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Attentional Suppression of Dynamic Versus Static Salient Distractors

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Abstract

Attention must be carefully controlled to avoid distraction by salient stimuli. The signal suppression hypothesis proposes that salient stimuli can be proactively suppressed to prevent distraction. Although this hypothesis has garnered much support, most previous studies have used one class of salient distractors: color singletons. It therefore remains unclear whether other kinds of salient distractors can also be suppressed. The current study directly compared suppression of a variety of salient stimuli using an attentional capture task that was adapted for eye tracking. The working hypothesis was that static salient stimuli (e.g., color singletons) would be easier to suppress than dynamic salient stimuli (e.g., motion singletons). The results showed that participants could ignore a wide variety of salient distractors. Importantly, suppression was weaker and slower to develop for dynamic salient stimuli than static salient stimuli. A final experiment revealed that adding a static salient feature to a dynamic motion distractor greatly improved suppression. Altogether, the results suggest that an underlying inhibitory process is applied to all kinds of salient distractors; but static salient features are easier to ignore than dynamic salient features.

Keywords: attentional capture, inhibition, eye movements, visual attention, motion

Attentional Suppression of Dynamic Versus Static Salient Distractors

We live in an age of distraction. Advertising agencies have perfected the art of co-opting our attention by using bright lights, flashy colors, and eye-popping animations. Cell phone notifications have been designed to hijack our attentional systems and redirect our cognitive resources to check the most recent text messages or the status of a post on social media. Even motor vehicles, which require immense concentration to safely operate, are now equipped with interactive media displays and onboard warning systems that demand our attention as we attempt to drive from one destination to the next.

There has been much debate about whether salient stimuli have the power to involuntarily attract attention (see review by Luck et al., 2021). As a potential resolution, the *signal suppression hypothesis* proposes that salient stimuli do attract attention, but can be suppressed in order to prevent distraction under certain conditions (Gaspelin & Luck, 2018c; Sawaki & Luck, 2010). Although this theory of attentional capture has garnered much recent support, most studies have used a single class of salient stimuli: color singletons. As a result, it remains unclear whether other types of salient stimuli can also be suppressed. The current study aims to bridge this gap in knowledge by testing whether various kinds of salient distractors can be suppressed.

The Attentional Capture Debate

Initially, research on attentional capture was divided into two competing theoretical accounts. *Stimulus-driven accounts* proposed that salient distractors capture attention even when entirely task-irrelevant (e.g., Franconeri & Simons, 2003; Theeuwes, 1992; Yantis & Jonides, 1984). Here, an object is considered salient if it differs from neighboring objects in low-level features, such as color (Nothdurft, 1993). In a seminal study, Theeuwes (1992) provided support for stimulus-driven accounts using an *additional singleton paradigm.* Participants searched for a target defined by shape (e.g., a circle) amongst homogenous distractors (e.g., a set of diamonds) and made a speeded buttonpress to indicate the orientation of a line inside the target. On some trials, one object in the display was differently colored than the others. This *color singleton* was never the target, and therefore should have been ignored. Nonetheless, response times (RTs) were slower when the color singleton was present than when it was absent (a *singleton-presence cost*), which was taken to suggest that attention was captured by the salient distractor and slowed detection of the target.

Goal-driven accounts, however, proposed that salient stimuli have no automatic power to capture attention and that objects will only capture attention if they match the perceptual goals of the observer. Initial support came from studies showing that salient cues captured attention only when they matched the features of the target stimulus (Folk et al., 1992; Folk & Remington, 1998). Further evidence suggested that previous studies supporting stimulus-driven accounts may have encouraged an attentional set for salience (*singleton detection mode*; Bacon & Egeth, 1994). For example, in Theeuwes (1992) and other studies, the target was a shape singleton in a homogenous field of distractor shapes and could therefore be found by searching for any type of "pop out." This might encourage participants to simplify visual search by looking for any feature singleton, which would lead to capture by the color singleton. As evidence of this, when this strategy was discouraged by using search displays of heterogenous shapes (*feature search mode*), capture by color singletons was eliminated (Bacon & Egeth, 1994). Importantly, this elimination in capture occurred even when heterogeneous and homogenous displays were intermixed, suggesting that the elimination of capture was due to a strategic change to the attentional set (Bacon & Egeth, 1994, Experiment 3; see also Leber & Egeth, 2006).[1]

In sum, stimulus-driven and goal-driven accounts have been in a longstanding debate about whether salient stimuli automatically capture attention. This debate has been difficult to resolve because both accounts are equally supported, and both have alternative justifications to explain the opposing camp's findings.

The Signal Suppression Hypothesis

As a potential resolution, the *signal suppression hypothesis* is a hybrid model which proposes that salient distractors automatically generate an "attend-to-me" signal, but that salient distractors can be suppressed to prevent capture (Gaspelin & Luck, 2018c; Sawaki & Luck, 2010). This model predicts that salient stimuli will capture attention if they are not suppressed, consistent with stimulus-driven accounts. Additionally, this model predicts that salient stimuli can be successfully ignored under conditions that promote top-down control of attention, consistent with goal-driven accounts.

One line of support for the signal suppression hypothesis has come from studies of eye movements. Gaspelin, Leonard, and Luck (2017) had participants perform an additional singleton paradigm that was adapted for eye-tracking. The destinations of first saccades were used to evaluate whether a salient distractor captured overt attention. In a control experiment, singleton detection mode was encouraged by using a target that was a shape singleton. The results showed that first saccades were directed to a color-singleton distractor *above* the baseline levels of nonsingleton distractors (an *oculomotor capture effect*), indicating that capture would

[1] Although it is widely agreed that homogenous displays with salient targets encourage capture, there has been some recent debate as to why this is the case (e.g., see Theeuwes, 2022; Gaspelin, Egeth, et al., 2023; Liesefeld & Müller, 2023).

occur when the singleton was task relevant. A second experiment adapted the task to encourage feature search by using a target that appeared amongst heterogeneous distractors. The results showed that first saccades were directed to singleton distractors *below* baseline levels (an *oculomotor suppression effect*), indicating that participants can suppress salient distractors that are task irrelevant to prevent capture (see also Bansal et al., 2021; Gaspelin et al., 2019; Gaspelin & Luck, 2018b; Hamblin-Frohman et al., 2022; Stilwell et al., 2023). Additional support for the signal suppression hypothesis has come from other methodologies, such as probe techniques (Gaspelin et al., 2015; Chang & Egeth, 2019; Ma & Abrams, 2023b) and ERP studies (see review by Gaspelin, Lamy, et al., 2023) which also indicate that salient distractors can be suppressed to prevent attentional capture.

