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Progress toward resolving the attentional capture debate

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ABSTRACT
For over 25 years, researchers have debated whether physically salient stimuli capture attention in an automatic manner, independent of the observer's goals, or whether the capture of attention depends on the match between a stimulus and the observer's task set. Recent evidence suggests an intermediate position in which salient stimuli automatically produce a priority signal, but the capture of attention can be prevented via an inhibitory mechanism that suppresses the salient stimulus. Here, proponents from multiple sides of the debate describe how their original views have changed in light of recent research, as well as remaining areas of disagreement. These perspectives highlight some emerging areas of consensus and provide new directions for future research on attentional capture.

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The attentional capture debate

Certain kinds of stimuli seem to automatically *capture* our attention, such as a red tomato on a bed of green lettuce or a blinking light warning of a hazard on a dark road. Early research found that *abrupt onsets*—stimuli that appear with a sudden change in luminance—were particularly powerful in capturing attention (Yantis & Jonides, 1984). Subsequent studies, however, suggested that *colour singletons* (i.e., items of a unique colour in a field of consistently coloured items) can also capture attention under some conditions (Pashler, 1988). These findings led to the formulation of *stimulus-driven accounts* of attention, which propose that certain kinds of physically salient stimuli can automatically guide visual attention even when completely task-irrelevant (Jonides & Yantis, 1988; Theeuwes, 1993).

However, the idea of goal-independent capture of attention by salient stimuli was challenged in the early 1990s by the *contingent involuntary orienting hypothesis* (Folk et al., 1992). According to this hypothesis, a given stimulus will capture attention only if it matches an *attentional set,* and cases of automatic capture of attention by salient stimuli are the result of tasks that implicitly encourage an attentional set that favours these stimuli. For example, if the target in a visual search task is a shape singleton, this may lead to an attentional set that favours all singletons, including task-irrelevant colour singletons. As a result, attention may be captured *involuntarily* by a colour singleton, but this capture is *contingent* on the attentional set that is encouraged by the task.

These competing hypotheses have led to over 25 years of conflicting findings and debate. Additional evidence for the contingent involuntary orienting hypothesis was provided by Folk, Remington, and others (Eimer & Kiss, 2008; Folk & Remington, 1999; Lien et al., 2008; Remington et al., 2001) and additional evidence for stimulus-driven capture was provided by Theeuwes and others (Franconeri & Simons, 2003; Geyer et al., 2008; Mounts, 2000; Pinto et al., 2005; Theeuwes, 1992, 1994). Recently, however, the debate has undergone significant transformation, partly as the result of growing evidence that an inhibitory process can sometimes prevent attentional capture even if a stimulus produces a priority signal (Cosman et al., 2018a; Gaspelin & Luck, 2018c, 2019; Vatterott et al., 2018; Weaver et al., 2017). The present article documents some areas of emerging consensus and describes several issues that remain to be resolved. Separate statements will be provided by proponents of the contingent

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involuntary orienting hypothesis (Folk and Remington), by a proponent of the opposing stimulus-driven selection hypothesis (Theeuwes), and by proponents of an intermediate hypothesis (Luck & Gaspelin). We begin by describing the original formulations of the opposing hypotheses to provide important historical context.

Original versions of the opposing hypotheses

The original version of the contingent involuntary orienting hypothesis (Folk et al., 1992) proposed that the orienting of attention to a given stimulus depends entirely on whether the properties of that stimulus match the current attentional control settings: "With a control setting established, events exhibiting the critical properties will involuntarily summon attention, whether or not the event is actually relevant to task performance" (p. 1041). In addition, physically salient stimuli such as abrupt onsets and colour singletons will not capture attention unless they contain properties that match the attentional control settings: "Stimuli not exhibiting these properties will not involuntarily summon attention" (p. 1041).

This account was initially supported by a *spatial cuing paradigm* (see Figure 1A). When participants searched displays for a target defined by a specific feature (e.g., red), nonpredictive spatial cues that matched this feature (red) seemed to attract attention, whereas salient cues that mismatched this feature (e.g., abrupt onsets) did not capture attention. According to this account, the task of searching for a red target will lead the observer to establish an attentional set for redness that will impact the processing of all incoming information. Consequently, any red object—such as a red spatial cue—will automatically capture attention. However, salient cues that do not match the attentional set (e.g., a white onset cue) will not capture attention. The original formulation of the contingent involuntary orienting hypothesis included two important caveats. First, in the absence of a specific task, the system might rely on default settings, which prioritise certain types of stimuli even in the absence of an explicit task. Second, when the location of the target is known in advance, attention will not be captured by stimuli at other locations.

