For now, however, we can conclude that our findings of a within-trial repetition effect, independent from across-trials statistical learning, align well with previous research indicating the existence of at least two rejection mechanisms operating on different time scales (inter-trial priming and statistical learning across trials). It is worth noting that the repetition effect that we report here occurs despite the fact that the repeated visual transients were not in a direct competition with the target (also see, Betteto et al., 2024).

Previous studies on within-trial repetition

Regarding the within-trial repetition effect, the findings of Pascucci and Turatto (2015), whose results partially inspired the present study, warrant discussion. Their results diverge from the present ones in an important way: they demonstrated a global repetition effect, where repeating the visual transient reduced costs even when occurring at different spatial

locations. However, several differences exist between the two paradigms. For one, their task required observers to maintain focused foveal attention and resist distraction from all peripheral stimuli. In contrast, in the present study, observers had to resist distraction from irrelevant peripheral transients while simultaneously orienting attention toward a peripheral target that appeared at an uncertain location. This may have reduced the benefit of local short-term visual transient rejection in their paradigm. More importantly, their transients were presented at random locations, whereas, with the exception of Experiment 4, in our study the repeated transients appeared at the same location. We cannot rule out that having multiple transients appear at random locations might have promoted a global repetition effect. In the end, however, the discrepancy may be more apparent than real, as Pascucci and Turatto (2015) measured performance using accuracy in a discrimination task, and when performance in the present study was measured in terms of error rates, the effect of repetition was global rather than local. This suggests a possible role for repeated transients in promoting readiness to respond to the target at the right moment in time.

A global within-trial repetition effect, alongside a local one, was also reported by Betteto and colleagues (2024) for color singletons in a variant of the additional-singleton paradigm. In their study, exposure to a sequence of three displays containing a singleton at random locations but in the same color, in the absence of a target, reduced the distraction effect when, in the fourth display, the same color singleton was presented together with the shape singleton target. This location-independent repetition effect with feature singletons might be related to the possibility that feature singleton distractors are partially managed by down-weighting the entire color map, as suggested by the dimension-weighting hypothesis (Liesefeld et al., 2019; Liesefeld & Müller, 2019). Alternatively, the reduced capture observed when the singleton was repeated within the trial might simply be explained, without invoking the notion of suppression, by assuming that because of such repetitions the singleton was less

surprising or unexpected in the last display, and it is well established that attention is captured by surprising or unexpected events (Itti & Baldi, 2009; Sokolov, 1963). At any rate, Betteto and colleagues (2024) ruled out voluntary top-down feature suppression as an explanation for their repetition effect, as they did not find any facilitation in a control condition where the color of the distractor was cued verbally, or when the color of the singleton in the last display was unpredictable.

Another study relevant to the repetition effect observed here is the work by Ruthruff and colleagues (2019). They investigated the effect of presenting a series of 10 visual transients in rapid succession (each lasting 100 ms and separated by 50 ms), which ended 500 ms before the onset of a final visual transient. This final transient preceded the target display by 250 ms. Their results suggested that, despite exposure to such a large number of repeated visual transients, the final one still produced a cue validity effect comparable to that found in a previous study (Gaspelin et al., 2016), where only a single transient preceded the target without repeated stimuli. This finding indicates a relatively limited effect of transient repetition, which seems at odds with the present findings.

However, their paradigm differs from ours in several potentially relevant ways. First, they employed a challenging search task (finding an E or H target letter within an array of four letters), whereas our task involved a simple search—discriminating a single character presented in isolation. Difficult search tasks are more sensitive to attentional capture by visual onsets (Gaspelin et al., 2016), though such difficulty alone is unlikely to produce capture effects that are completely insensitive to habituation. Indeed, in our recent study (Valsecchi & Turatto, 2024), we found that making search more difficult (Experiment 3 vs. 2) increased both distractor interference and the effect of local distractor probability. This suggests that, at least for slow habituation, attentional capture can still be reduced even in difficult search tasks. Second, the rapid pace of the visual transients in Ruthruff et al. (2019)'s study may have

caused them to be processed as a single, grouped stimulus—flickering or moving in the display—rather than as distinct onsets. This grouping might have reduced the level of generalization between the repeated transients and the final transient. Third, in our study, repeated, single, and absent trials were randomly interleaved, with most trials containing no visual transient before the target. In contrast, Ruthruff et al. (2019) presented repeated onsets in every trial. It is possible that repetition effects are stronger when there is greater uncertainty about the upcoming stimulus.