More recent evidence has suggested that the ability to suppress salient distractors results from learning regularities associated with the distractors. Observers can learn to suppress salient distractors based upon their expected features (Gaspelin & Luck, 2018b; Lien et al., 2021; Ramgir & Lamy, 2023; Vatterott & Vecera, 2012; Anderson & Kim, 2020), their expected locations (Theeuwes et al., 2022; Wang & Theeuwes, 2018a, 2018b), and a general expectation of their presence (Ma & Abrams, 2022, 2023a; Won et al., 2019; Won & Geng, 2020). For example, Vatterott and Vecera (2012) had participants perform a task similar to those described above. Critically, the singleton distractor changed to a new color in each block. In the first half of each block, the singleton distractor in the new color produced a singleton-presence cost, indicating capture. In the second half of each block, this capture effect was eliminated, suggesting it was ignored. This *learned distractor rejection* is consistent with the idea that participants learned to suppress the singleton based upon its specific color and that when this color changed it took participants time to learn to suppress the new color (see also Stilwell &

Vecera, 2019, 2020; Savelson & Leber, in press). Learned distractor rejection seems to largely result from implicit learning, as participants cannot suppress singletons via explicit cueing of the upcoming distractor color (Cunningham & Egeth, 2016; Gaspelin et al., 2019) and have a limited awareness of when attentional capture occurs (Adams & Gaspelin, 2020, 2021).[2]

In sum, there is now extensive evidence that observers can suppress distractors, and this seems to result, in large part, from implicit learning. Recent formulations of the signal suppression hypothesis have therefore proposed that inhibitory gain modulations can be used to ignore salient distractors (Luck et al., 2021).

Can Other Kinds of Salient Stimuli Be Suppressed?

Most of the current evidence of distractor suppression has come exclusively from studies of a single type of salient stimuli: color singletons. This might reflect a broader bias in the attentional capture literature, in which color singletons are more commonly studied than other kinds of salient stimuli. As a result, it is unclear whether other kinds of salient stimuli can be suppressed like color singletons.

We broadly distinguish between two types of salient distractors. *Static distractors* are feature singletons that remain unchanged for the entirety of their exposure duration. This would include, for example, color singletons which are uniquely colored for the duration of the search display. It could also include other kinds of feature singletons that remain constant for the duration of a trial, such as size singletons that are uniquely sized compared to other objects in the search display. *Dynamic distractors*, on the other hand, are feature singletons that involve some kind of change over time. For example, a moving object in a field of non-moving objects (i.e., a

[2] To be fair, there seems to also be a role for explicit knowledge to influence inhibition of distractors (e.g., see Carlisle, 2023; Anderson & Mrkonja, 2021; Z. Zhang et al., 2019).

motion singleton) would be an example of a dynamic distractor. Similarly, objects that appear suddenly in a visual scene (called abrupt onsets) would also be a form of a dynamic distractor.

Some studies suggest that dynamic distractors may not be suppressed like static distractors (Adam et al., 2022; Folk & Remington, 2015; Franconeri & Simons, 2003; Gaspelin et al., 2016; Lamy & Egeth, 2003; Yantis & Jonides, 1984). For example, a recent study by Adams, Ruthruff, and Gaspelin (2022) directly evaluated whether abrupt onsets can be suppressed like color singletons. Participants performed an additional singleton paradigm adapted for eye tracking similar to Gaspelin et al. (2017). The salient distractor was either a color singleton or an abrupt onset (i.e., four dots that suddenly appeared around one distractor). Shifts of gaze to color singletons were suppressed, replicating previous studies. Interestingly, the results indicated that abrupt onsets captured attention. This finding suggests that dynamic distractors may be more difficult to suppress than static distractors; however, the conclusions that can be drawn are limited because this study did not evaluate other kinds of dynamic distractors such as motion singletons.

Other studies have further suggested that motion stimuli may also be difficult to suppress (Abrams & Christ, 2003, 2005; Al-Aidroos et al., 2010; Franconeri & Simons, 2003; but see Folk et al., 1994). For example, Franconeri and Simons (2003) had participants search arrays of letters for a target letter (e.g., U or H). A motion singleton was nonpredictive of the target location (i.e., it occurred at the target location on $1/n^{th}$ trials where n is the set size). On trials where the target happened to be a motion singleton, search slopes were flat, which would seem to indicate that motion singletons automatically attracted attention and eliminated the need for visual search. This led the authors to conclude that certain types of dynamic features will automatically capture attention because they require immediate action by the observer.

Although interesting, the results of previous studies of capture by motion stimuli are difficult to compare to studies of signal suppression, because many did not use methods that have been established to produce suppression effects. For example, many of these studies let the target sometime appear as a motion singleton, which may generally discourage suppression because it would sometimes result in suppression of the target (e.g., Abrams & Christ, 2003; Al-Aidroos et al., 2010; Franconeri & Simons, 2003). Similarly, other studies may have accidentally encouraged singleton detection mode by having a target that was a salient popout stimulus and this may have made the motion singleton difficult to ignore (Abrams & Christ, 2005; Pinto et al., 2006). Furthermore, most previous studies of motion distractors have evaluated attentional capture solely using RT-based effects, which make it challenging to evaluate whether a distractor stimulus was suppressed below baseline levels of other items in the display (e.g., see Gaspelin et al., 2015; 2017). In addition, RT-based capture effects also have other important limitations in that they can sometimes occur in the absence of actual capture (i.e., *filtering costs*; Becker, 2007; Folk & Remington, 1998) and they do not directly indicate the relative probability that the salient distractor attracted attention (Rigsby et al., 2023).

In sum, there is some evidence that dynamic distractors may be more difficult to ignore than other kinds of salient singletons. However, it is difficult to compare these results to studies of signal suppression because most previous studies have not used methods that are established to encourage suppression. The current study aims to bridge these gaps in knowledge by testing whether a wide variety of salient distractors (static and dynamic) can be suppressed.

Experiment 1

Participants performed an eye-tracking paradigm that has been commonly used to study signal suppression of color singletons (Figure 1A; Gaspelin et al., 2017). On each trial, participants searched for a target that was a specific shape (e.g., diamond) and reported the tilt of a line inside via buttonpress. Distractors were a set of heterogenous shapes meant to encourage feature search mode (Bacon & Egeth, 1994). Importantly, there were several types of salient distractors which were varied between subjects (Figure 1B). There were three types of static distractors (a *color singleton*, a *size singleton*, and a *fill singleton*) and three types of dynamic motion distractors (a *linear motion singleton*, *jitter singleton*, and a *rotation singleton*).

The key question was whether static and dynamic distractors would be suppressed. The signal suppression hypothesis generally predicts that salient distractors should be suppressed as participants gain experience with their anticipated feature values, yielding two potential results. First, if the salient distractor is suppressed below baseline levels, shifts of gaze should be less likely to be directed to the salient distractor than the average nonsalient distractor (Gaspelin et al., 2017). In what follows, these overall suppression effects collapsed across the experimental session will be referred to as *oculomotor suppression effects*. Second, there should also be evidence of *learned distractor rejection*: shifts of gaze to salient distractors should be reduced as

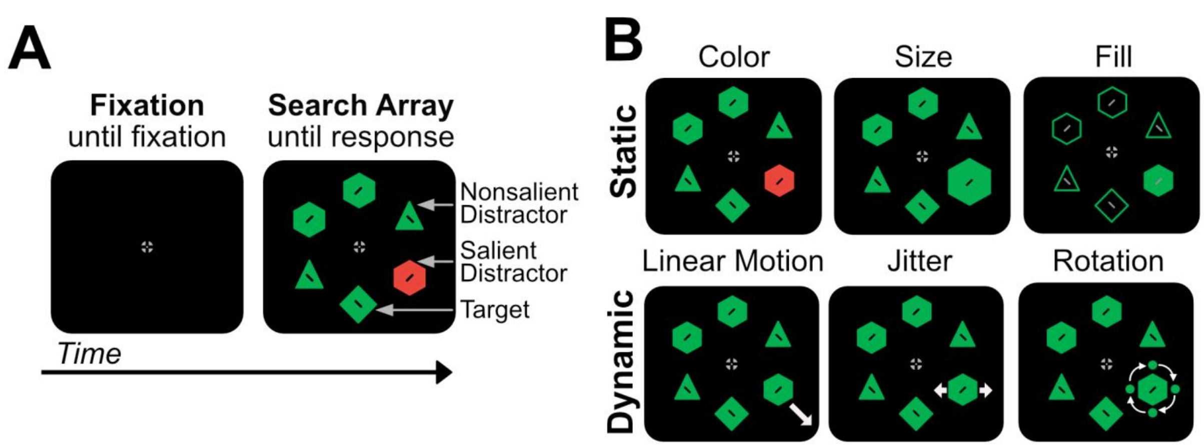

Figure 1. Task and stimuli for Experiment 1. (A) A trial progression in the experiment. (B) The different types of salient distractors. Static features included color, size, and fill singletons. Dynamic features included linear motion, jitter, and rotation.

participants are able to learn their expected features (Gaspelin & Luck, 2018a; Vatterott & Vecera, 2012).