At the opposite end of the theoretical spectrum, the original formulation of the stimulus-driven selection hypothesis (Theeuwes, 1993) proposed that the item with the greatest physical saliency automatically drives the first shift of attention. Saliency was proposed to be independent of attentional control settings: "This computation is assumed to be independent of strategic control and to occur irrespective of whether an item is a target or a nontarget" (p. 109). As a result, "the item with the highest bottom-up activity (i.e., the 'oddest' or most salient item in the display) is selected irrespective of the intentions of the subject" (p. 109). Thus, according to this account, an observer's attentional set will have no impact on the first sweep of attentional selection and, instead, the initial allocation of attention will be guided entirely by physical salience. This hypothesis has one major caveat: the computation of saliency can be limited to a preselected area of space. Consequently, just as proposed by the contingent involuntary orienting hypothesis, physically salient items outside of the spatial focus of attention will not necessarily capture attention.

Although these two hypotheses are diametrically opposed, they have persisted for over 25 years. This largely reflects two empirical challenges. First, there is usually no independent means of determining the attentional control settings that are *actually* produced by a given task. Consequently, it is difficult to rule out the possibility that a given case of stimulus-driven attentional capture by a given salient feature actually reflects an attentional control setting for that feature. A second challenge is the difficulty of ascertaining whether a given item has actually captured attention. For example, if the presence of a salient object does not slow the response time (RT) for a target, this may indicate that the salient object did not capture attention, but it is also possible that attention was briefly captured by the distractor but was then *rapidly disengaged* from this item (Theeuwes et al., 2000). This is particularly plausible in spatial cuing paradigms (Figure 1a), in which the salient stimulus occurs prior to the target array that is used to assess attention capture, providing time for attention to be reoriented from the cue before the target appears.

Although these challenges have not been completely overcome, significant progress has been made. First, research has identified several experimental design features that minimise implicit task demands that might bias attentional control settings toward salient stimuli (Bacon & Egeth, 1994; Gibson &