Perhaps the most critical difference, however, is that in Ruthruff et al.'s (2019) study , the repeated transients appeared at random locations unrelated to the final cue's position. This aspect of their procedure is more similar to the displaced trials in Experiment 4 of the current study, where no advantage was observed, rather than to the repeated trials in Experiments 1–3. Thus, strictly speaking, there is no contradiction between our findings and those of Ruthruff and colleagues (2019). A more substantial discrepancy might exist with the global repetition effect reported by Turatto and Pascucci (2016). However, this difference could be explained by their use of central targets and peripheral irrelevant transients, as discussed both above and by Ruthruff et al. (2019).

Interplay of the effects of transient repetition and transient probability

Repetition effect is insensitive to probability

The second result from the present study was that within-trial habituation to visual transients was insensitive to across-trials habituation to visual transients. This suggests that the effects of repeating transients at a given location within a trial and across trials are independent and additive. This finding parallels the IOR literature, where Maylor and Hockey (1987) found that IOR was not reduced even when the cue, i.e. the irrelevant peripheral onset that preceded the target, was presented repeatedly at the same location for up to 30

consecutive trials. Of course, our result may be specific to the experimental design used in the present study. A more rigorous test would involve demonstrating that the repetition effect persists unchanged even when the observer is fully habituated, i.e., when the cost associated with the visual transient reaches an asymptotic level over time. Nevertheless, our results suggest that the effect of repeated transients does not simply contribute to across-trials local habituation of capture; otherwise, no difference would have emerged between repeated and single-at-repeated trials.

Contribution of repeated trials to local and global habituation at the longer time scale

The third main result from the present study was that repeated trials were as effective in generating local habituation over trials as single trials. In principle, this could mean that habituation occurs only when transients are presented with a timing that ensures their interference with target processing. One key finding in the exogenous cueing-IOR literature is that onsets maximally interfere with target processing when they precede the target by up to 200 ms (e.g., Posner & Cohen, 1984). Therefore, in our experiments, only (or mainly) the last transient in the repetition sequence would be expected to interfere with the target. This result is consistent with the idea that across-trials habituation of capture is contingent upon the need to reduce the salience of the transient and/or to quickly re-orient attention from the irrelevant transient location to the target (Mathôt et al., 2010; Valsecchi & Turatto, 2024). However, this does not mean that transients which do not directly interfere with the target are entirely irrelevant or forgotten. Indeed, the fourth main result from our study—namely, that doubling the probability of repeated trials produces a global habituation of capture—demonstrates that increasing exposure to multiple transients at one location affects the cost associated with single transients that appear at other locations. This finding is consistent with previous research showing that habituation can occur even when observers are passively exposed to onsets, thus confirming that habituation to onsets

939 does not necessarily require direct interference with target processing (Turatto, Bonetti,
940 Pascucci, et al., 2018). Unfortunately, Turatto and colleagues (2018) did not include a spatial
941 imbalance in the occurrence of onsets during the passive exposure phase, making it
942 impossible to determine whether the reduction in attentional capture observed in that
943 study was due to local or global habituation.

944 Notice that the finding that repeated trials were as effective as single trials in producing
945 habituation across multiple trials is a result that challenges an interpretation based solely on
946 contingent capture. The contingent capture hypothesis (Folk et al., 1992) posits that stimuli
947 interfere with search to a greater extent when they are compatible with the search set—that
948 is, when they are similar to the target. In the context of our study, this could mean that single
949 transients produce interference because the target is also a brief luminance transient,
950 whereas repeated transients, being extended in time, fall outside the search set and thus
951 produce little or no interference. If repeated transients were treated by the attentional system
952 as entirely separate from the search set, with no relation to the habituation mechanism that
953 handles single transients interfering with the target, one could explain why the repetition
954 effect appears insensitive to the manipulation of the global and local probability of single
955 trials. This might also explain why no benefit was observed in Experiment 4 for displaced
956 trials: the final displaced transient would more closely resemble the isolated target transient
957 in appearance. While this account provides a parsimonious explanation for much of our data,
958 we argue that the fact that repeated trials contribute to local habituation across trials—at a
959 level comparable to that of single trials—indicates that the attentional system does not treat
960 repeated stimuli as different from the search set.

961 **Conclusion**

962 Our study opens new perspectives on the multiple mechanisms that underlie our
963 ability to cope with irrelevant visual transients.Instead of relying on a single habituation

process that takes into account the number of irrelevant transients experienced at a given location, our results suggest the existence of distinct mechanisms for distractors rejection operating on different time scales. A within-trial habituation mechanism, operating on a shorter time scale, attenuates capture to repeated transients that recur at the same location within a brief temporal window; a different one deals with the local probability of irrelevant transients across trials (see also Turatto & Valsecchi, 2023); a further mechanisms attenuates the global attentional weight of irrelevant transients even if they do not directly interfere with the processing of the task-instructed target. Further research is needed to detail the specific characteristics of these habituation mechanisms and to determine their distinct operative time scales.

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