Method

Participants. For each type of salient distractor**,** a sample of 24 participants was collected. This resulted in a total sample of 144 participants across the 6 distractor types. Participants were undergraduate students from State University of New York at Binghamton who volunteered for course credit. This sample size was established a priori based upon previous studies of oculomotor suppression. Assuming that the oculomotor suppression effect is comparable to previous studies (d_z = 1.63; Gaspelin et al., 2017, Experiments 2–3), a sample size of 24 participants per salient distractor should result in >.999 power to detect an oculomotor suppression effect.

All participants had normal color vision as well as normal or corrected-to-normal visual acuity. Two participants (one in the color singleton condition and one in the rotation singleton condition) were replaced due to a manual-response accuracy 3.5 standard deviations below the group mean (i.e., less than 80%). In the final sample of 144 participants, the mean age was 18.6 years (100 women, 43 men, and 1 nonbinary individual).

Apparatus. Stimuli were presented using PsychToolbox for MATLAB (Kleiner et al., 2007). An Asus VG248QG LED monitor presented stimuli at a viewing distance of 100 cm. A photosensor was used to measure the timing delay of the stimulus system (12 ms) and this delay was subtracted from all latency values in this paper. An SR Research Eye Link 1000+ desk-mounted eye tracker recorded gaze position from the right eye at 500 Hz. The Eye Link Toolbox was used to interface the stimulus-presentation system and eye-tracking system (Cornelissen et al., 2002).

Stimuli & Procedure. The basic task was based upon previous studies of oculomotor suppression (Gaspelin et al., 2017; see also Adams et al., 2022; Bansal et al., 2021; Gaspelin et al., 2017; Stilwell et al., 2023; Z. Zhang et al., 2019). Search displays contained six shapes arranged in a notional circle (see Figure 1A). Each shape was 4.5° from fixation, with distance calculated between the center of the search display and the center of each shape. Shapes consisted of diamonds (1.0° in diameter), hexagons (0.9° in diameter), and triangles (0.9° in base and height). The shapes were drawn in photometrically isoluminant colors: green (30.0 cd/m^2, x = .30, y = .63) and red (30.0 cd/m^2, x = .63, y = .33). Each shape contained a small black line (0.2° in length and 0.03° in thickness), tilted 45° to either the left or right. These lines were designed to be too small to be discriminated from central fixation, necessitating that the participants directly fixated the target to identify the line orientation. The fixation cross was a symbol that was empirically optimized to allow participants to hold central fixation until the search array appeared (Thaler et al., 2013).

Each search display contained a target shape that was a diamond. The remaining five distractors were hexagons and triangles, which were generated randomly with the exception that two distractors were one shape, and three distractors were the other shape. These heterogeneous distractor shapes, which were similar to the target, were intended to keep the target shape from popping out and to thereby discourage use of singleton detection mode (Bacon & Egeth, 1994; Gaspelin et al., 2017; Leber & Egeth, 2006). The target color was held constant for the entire experimental session and was counterbalanced across participants. The target location was randomly selected on each trial. One location was randomly selected as a salient distractor, with the exception that it was never the target location. Participants were tasked with finding the target shape as quickly as possible, then making a speeded buttonpress to indicate the orientation of the line inside (left- or right-tilted) on a gamepad (using the left or right trigger buttons, respectively).

The salient distractor types are depicted in Figure 1B. First, there were three types of *static distractors*. A *color singleton* was a distractor that was drawn in a unique color from the other items (e.g., red when the target color was green). A *size singleton* was a shape that was larger than other items (2.7° in diameter for hexagons; 2.7° in base and height for triangles). A *fill singleton* that was the only filled item in a field of framed search items (0.1° in thickness). In the fill distractor condition, the to-be-reported lines were gray to make them visible on a black background (30.0 cd/m^2, x = .31, y = .32). There were also three types of *dynamic distractors*. A *linear motion singleton* was a distractor that moved outward from the center of the search array at a rate of 15.8° per second. A *jitter singleton* was a distractor that moved back and forth in place (6 Hz at 0.3° to both the left and right of the original location). A *rotation singleton* was a distractor that was encircled by four rotating dots (0.2° by 0.2° in diameter with 31.6° of clockwise rotation per second). All dynamic distractors remained in motion from the onset of the search array until a participant response or response timeout. The type of salient distractor remained constant for the entirety of the experiment, appeared on every trial, and never appeared at the target location. All of these design choices were meant to maximally encourage suppression of the salient distractor.

Each trial began with a fixation cross, and participants were required to maintain gaze position within 1.5° of the fixation cross for 500 ms to initiate each trial. Once this fixation criterion was met, the search array then appeared until a manual response was made, or until 2000 ms had elapsed (the timeout period). Participants completed 10 blocks of 60 trials and the first block was a practice block, resulting in 540 trials per participant for all analyses except the learning effects (which included the practice block). If participants took more than 2,000 ms to respond, they were presented with a 500-ms timeout display (“Too Slow”). If an incorrect response was made, a 200 Hz tone sounded for 500 ms. At the end of each block, participants were provided with feedback on mean response time (RT) and accuracy. These block breaks also warned participants whose accuracy fell below 90%.

Data Analysis. Saccades were analyzed using techniques similar to those of previous studies of oculomotor capture (Adams et al., 2022; Adams & Gaspelin, 2021; Gaspelin et al., 2017; Gaspelin & Luck, 2018b; Leonard & Luck, 2011; Talcott & Gaspelin, 2020). Saccades were defined by a minimal eye velocity threshold of 30° per second and a minimum acceleration threshold of 9500°/sec^2. To identify the destination of the first saccade, an annulus was defined around the search array, with an inner radius of 1.5° from fixation and an outer radius of 7.5° from fixation. The first saccade on each trial was then defined as the first eye movement landing within the annulus. The nearest search item was then selected as the first saccade destination. This effectively creates wedge-shaped interest areas around each search item (Leonard & Luck, 2011). Saccadic latency was measured as the start time of the first saccade that landed within the annulus.

Trials with RTs less than 200 ms or greater than 2,000 ms; 0.9% of trials) were excluded from all analyses, as well as trials in which participants did not move their eyes from central fixation (0.9% of trials) and trials with abnormal saccade latencies (less than 50 ms or greater than 1000 ms, comprising 2.6% of trials). Trials with incorrect responses (3.5%) were omitted from RT analyses. In total, 6.0% of trials were excluded. For analyses of variance (ANOVAs), Greenhouse-Geisser corrected *p* values are reported to avoid issues of sphericity.