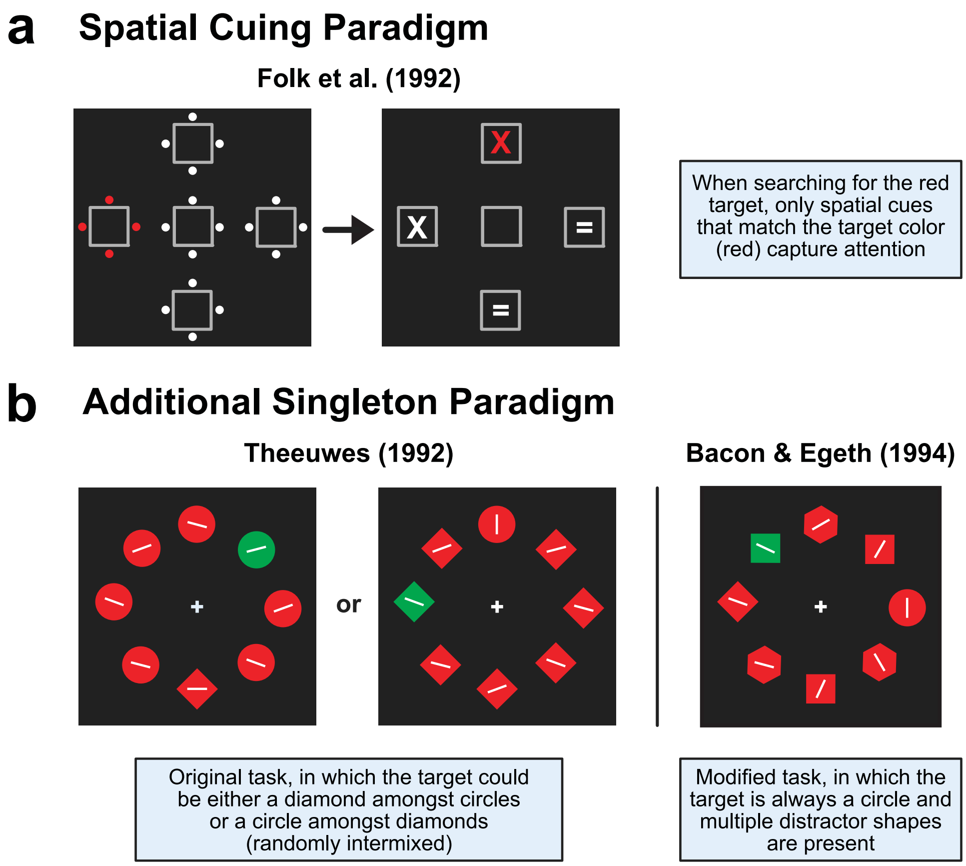

Figure 1. Classic paradigms used to study capture of attention by singletons. (a) The spatial cuing paradigm supported the contingent involuntary orienting hypothesis by demonstrating that only cues matching the target feature captured attention (Folk et al., 1992) (b) The additional singleton paradigm was initially used to support stimulus-driven accounts by demonstrating that an irrelevant singleton seemed to capture attention (Theeuwes, 1992). This finding was later challenged by a variant that used heterogenous displays to prevent singleton detection mode (Bacon & Egeth, 1994), but the interpretation of this new variant has also been challenged (Belopolsky et al., 2010; Theeuwes, 2004; Wang & Theeuwes, 2020).

Kelsey, 1998; Leber & Egeth, 2006). For example, in the *additional singleton paradigm* (Figure 1B; Theeuwes, 1991a, 1992), participants search for a shape singleton target and make a buttonpress response to indicate some property of a stimulus enclosed within the target (e.g., the orientation of a line inside the target shape). A salient colour singleton is either present or absent, and this item is never the target. Early studies found that responses were slowed when the singleton was present, suggesting that it automatically captured attention (Theeuwes, 1992).

However, Bacon and Egeth (1994) proposed that this task encourages participants to use *singleton detection mode*, in which they search for singletons in any dimension, which subsequently causes the colour singleton to capture attention. As evidence for this claim, they showed that capture by the colour singleton could be reduced or eliminated by using multiple different distractor shapes (Figure 1C). This eliminated the possibility that participants could use singleton detection mode to find the target, and it instead encouraged them to adopt a *feature search mode* in which they looked for the specific shape of the target. Many subsequent studies have found that capture of attention by a colour singleton is strongly modulated by whether or not the task encourages singleton detection mode or feature search mode (e.g., Burra & Kerzel, 2013; Gaspelin et al., 2015, 2017; Gaspelin & Luck, 2018b; Lamy et al., 2006; Leber, 2010; Leber & Egeth, 2006). However, it is important to mention some of this evidence has been questioned by proponents of stimulus-driven accounts (Belopolsky et al., 2010; Theeuwes, 2004; Wang & Theeuwes, 2020).

A second source of progress in the attentional capture debate has come from additional measures of the orienting of attention that are now widely available, making it easier to determine if attention was actually captured by a given stimulus. One such measure is the *N2pc* component of the event-related potential (ERP) waveform (Luck, 2012; Luck & Hillyard, 1990, 1994), which is more negative contralateral to the side of an attended object. Because ERPs provide a continuous measure of processing, it is possible to observe shifts of attention that are very rapid. Alpha-band EEG oscillations are also lateralised with respect to an attended object (Bacigalupo & Luck, 2019) and can be used to track the allocation of attention in capture paradigms (Wang et al., 2019). Finally, eye tracking can be used to track overt attention (Henderson, 2003; Theeuwes et al., 1998), and the shortest latency saccades are often so fast that it is implausible that covert attention was first directed to a different location prior to the saccade.

In the attention capture debate, the terms *top-down* and *bottom-up* have proven problematic (Awh et al., 2012; Egeth, 2018; Gaspelin & Luck, 2018d; Theeuwes, 2018) and we will simply avoid them in this article. Recent research has shown that it is more productive to make a three-way distinction between pure sensory factors, explicit goals, and implicit factors such as *selection history* (see, e.g., Awh et al., 2012; Failing & Theeuwes, 2018; MacLean & Giesbrecht, 2015; Tseng et al., 2014). Similarly, the term *salience* is used to mean different things by different authors. Here we use the term exclusively to refer to *physical salience*, which is how much a given stimulus differs from neighbouring stimuli in low-level visual features (e.g., colour, line orientation, size luminance, etc.; see Itti & Koch, 2001; Wolfe & Horowitz, 2017).