Results

Manual Responses

Table 1 depicts manual RT and error rates for each distractor type. We had no a priori hypotheses about manual RT or error rates because salient distractors were present on every trial to maximally encourage suppression. Previous evidence has shown that, as salient distractors become more probable, they are also more likely to be suppressed (Won et al., 2019; Won & Geng, 2020). This design choice, however, made us unable to evaluate singleton presence costs. Overt attentional capture is therefore directly evaluated by the destination of first saccades in the next section.

As shown in Table 1, manual RTs were generally slower with dynamic distractors present (998 ms) than with static distractors present (915 ms), $t(142) = 4.26$, $p < .001$, $d = 0.71$, suggesting that dynamic distractors were more difficult to ignore than static distractors and that this resulted in interference while searching for the target. Manual error rates were generally quite low, and did not reliably differ between dynamic distractors (2.7%) and static distractors (2.8%), $t(142) = 0.29$, $p = .776$, $d = 0.05$, $BF_{01} = 5.38$.

Table 1

Manual RT and Error Rate by Singleton Type for Experiment 1.

Experiment	RT	Error Rate	*Experiment*	RT	Error Rate
Color	901	2.3%	Linear Motion	974	2.6%
Size	931	2.9%	Jitter	1052	3.2%
Fill	913	3.1%	Rotation	966	2.3%
Static	915	2.8%	Dynamic	998	2.7%

Note. Pooled estimates were created by averaging across all distractor types within a given category.

First Saccades: Oculomotor Suppression Effects

Figure 2A depicts the percentage of first eye movements to each search item (target, nonsalient distractor, salient distractor) for each distractor type. These percentages were pooled across the entire experimental session, excluding the practice block. The percentage of first eye movements to nonsalient distractors was divided by four to give a per item estimate to allow a direct comparison with the target and salient distractor. With static distractors (color, size, fill), first saccades were *less* likely to be directed to the salient distractor than to the average nonsalient distractor. With dynamic distractors (linear motion, jitter, rotation), salient distractors were equally likely to be fixated as nonsalient distractors.

To assess whether each type of distractor was suppressed, we calculated oculomotor capture effects (Figure 2B). This is a difference score subtracting the percentage of first saccades to the average nonsalient distractor from those to the salient distractor. A positive score indicates capture (i.e., gaze was biased toward the salient distractor above baseline), whereas a negative score indicates suppression (i.e., gaze was biased away from the salient distractor below baseline). As can be seen, static distractors elicited oculomotor suppression effects whereas dynamic distractors did not. Preplanned one-sample *t* tests were conducted to evaluate each salient distractor type. All static distractors produced a significant negative score, indicating oculomotor suppression: color singletons [$t(23) = 18.21$, $p < .001$, $d = 3.72$], size singletons [$t(23) = 9.06$, $p < .001$, $d = 1.85$], and fill singletons [$t(23) = 10.16$, $p < .001$, $d = 2.07$]. Dynamic distractors, however, produced nonsignificant scores, indicating that there was no overall suppression nor capture: linear motion [$t(23) = 0.41$, $p = .685$, $d = 0.08$, $BF_{01} = 4.31$], jitter [$t(23) = 0.99$, $p = .333$, $d = 0.20$, $BF_{01} = 3.00$], and rotation [$t(23) = 1.18$, $p = .249$, $d = 0.21$, $BF_{01} = 2.50$].

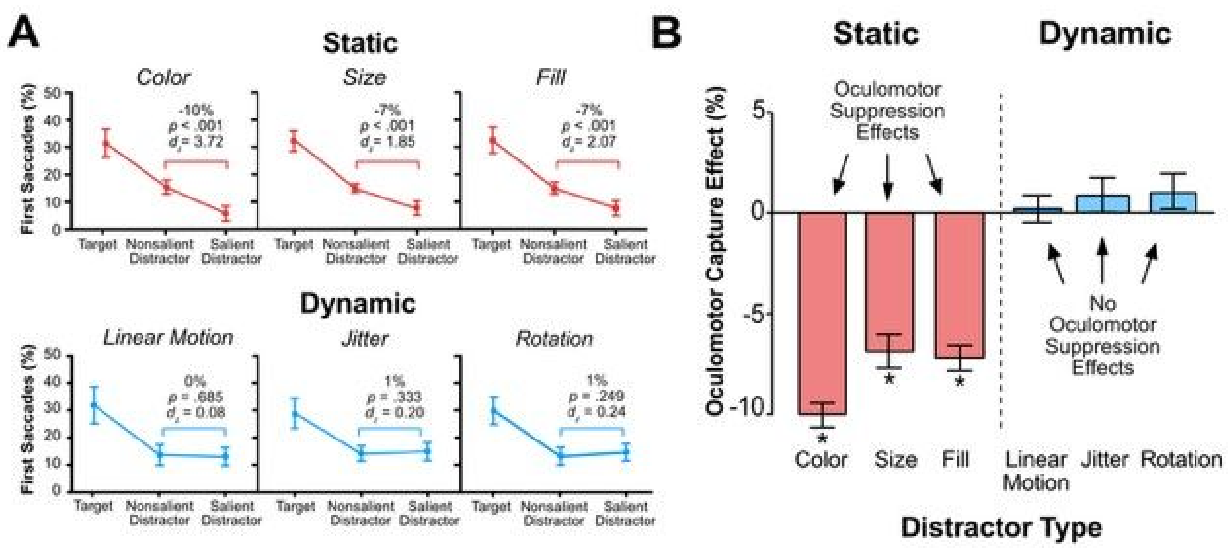

Figure 2. First saccade results in Experiment 1. (A) Percentage of first saccades to each search item by salient distractor type. Error bars indicate within-subject 95% confidence intervals (Cousineau & Morey, 2006). (B) Oculomotor capture effects by salient distractor type. Error bars indicate between-subject standard error of the mean. Asterisks indicate effects that reliably differed from zero (p < .001).

To assess whether static distractors were more strongly suppressed than dynamic distractors, we pooled the data across each of the three types of static and dynamic distractors to improve statistical power by increasing the observations from N = 24 to N = 72. Oculomotor suppression effects were indeed significantly stronger for static distractors (-8%) than dynamic distractors (-1%), $t(142) = 13.74$, $p < .001$, $d = 2.29$. In the supplemental materials, we also compared oculomotor suppression effects for each individual type of salient distractor to one another using between-subject t tests. To summarize here, each type of static distractor (color, size, fill) had a significantly larger oculomotor suppression effect than each type of dynamic distractor (linear motion, rotation, jitter; p's < .001), providing additional evidence that static distractors were easier to ignore than dynamic distractors. Also, color singletons produced larger oculomotor suppression effects than any other static distractor, fill singletons, $t(46) = 2.78$, p =

.008, d = 0.80, or size singletons, t(46) = 2.72, p = .009, d = 0.79, suggesting that they were the easiest stimulus to ignore.

In the supplemental materials, we also evaluated target enhancement effects, which are difference scores between the percentage of first saccades to the target and the percentage of first saccades to the average nonsalient distractor. To summarize here, we found that target enhancement effects occurred for each distractor type (p's < .001). Target enhancement effects did not differ for static versus dynamic distractors, t(142) = 0.58, p = .561, d = 0.10, indicating that suppression did not necessarily enhance target processing, per se.

First Saccades*: *Learned Distractor Rejection

We also evaluated learned distractor rejection effects that would result in a reduction of attentional allocation to the salient distractors as the experiment progressed. Previous studies have shown that participants can learn to suppress color singletons quite quickly (e.g., within 5–25 trials; Gaspelin et al., 2019; Gaspelin & Luck, 2018b; Savelson & Leber, in press; Ramgir & Lamy, 2023; Vatterott & Vecera, 2012). For this reason, we also included practice blocks in this specific analysis to ensure that we were able to observe learning effects in their entirety. Figure 3A depicts oculomotor capture effects—the difference score between salient distractors and nonsalient distractors calculated in the previous section—as a function of block for each salient distractor type (linear motion, jitter, rotation, color, size, fill). For most of the salient distractors, there was a clear reduction in the oculomotor capture effect across the session, with the largest reduction occurring within the first few blocks. Dividing the data into tenths (i.e., ten blocks) will naturally make the data noisier. Figure 3B pools across dynamic and static distractors to improve statistical power by increasing the number of participants for each data point from N = 24 to N = 72.

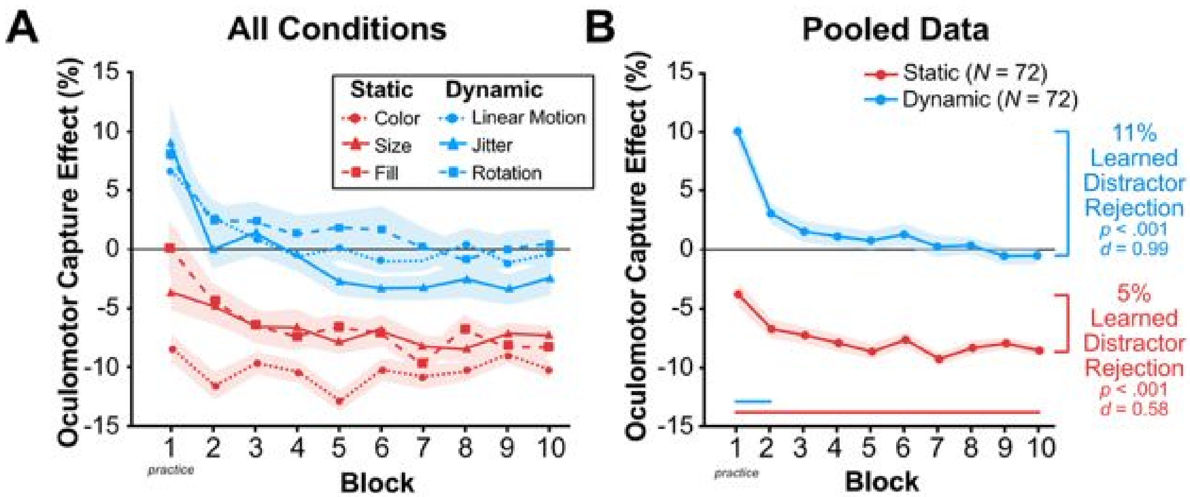

Figure 3. Learned distractor rejection for Experiment 1. (A) Oculomotor capture effects by block for each condition of salient distractor (B) Oculomotor capture effects by block pooled across dynamic and static distractors. Shaded regions indicate between-subject standard error of the mean. The lines just above the x-axis indicate whether oculomotor capture effects reliably differed from zero, as indicated by one-sample *t* tests. ($p < .05$).

One-sample *t* tests were used to compare oculomotor capture effects for each block to zero for both dynamic and static distractors. These *t* tests were corrected for multiple comparisons using a false discovery rate (Benjamini & Yekutieli, 2001). Significant effects are indicated in Figure 3B using a line above the x-axis. With dynamic distractors, there was a significant oculomotor capture effect in the first two blocks (*p's* < .001), indicating that the distractor initially attracted attention. These capture effects were eliminated for the remaining blocks (*p*'s > .999). With static distractors, there was a significant oculomotor suppression effect in every block (*p*'s < .005), indicating that the shifts of gaze were preferentially directed away from the salient distractors.

The key question is whether attentional allocation to the salient distractor was reduced across the experimental session. To evaluate this, learned distractor rejection effects were calculated as a difference score between oculomotor capture effects in the first block (block 1) and last block (block 10). The magnitude of this difference score reflects reduced attentional orienting to the salient distractor across the experiment. Learned distractor rejection effects were reliably greater than zero percent for both dynamic distractors (11%), $t(71) = 8.41$, $p < .001$, $d = 0.99$, and static distractors (5%), $t(71) = 4.93$, $p < .001$, $d = 0.58$. Thus, both dynamic and static salient distractors showed evidence of learned distractor rejection effects.

In the supplement, we evaluated the significance of learned distractor rejection effects for each individual type of distractor (color, fill, size, jitter, rotation, and linear motion). To summarize here, learned distractor rejection effects were significant for all types of distractors (p's < .05), except color singletons ($p = .120$). The main reason was that distractor suppression had already occurred for color singletons within the first block. This is consistent with previous studies which have shown that oculomotor suppression of color singletons may occur within 5 trials (Gaspelin et al., 2019; Gaspelin & Luck, 2018b; Savelson & Leber, in press).

Suppression Effects by Saccadic Latency

Some previous studies have suggested that top-down control may be limited for fast saccades (van Zoest et al., 2004; see also Anderson & Mrkonja, 2021). However, prior studies of signal suppression have shown that even the fastest saccades can successfully suppress color singletons (Gaspelin et al., 2017; Stilwell et al., 2023; H. Zhang et al., under revision). We therefore conducted an exploratory analysis that compared oculomotor capture effects at each potential quartile of saccadic latency (fastest, fast, slow, and slowest) to zero. We did this separately for dynamic and static singletons (see Table 2).

A negative value indicates suppression, whereas a positive value indicates capture. Static singletons were suppressed at all quartiles (p's < .001) similar to previous studies of color singletons (Gaspelin et al., 2017). That is, even the fastest quartile (mean latency: 150 ms), there was an oculomotor suppression effect for static distractors (-4.6%), $t(71) = 6.79$, $p < .001$, $d =$

Table 2

Mean Saccadic Latency (ms) and First-Saccade Suppression Effects by Saccadic Latency Quartile

	Fast		Fast		Slow		Slowest	
	Mean Latency (ms)	Mean Capture Effect	Mean Latency (ms)	Mean Capture Effect	Mean Latency (ms)	Mean Capture Effect	Mean Latency (ms)	Mean Capture Effect
Experiment 1								
Static	150	-4.6%*	182	-8.1%*	212	-10.0%*	286	-9.6%*
Dynamic	186	1.5%†	222	3.6%*	253	1.5%†	322	-3.7%*
Experiment 2								
Combined	197	-8.2%*	236	-9.3%*	270	-10.1%*	350	-9.4%*

Note. Capture effects were calculated as the percentage of saccades landing on the singleton distractor minus the percentage of saccades landing on the average nonsingleton distractor. Asterisks indicate statistically significant effects in a one-sample *t* test. (*p's* < .001); dagger symbols indicate marginally significant effects (*p* < .10).