Progress in the attention capture debate

The key areas of progress in the attention capture debate can be described—to a first order of approximation—by two statements:

(1) Certain kinds of stimuli (e.g., abrupt onsets, colour singletons) automatically generate a priority signal that, in the absence of specific attentional control settings, will automatically capture attention.
(2) The capture of attention by salient singleton stimuli can be prevented if the attentional control system is appropriately configured.

The first statement is consistent with the stimulus-driven selection hypothesis but conflicts with the original formulation of the contingent involuntary orienting hypothesis, which specified that attention will be captured only if a stimulus matches the control settings. The second statement is consistent with the contingent involuntary orienting hypothesis but conflicts with the original formulation of the stimulus-driven selection hypothesis, which specified that control settings have no impact on the initial orienting of attention with the exception of the spatial distribution of attention. The stimulus-driven account now specifies that proactive weighting of nonspatial features is possible but cannot overcome moderate or high levels of physical salience (Wang & Theeuwes, 2020). Although there are still areas of debate, agreement on these two statements by researchers on both sides represents progress toward a resolution of the attention capture debate and will be useful for focusing the field on mechanisms that can satisfy both statements.

Figure 2 shows a framework for describing multiple models of attention capture and how they vary. According to this model, all information is first received by a *sensory register* and is then parsed into *feature maps* that represent simple features, such as colour or orientation. This model includes the possibility that both explicit goals and implicit learning can modulate the flow of information from specific features or spatial locations to the *priority map*, allowing for *proactive control* (boosting specific feature values prior to stimulus onset; see Braver, 2012). It also includes the possibility that the flow of information can be influenced by *reactive control* mechanisms that directly boost or suppress the priority at specific locations after the initial allocation of attention has already occurred (Sawaki et al., 2012). The solid lines in the figure represent attributes that are shared by all three models considered here, whereas the broken lines represent current areas of disagreement. The remaining major disagreements concern (a) the extent to which explicit goals and/or selection history can exert proactive control over the gain of nonspatial features prior to saliency computations, and (b) whether explicit goals and implicit learning operate independently or are integrated into a unitary control state.

The fact that the existing models can all be captured within a single diagram is significant progress,