0.80. This was not the case for dynamic distractors, which did not produce oculomotor suppression effects until the slowest quartile (oculomotor suppression: -3.7%; mean latency: 322 ms), $t(71) = 5.55$, $p < .001$, $d = 0.65$. Faster quartiles revealed small oculomotor capture effects that trended near significance. In sum, the results suggest that suppression of static distractors occurred rapidly, whereas top-down control to ignore dynamic distractors may have only occurred at a relatively delayed onset, which is consistent with some previous studies (e.g., see van Zoest et al., 2004).

Discussion

Experiment 1 revealed some important similarities and differences in how static and dynamic distractors are ignored. In terms of overall oculomotor suppression effects, static distractors were suppressed below baseline levels, whereas dynamic distractors were not. These oculomotor suppression effects occurred rapidly for static distractors (within 150 ms) but only occurred in the slowest quartiles for dynamic distractors. In terms of learned distractor rejection effects, both dynamic and static distractors showed evidence that attentional orienting to salient distractors was reduced across the session. Altogether, these results suggest that a learned suppression process is applied to both kinds of salient distractors, but this process is generally slower to develop and is ultimately less effective for dynamic distractors than static distractors. We will explore this pattern further in the next experiment.

Experiment 2

Experiment 1 demonstrated that dynamic distractors were not suppressed below baseline levels like static distractors. A possible explanation for this is that dynamic features may be more difficult to ignore than static features. According to the suppression model proposed by Luck et al. (2021; see Figure 2), feature-based gain controls can be used to reduce the attentional priority of salient distractors. That is, inhibition occurs relatively early in visual processing via gain modulations of specific features. This type of gain modulation is proposed occur just after preattentive feature maps have been generated and just before a global attentional priority map is generated. This type of feature-based inhibition may not be applied to motion. However, it has been well-established that this type of inhibitory process can be applied to static features. It is therefore possible that adding a static feature to the dynamic salient distractor would make it suppressible by enabling static feature-based gain controls that that proactively reduce its attentional priority. Consistent with this prediction, previous research has indicated that moving items and other dynamic stimuli such as abrupt onsets attract attention to a lesser degree when presented in task-irrelevant colors (Adams et al., 2022, Experiment 4; Saenz et al., 2002).

Experiment 2 therefore tested whether adding a static feature to a dynamic salient distractor would enable suppression. As shown in Figure 4, a jitter motion singleton was combined with a color singleton. The key question was whether the salient distractor would now be suppressible because gain modulations on the color dimension could be used to reduce the salient distractor's attentional priority.

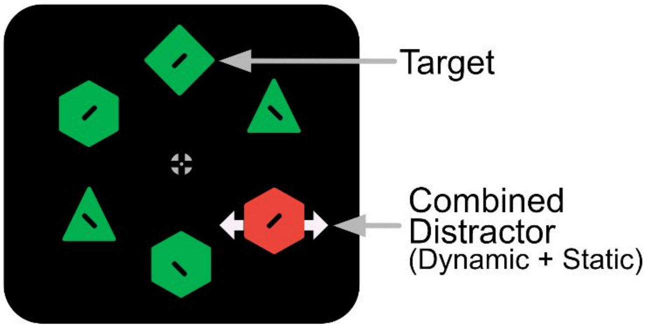

Figure 4. Search display from Experiment 2. The task was identical to Experiment 1 except that the salient distractor had both dynamic and static features. Specifically, it was a combination of a color singleton and jitter singleton.

Method

All procedures were identical to Experiment 1, except for the following changes.

A new sample of 24 participants (7 men, 17 women) was collected. One participant was replaced for manual error rate more than 3.5 standard deviations above the group mean, and one participant was replaced for making eye movements away from central fixation on fewer than 75% of trials. This experiment used a *combined distractor* (Figure 4) that combined the jitter motion singleton and color singleton from Experiment 1. We chose these specific features because testing all potential combinations of dynamic and static singletons would have yielded 9 additional experiments. We therefore chose a representative motion singleton from Experiment 1 (jitter). We chose color singletons as the static feature because they have been established to be highly suppressible by prior studies (Adams et al., 2022; Gaspelin et al., 2017; Stilwell et al., 2023). The color of the target and color singleton were held constant for the entirety of the experiment (as in Experiment 1).

The same trial exclusion criteria from Experiment 1 were used. Trials with RT less than 200 ms or greater than 2,000 ms (0.5% of trials) were excluded from all analyses, as well as trials in which participants did not move their eyes from central fixation (2.3% of trials) and trials with abnormal saccade latencies (less than 50 ms or greater than 1000 ms, comprising 2.3%

of trials). Trials with incorrect responses (2.3%) were omitted from RT analyses. In total, 4.5% of trials were excluded.

Results

Manual Responses

We had no a priori predictions about manual responses because the salient distractor was present on every trial to maximize the incentive to suppress the distractor (as in Experiment 1). Mean RT was 964 ms and error rates were relatively low (1.8%).

First Saccades: Oculomotor Suppression Effects

As can be seen in Figure 5A, first saccades were *less* likely to be directed to the combined distractor than to the average nonsalient distractor. This can be more clearly seen in Figure 5B. Combined distractors produced a reliable oculomotor suppression effect (9%), indicating that they were suppressed, $t(23) = 15.13$, $p < .001$, $d = 3.09$. We also compared

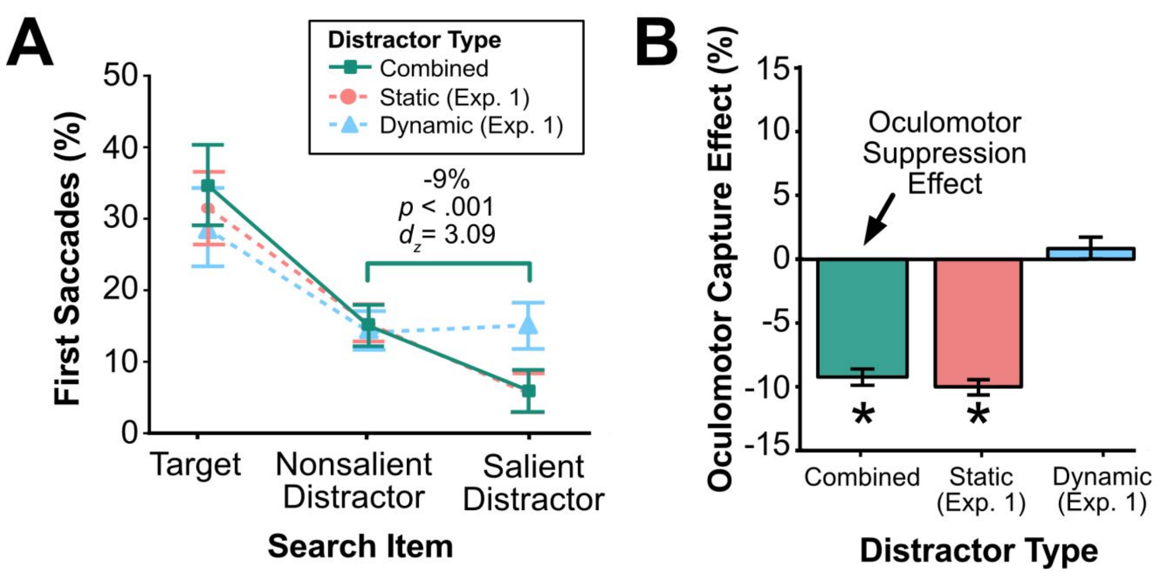

Figure 5. Results from the combined distractor in Experiment 2 (green) compared to the respective conditions from Experiment 1 (red = static; blue = dynamic). (A) Percentage of first fixations by search item for each salient distractor type. (B) Oculomotor capture effects for each distractor type.

oculomotor suppression of combined distractors with their respective conditions from Experiment 1 (i.e., color singleton and jitter singleton) using between-subject *t* tests. Oculomotor suppression effects were significantly larger for the combined distractors (9%) than the jitter singletons from Experiment 1 (-1%), $t(46) = 8.99$, $p < .001$, $d = 2.60$; but did not differ from the color singletons from Experiment 1 (10%), $t(46) = 0.61$, $p = .544$, $d = 0.18$, $BF_{01} = 2.99$. Altogether, these results clearly suggest that combined distractors were suppressed below baseline, similar to the color singletons in Experiment 1.