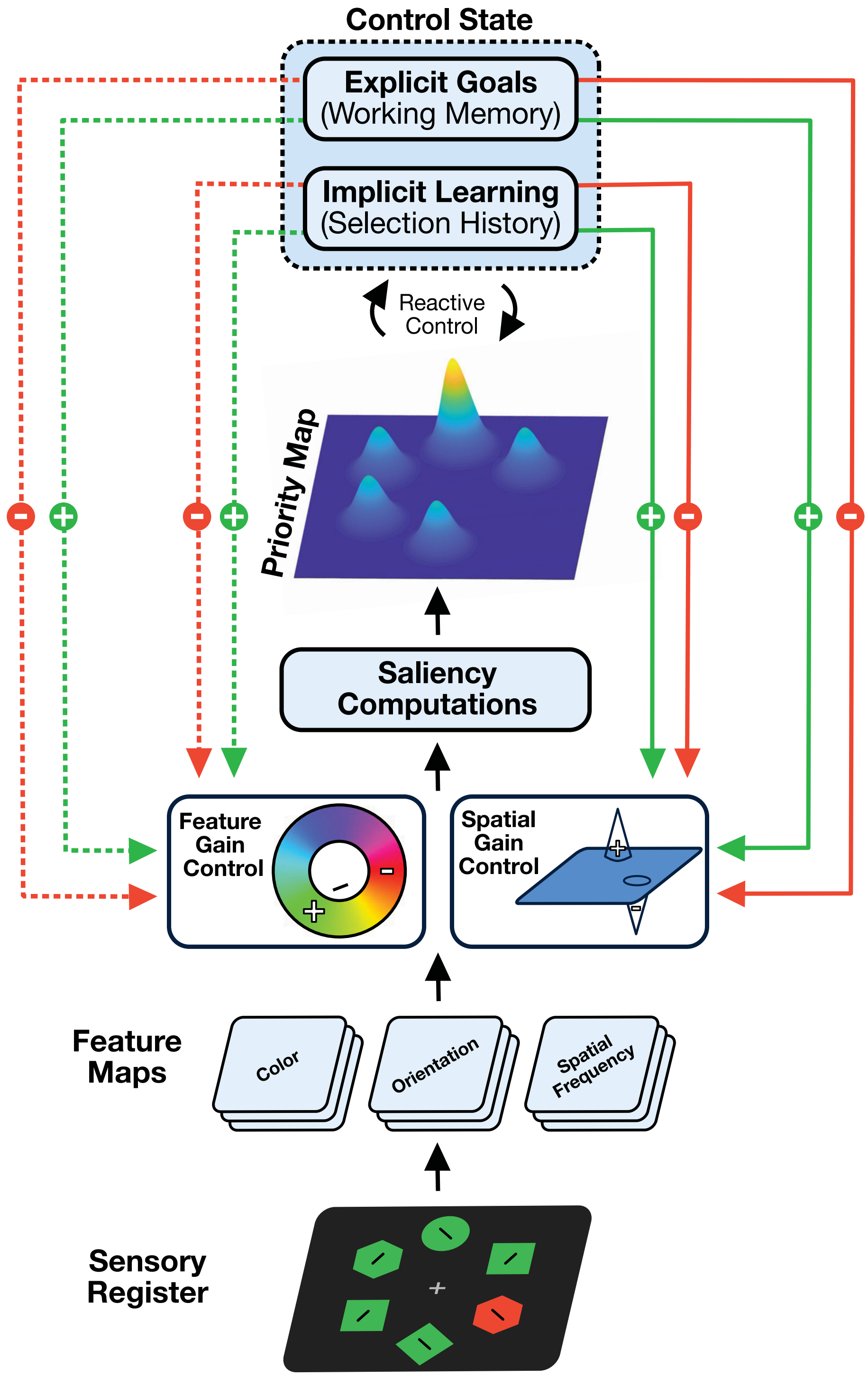

Figure 2. Common framework for the models of attentional control discussed in this article. Following previous models, the sensory input is decomposed into different feature maps, which are then combined via a set of saliency computations to produce a priority map. In all three of the present models, both explicit goals and implicit learning can reactively operate on the priority map to increase or decrease the priority of a specific location (indicated by solid lines). The models disagree about whether explicit goals and implicit learning can proactively suppress or enhance the transmission of features or spatial locations (indicated by broken lines). The models also disagree about whether explicit goals and implicit learning are integrated into a unitary control state (indicated by the broken line around the control state).

and it also clarifies the areas in which more research is needed to come to a consensus. The rest of this article is structured to describe how the existing models have evolved over time to become more similar, the remaining areas of disagreement, and the specific patterns of results in future experiments that could resolve the remaining areas of dispute. Each of the following sections will provide the perspective of the proponents of each existing model, and these individual perspectives will be followed by a general summary.

Viewpoint: Gaspelin and Luck

We would like to emphasise the role that recent studies of singleton suppression have played in moving toward a resolution of the attention capture debate (see reviews by Gaspelin & Luck, 2018c, 2019). These studies have shown that, under certain conditions, salient colour singletons do not capture attention and are in fact proactively suppressed (Chang & Egeth, 2019; Cosman et al., 2018a; Feldmann-Wüstefeld et al., 2015, 2020; Feldmann-Wüstefeld & Vogel, 2018; Gaspar et al., 2016; Gaspar & McDonald, 2014; Gaspelin et al., 2015, 2017, 2019; Gaspelin & Luck, 2018a, 2018b; Sawaki & Luck, 2010; Stilwell et al., 2019; van Moorselaar & Slagter, 2019; Vatterott & Vecera, 2012; Weaver et al., 2017; Won et al., 2019). Such results have led to the *signal suppression hypothesis*, which describes how attentional control mechanisms can prevent the capture of attention.

Evidence for singleton suppression

Consider, for example, the oculomotor search task illustrated in Figure 3(A), in which observers were instructed to find a target item of a particular shape (e.g., the circle) and report whether the small line inside it is tilted leftward or rightward (Gaspelin et al., 2017). The line was very small, so the task implicitly required participants to fixate the target object so they could perceive the line orientation. A salient colour singleton (i.e., the red object in Figure 3A) was present on a subset of trials, and this item was never the target. The study examined the first eye movement on each trial to assess the initial allocation of (overt) attention. The initial eye movement typically landed on the target, but sometimes it landed on one of the distractors. The key result was that gaze was actually *less* likely to land on the singleton distractor than on the average nonsingleton distractor (see also Weaver et al., 2017). Thus, the singleton distractor did not capture attention but was instead suppressed below the baseline level of the nonsingleton distractors. Similar results have been obtained using a *capture-probe paradigm* that measures covert rather than overt attention (Gaspelin et al., 2015).