First Saccades: Learned Distractor Rejection

We had no a priori predictions about how learned distractor rejection effects would be influenced by combining dynamic and static salient features. In the first (practice) block, the combined distractors were not suppressed nor did they capture attention (oculomotor capture effect: 0.1%), $t(23) = 0.34$, $p = .738$, $d = 0.07$. In the following blocks, however, the combined distractor was suppressed below baseline levels (oculomotor capture effects: -6.5% to -10.3%; *p's* < .001). Learned distractor rejection effects were again calculated as difference scores between oculomotor capture effects in the first block (block 1) and last block (block 10). Learned distractor rejection effects for combined distractors were significantly greater than zero (9%), $t(23) = 4.26$, $p < .001$, $d = 0.87$. Altogether, these results suggest that combined distractors also showed evidence of learned distractor rejection.

Suppression Effects by Saccadic Latency

We again conducted an exploratory analysis that compared oculomotor capture effects at each potential quartile of saccadic latency to zero (see Table 2). Combined distractors were suppressed at each quartile of saccadic latency (*p*'s < .001). Critically, in the fastest quartile (mean latency: ~186 ms), there was a robust oculomotor suppression effect (-8.2%), $t(71) = 9.42$,

$p < .001$, $d = 1.94$. This suggests that, like static singletons in Experiment 1, oculomotor suppression effects occurred even for the fastest saccades (see also Gaspelin et al., 2017; Stilwell et al., 2023).

Discussion

Experiment 2 evaluated why dynamic motion distractors were difficult to suppress in Experiment 1. Specifically, a static and dynamic feature were combined into a single distractor to test whether adding a suppressible feature would enable suppression of a dynamic distractor. The results demonstrated that the combined distractor was ignored just as static distractors were in Experiment 1. This result is broadly consistent with the notion that feature-specific gain controls can be used to inhibit static features but not dynamic features.

General Discussion

There has been a longstanding debate about whether salient distractors can capture attention. Much recent evidence has supported a possible reconciliation whereby salient stimuli can be suppressed to prevent attentional capture (see reviews by Gaspelin & Luck, 2018c; Luck et al., 2021; Theeuwes et al., 2022). However, this evidence has come almost exclusively from studies of color singletons, making it unclear whether other salient distractors can also be suppressed. The current study aimed to test the generalizability of distractor suppression by evaluating whether a variety of static and dynamic salient distractors can be suppressed to prevent capture.

Experiment 1 used an additional singleton paradigm adapted for eye tracking that has previously produced strong evidence of suppression of color singletons (Gaspelin et al., 2017; see also Adams et al., 2022; Gaspelin et al., 2019; Gaspelin & Luck, 2018b; Stilwell et al., 2023). Participants searched for a target defined by shape and color amongst heterogenous distractors while attempting to ignore a salient distractor. Various types of salient distractors were tested that were either static singletons (e.g., color, size, or fill) or dynamic singletons (e.g., linear motion, jitter, rotation). Suppression was evaluated via (a) oculomotor suppression effects effects that were pooled across the entire experimental session and (b) learned distractor rejection effects that showed reduced attentional allocation to the salient distractor across the session. The oculomotor suppression effects results showed that static distractors were suppressed below baseline levels, whereas dynamic distractors were not. The learned distractor rejection effects, however, revealed that attentional allocation to all types of salient distractors was reduced as the experiment progressed. Altogether, the results suggest that a learned ignoring process was applied to all kinds of salient distractors; however, this learned ignoring was less effective for dynamic distractors than static distractors.

Experiment 2 explored why dynamic distractors were difficult to ignore in Experiment 1. A static and dynamic feature were combined into a single distractor. If lack of suppression in Experiment 1 was due to the high salience of motion, then this new combined singleton should also be difficult to ignore because adding a static salient feature should not reduce the salience of the dynamic motion. Alternatively, if it is difficult to suppress a dynamic distractor because it is difficult to direct a suppressive mechanism to an object that is changing, adding a suppressible static feature should make the distractor easier to ignore because suppression should be applicable to the static feature. The latter was clearly observed: Combined distractors were suppressed much easier than the dynamic salient distractors from Experiment 1.

The current findings have broad implications for theories of attentional capture. First, the current results are inconsistent with purely stimulus-driven models of attentional capture. Recent formulations of these models have suggested there is no feature-based suppressive mechanism and propose that salient distractors can only be suppressed based upon knowledge of their upcoming locations (see Theeuwes in Luck et al., 2021; Theeuwes, 2022). The current study challenges this account by showing that a variety of salient features failed to capture attention, even though their spatial locations were unpredictable. Thus, stimulus-driven models need to be updated to account for top-down inhibitory control, as was suggested in Luck et al. (2021).

The current results are consistent with models proposing that top-down control can be used to prevent distraction (e.g., Folk et al., 1992; Gaspelin & Luck, 2018c). However, it seems that top-down control is imperfect because many of the dynamic distractors initially captured attention. The current results are perhaps most consistent with a version of the signal suppression hypothesis with an added caveat that suppressive mechanisms are difficult to apply to dynamic distractors. These results could also be consistent with a contingent capture model whereby top-down control is not immediately implemented in an experimental session. Several studies have now shown that it is likely that both feature enhancement and suppression simultaneously guide attention in attentional capture tasks (Chang & Egeth, 2019; Hamblin-Frohman et al., 2022). If true, this would suggest that both accounts have merit.

These results provide additional evidence of learned distractor rejection, whereby participants learn to ignore distractor features and locations that repeat across trials (e.g., Anderson & Kim, 2020; Gaspelin & Luck, 2018b; Ramgir & Lamy, 2023; Vatterott & Vecera, 2012; Wang & Theeuwes, 2018a). Interestingly, even passive viewing of displays with salient distractors is enough to reduce capture by salient items under certain conditions (Won & Geng, 2020). Similar findings have also been obtained with dynamic distractors. For example, some studies have reported decreases in capture by abrupt onsets after they are repeatedly presented. Turatto et al. (2018) demonstrated such a decrease when participants were tasked with reporting the orientation of a line inside of a uniquely colored circle and ignoring a nonpredictive abrupt-onset cue. The results demonstrated not only that abrupt onsets captured attention less across the experiment, as evidenced by a decrease in distractor presence costs, but that this learning effect remained robust even in follow-up assessments several days later. In a recent study, we used a paradigm that was very similar to the current study to compare suppression of color singletons and abrupt onsets (Adams et al., 2022). Interestingly, we found that abrupt onsets were (a) also more difficult to suppress than color singletons, and (b) that learned distractor rejection effects often occurred for abrupt onsets (e.g., see Figure 3). Altogether, these findings seem to indicate that learned distractor rejection is a robust process that applies to many kinds of salient features.