When the task was changed so that the target was defined as a shape singleton (see Figure 3B), which encouraged the use of *singleton detection mode*, the colour singleton captured attention rather than being suppressed: The initial eye movement landed on the colour singleton more often than it landed on the average nonsingleton distractor. This demonstrates that the colour singleton was in fact salient and that task demands determined whether it captured attention or was suppressed.

As described earlier, all three theories discussed in this article predict the absence of capture if participants focus spatial attention narrowly. Could this be why no capture was observed in the experiment shown in Figure 3(A)? This is unlikely. First, fixations of the singleton were suppressed below baseline levels, which should not have been necessary if the singleton was already filtered. Second, on singleton-absent trials, the time required for gaze to reach the target was virtually identical in the tasks shown in Figures 3(A and B), which is inconsistent with the hypothesis that participants focused attention narrowly (i.e., used a serial search strategy) in the Figure 3(A) task but not in the Figure 3(B) task. Third, the locations of the singleton and target were randomised, ruling out the possibility that the suppression reflected a proactive spatial filtering strategy (as in Wang & Theeuwes, 2018c; see also Burnham, 2018; Ruthruff & Gaspelin, 2018).

Another possibility is that the singleton briefly captured covert attention in the task shown in Figure 3 (A), but attention was rapidly reoriented to the target before the first eye movement was initiated. However, this shift and subsequent reorienting of covert attention would take time and would therefore be possible only on trials with relatively long saccade latencies. However, even the fastest eye movements (ca. 175 ms) were less likely to be directed to the singleton than to the nonsingleton distractors, providing no evidence of an initial capture of covert attention by the singleton. Additional evidence against this notion of initial capture followed by suppression comes from experiments using the capture-probe paradigm. For example, Gaspelin et al. (2015, Exp. 4) used extremely brief probe stimulus durations (less

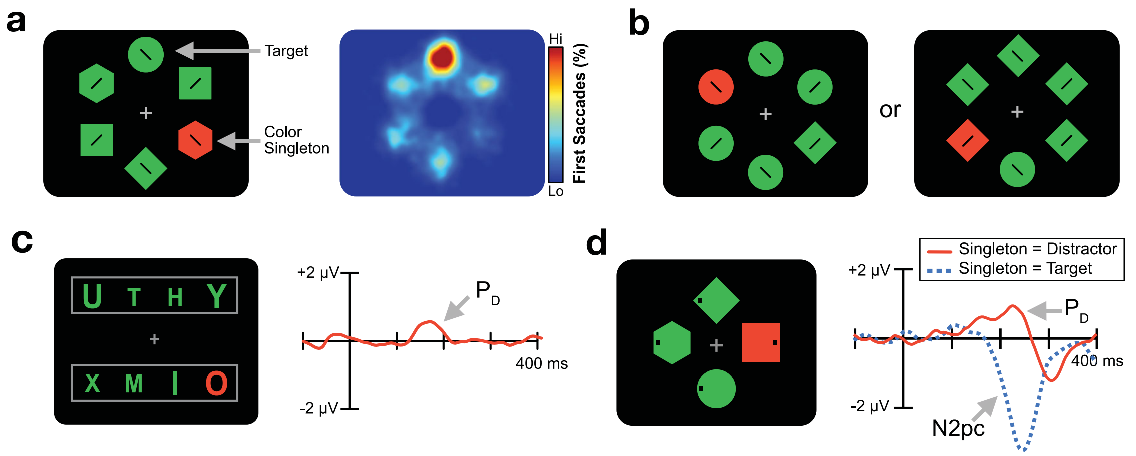

Figure 3. (a) Version of the additional singleton paradigm used to examine oculomotor suppression by Gaspelin et al. (2017, 2019). The target was a specific shape (e.g., the circle), and multiple distractor shapes were present to discourage the use of singleton detection mode. The task was to report whether the line inside the target was left-tilted or right-tilted. The actual lines were much smaller than those shown here, requiring fixation to be discriminated. The target was never the colour singleton. The first shift of gaze on a given trial was found to be less likely to be directed to the colour singleton than to the average of the nonsingleton distractors (indicated by the heat map of saccade landing positions), providing evidence that the singleton was suppressed. (b) Version of the task that was designed to encourage singleton detection mode. In this version, the target was a circle among squares on some trials and a square among circles on other trials. Consequently, the actual shape of the target could not be known in advance. (c) Stimuli and results from an early ERP study of attention capture (Sawaki & Luck, 2010). Participants searched for a target letter of a specific size and colour (e.g., large green A). On some trials, the target was absent and a singleton was present instead. The singleton elicited a P_D component indicating suppression rather than an N2pc component indicating capture. (d) Stimuli and results from another ERP study (Gaspelin & Luck, 2018b). The singleton elicited a strong N2pc component when it was the target but elicited a P_D component when it was a distractor.

than 100 ms) and still found strong evidence that singleton distractors were inhibited.

The possibility that salient singletons briefly capture covert attention can be assessed more directly via ERP recordings, which provide a continuous, millisecond-by-millisecond measure of processing between the stimulus and the response. In particular, the N2pc component can be used as an index of attentional selection (Luck, 2012), and the distractor positivity (P_D) component can be used as an index of suppression (Hickey et al., 2009). When the stimuli and task encourage singleton detection mode, colour singleton distractors elicit an N2pc component, indicating that they have captured attention (Burra & Kerzel, 2013; Hickey et al., 2006).

When singleton detection mode is discouraged, however, colour singleton distractors elicit a P_D component, indicating that they have been suppressed (see Figure 3C and D; Eimer & Kiss, 2008; Gaspar & McDonald, 2014; Gaspelin & Luck, 2018b; Sawaki & Luck, 2010). The P_D effects in these experiments typically begin within 150 ms of stimulus onset, making it very unlikely that attention was shifted to the colour singleton before the suppression began. Moreover, the magnitude of the P_D component is correlated with the magnitude of the behavioural suppression, whether assessed by examining differences across participants (Gaspar et al., 2016; Gaspelin & Luck, 2018b) or differences across trials (Feldmann-Wüstefeld et al., 2020; Weaver et al., 2017). Electrophysiological evidence of suppression has also been observed in macaque single-unit recordings (Cosman et al., 2018a).

These results provide no evidence that the singleton captured attention briefly prior to being suppressed. That is, no evidence of capture was observed in the fastest eye movements, in the ERP waveform, or in single-unit activity. By contrast, clear evidence of capture was observed when the task encouraged an attentional set that favoured singletons. Thus, these results provide strong evidence that the capture of attention by colour singletons can be modulated by task demands.

Implications for the architecture of attention

Together, the results reviewed here support the two main areas of agreement described earlier. First, they indicate that colour singletons automatically generate a priority signal, because there would be no need to suppress the colour singletons if they did not produce what Sawaki and Luck (2010) called an *attend-to-me* signal. In Figure 2, this is indicated by the arrow from the feature maps to the saliency computations; in the absence of control signals feeding into the feature gain control and spatial gain control mechanisms, feature discontinuities will lead to increased activity within the priority map. Thus, in the absence of task-dependent control, colour singletons will automatically generate a priority signal and attract attention.

The results reviewed here are also consistent with the hypothesis that task-dependent control signals can proactively modulate attention capture via the featural and spatial gain control mechanisms (the downward arrows connecting the control state to the gain control mechanisms in Figure 2). That is, either capture or suppression can be produced depending on the extent to which the task encourages singleton detection mode.

At present, we (Gaspelin and Luck) believe that the data support the idea that proactive suppression of feature gain (the broken red lines in Figure 2) is possible only on the basis of implicit memory (selection history) and cannot be achieved by explicit goals (working memory). For example, participants cannot suppress a singleton simply by being explicitly told its colour in advance; instead, suppression builds up over a period of several trials with a specific singleton colour (Gaspelin et al., 2019; Gaspelin & Luck, 2018a; Stilwell et al., 2019; Vatterott & Vecera, 2012). Moreover, when the colour of the distractor is cued on a trial-by-trial basis, it is not suppressed and instead captures attention (Cunningham & Egeth, 2016; de Vries et al., 2019; Gaspelin et al., 2019, Experiment 4). Thus, task goals appear to be necessary for feature-based suppression only insofar as the goals produce the selection history necessary to drive a largely unconscious suppression process. However, we are open to the possibility that future research will demonstrate that proactive suppression of features is possible on the basis of explicit goals under some conditions.