More broadly, there is a question of how learned distractor rejection develops. One potential mechanism for learned distractor rejection is that observers learn to suppress the feature values associated with repeatedly presented distractors. This would be broadly consistent with what is proposed by Luck et al. (2022; Figure 2) in their recent paper outlining a comprehensive model of attentional capture, in which implicit learning and explicit goals can influence feature-based gain control settings to either boost or down-weight certain feature values. Another possibility is that observers learn to habituate to the feature values associated with repeatedly presented distractors (Turatto et al., 2018; Turatto & Pascucci, 2016; Turatto & Valsecchi, 2023). To distinguish between these possibilities, the mechanisms underlying learned distractor rejection still need to be better understood. A passive habituation account would seem to struggle to explain why static features are actively suppressed below baseline levels (Chang & Egeth, 2019; Hamblin-Frohman et al., 2022) and why salient distractors elicit the P_D ERP component when ignored (Gaspelin, Lamy, et al., 2023).

Experiment 2 suggested that adding a suppressible feature to a dynamic salient distractor enabled it to be suppressed just like a static singleton. In a previous study, we found a similar pattern with abrupt onsets: abrupt onsets were difficult to suppress in an oculomotor capture task. When the abrupt onsets were combined with color singletons, they were suppressed at the same level as color singletons (Adams et al., 2022, Experiment 4). This pattern is somewhat ironic because it suggests that improving the overall salience of the distractor—by adding an additional salient feature—may make it more likely to be ignored. This finding is also broadly consistent with recent studies showing that improving the salience of a distractor seems to increase suppression (Drisdelle & Eimer, 2023; Gaspar & McDonald, 2014; Stilwell et al., 2023).

In conclusion, the current findings indicate that a learned suppressive process is applied to a wide variety of salient stimuli, which is broadly consistent with the signal suppression hypothesis. However, the current findings also suggest a clear limitation on signal suppression: dynamic distractors are more difficult to ignore than static distractors.

Open Practices Statement

All stimulus programs, data analysis programs, and data are publicly available at https://osf.io/dmysp/. None of the experiments were preregistered.

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Oculomotor Suppression Across Individual Conditions

In the current section, we compare oculomotor suppression effects from Experiment 1 as a function of salient distractor type (color, size, fill, linear, jitter, rotation) using independent-samples *t* tests. As can be seen in Supplemental Table 1, this analysis revealed reliably larger suppression effects for static distractors (color, size, fill) than dynamic distractors (linear motion, jitter, and rotation). This pattern was similar regardless of which static and dynamic distractors were compared, consistent with the hypothesis that dynamic distractors capture attention to a greater degree than static distractors.

We also assessed whether certain types of static and dynamic distractors were suppressed more reliably than others. Interestingly, color singletons produced larger suppression effects than the other static distractors, fill singletons [$t(46) = 2.78$, $p = .008$, $d = 0.80$] or size singletons [$t(46) = 2.72$, $p = .009$, $d = 0.79$], suggesting that they were the easiest static stimulus to ignore. There were no reliable differences between suppression effects for fill singletons and size singletons, $t(46) = 0.11$, $p = .913$, $d = 0.03$. Furthermore, there were no reliable differences between suppression effects for linear motion distractors and the other dynamic distractors, jitter [$t(46) = 0.60$, $p = .552$, $d = 0.17$] or rotation [$t(46) = 0.75$, $p = .456$, $d = 0.22$]. Finally, there were no reliable differences between suppression effects for jitter and rotation distractors, $t(46) = 0.13$, $p = .901$, $d = 0.04$.

Supplemental Table 1

Pairwise Comparisons of Net Suppression Effects Between Static and Dynamic Distractors

	Linear Motion			Jitter			Rotation		
	t	*p*	*d*	*t*	*p*	*d*	*t*	*p*	*d*
Color	12.09	< .001	3.49	9.77	< .001	2.82	10.04	< .001	2.90
Size	7.33	< .001	2.12	6.53	< .001	1.89	6.73	< .001	1.94
Fill	7.89	< .001	2.28	6.88	< .001	1.99	7.09	< .001	2.05

Target Enhancement Effects

We also calculated *target enhancement effects*, difference scores between the percentage of first saccades to the target and average nonsalient distractor, for each salient distractor type in Experiment 1. Preplanned independent-sample *t* tests were then used to evaluate the significance of target enhancement effects between individual static and dynamic distractors. As can be seen in Supplemental Table 2, this analysis revealed no reliable differences in target enhancement effects between static distractors (color, size, fill) and dynamic distractors (linear motion, jitter, and rotation). There were no differences regardless of which static and dynamic distractors were compared, consistent with the hypothesis that target enhancement effects were similar for static and dynamic distractors. Furthermore, there were no reliable differences in target enhancement effects between individual static or dynamic distractors. Color singletons produced target enhancement effects that were similar in magnitude to the other static distractors, fill singletons [$t(46) = 0.39$, $p = .697$, $d = 0.11$] and size singletons [$t(46) = 0.31$, $p = .758$, $d = 0.09$]. Target enhancement effects were also similar for size singletons and fill singletons, $t(46) = 0.14$, $p = .892$, $d = 0.04$. Finally, there were no reliable differences between target enhancement effects for linear motion distractors and the other dynamic distractors, jitter [$t(46) = 0.43$, $p = .668$, $d = 0.13$] or rotation [$t(46) = 0.17$, $p = .869$, $d = 0.05$], or between target enhancement effects for jitter and rotation distractors, $t(46) = 0.26$, $p = .794$, $d = 0.08$.

Supplemental Table 2
Pairwise Comparisons of Target Enhancement Effects Between Static and Dynamic Distractors

	Linear Motion			Jitter			Rotation		
	t	*p*	*d*	*t*	*p*	*d*	*t*	*p*	*d*
Color	0.11	.915	0.03	0.30	.767	0.09	0.05	.963	0.01
Size	0.24	.810	0.07	0.62	.538	0.18	0.38	.707	0.11
Fill	0.34	.735	0.10	0.67	.505	0.19	0.45	.652	0.13

Learned Distractor Rejection for Individual Distractor Types

We calculated *learned distractor rejection effects*, difference scores between oculomotor capture effects in the first block (block 1) and last block (block 10), for each individual distractor type in Experiment 1. Preplanned one-sample *t* tests were then used to evaluate the significance of the learned distractor rejection effects for each individual distractor type. This analysis revealed reliable learned distractor rejection effects for two static distractor types: size singletons [$t(23) = 2.12$, $p = .045$, $d = 0.43$] and fill singletons [$t(23) = 4.91$, $p < .001$, $d = 1.00$]. Interestingly, however, learned distractor rejection effects for color singletons were not reliably larger than zero, $t(23) = 1.61$, $p = .120$, $d = 0.33$, indicating that color singletons were already maximally suppressed in the first block. In contrast, all dynamic distractor types produced reliable learned distractor rejection effects: linear motion [$t(23) = 3.78$, $p < .001$, $d = 0.77$], jitter [$t(23) = 6.53$, $p < .001$, $d = 1.33$], and rotation [t(23) = 5.57, $p < .001$, $d = 1.14$]. Overall, these results indicate that capture by dynamic distractors early in the experiment allowed for larger reductions in capture as the experiment continued, whereas capture by static distractors was suppressed early in the first block such that static distractors produced comparatively small (but still reliable) reductions in capture.