By contrast, prior research provides strong support for the hypothesis that control signals can produce proactive *enhancement* of feature gain (the broken green lines in Figure 2), leading to increased sensory-evoked neural responses for target features (Maunsell & Treue, 2006; Valdes-Sosa et al., 1998; Zhang & Luck, 2009). Like the contingent involuntary orienting hypothesis and the stimulus-driven selection hypothesis, the signal suppression hypothesis assumes that both implicit memory and explicit goals can proactively suppress and enhance spatial gain (the solid red and green lines on the right side of Figure 2).

Whereas the original version of the signal suppression hypothesis proposed that suppression could operate directly on the priority signal (which would involve an arrow from the control state to the priority map in Figure 2), the current version assumes that suppression operates by modulating the gain for specific feature values prior to the saliency computations. This modification was based on evidence that participants could not suppress a singleton unless the colour of the singleton (or at least the general region of colour space) was predictable (Gaspelin & Luck, 2018a). However, more recent evidence suggests that people can learn to suppress singletons even if the colour is not known in advance (Vatterott et al., 2018; Won et al., 2019), so this issue remains to be resolved.

Moving toward a resolution of the attention capture debate

The main disagreement between the signal suppression hypothesis and the contingent involuntary orienting hypothesis is whether explicit goals (in addition to selection history) can produce proactive suppression of specific features. As described above, we (Gaspelin and Luck) are open to the possibility that explicit goals can proactively suppress singletons. However, this would require a demonstration of feature-based suppression that cannot be explained by reactive suppression or by selection history. To rule out reactive suppression (e.g., rapid reorienting), it would be necessary to demonstrate that the suppression operates very rapidly (e.g., using ERPs or fast-latency saccades). Selection history can usually be ruled out by using trial-by-trial cuing rather than blocked instructions (see Theeuwes, 2018). The evidence to date indicates that suppression is not possible when the distractor colour is cued on a trial-by-trial basis (Cunningham

& Egeth, 2016; de Vries et al., 2019; Gaspelin et al., 2019).

The signal suppression hypothesis agrees with the stimulus-driven selection hypothesis about the importance of selection history in driving many attention effects. The key disagreement is whether feature gain can be proactively controlled. Recently, Wang and Theeuwes (2020) concluded that feature gain can indeed by proactively decreased for a singleton colour, but singleton suppression will be successful only if the singleton has relatively low salience. Specifically, they found suppression of a colour singleton when it was accompanied by only 3 nonsingleton items (i.e., at set size 4), but they failed to find suppression at set sizes 6 and 10. Thus, the only remaining disagreement is whether proactive control of feature gain can be strong enough to overcome high levels of salience, not whether proactive control of feature gain is possible at all. There is good reason to believe that it may not always be possible to suppress highly salient objects, especially abrupt onsets, which tend to be particularly powerful (Folk & Remington, 2015; Franconeri & Simons, 2003; Gaspelin et al., 2016; Hollingworth et al., 2010; Jonides & Yantis, 1988; Lamy & Egeth, 2003; Ruthruff et al., 2020; Zivony & Lamy, 2018).

However, we (Gaspelin and Luck) would need to see further evidence that suppression of feature singletons is impossible at high set sizes before concluding that proactive control of feature gain is too weak to prevent the capture of attention by salient feature singletons. Indeed, we have observed oculomotor suppression of colour singletons at set size 6 (Gaspelin et al., 2017, 2019; Gaspelin & Luck, 2018a). Moreover, in some experiments showing suppression of colour singletons, the singletons *did* capture attention when the singleton colour was unpredictable (Gaspelin & Luck, 2018a; Stilwell et al., 2019; Vatterott & Vecera, 2012). Furthermore, the singletons were salient enough to attract attention in various control experiments that encouraged singleton detection mode (Gaspelin et al., 2015, 2017). Thus, the current evidence suggests that proactive control of feature gain can suppress the capture of attention by singletons that are sufficiently salient to capture attention in the absence of control, but it remains to be seen whether capture can be prevented for more salient stimuli.

Another important empirical issue is whether prior evidence of proactive singleton suppression can be explained by reactive control (e.g., rapid disengagement). It is virtually impossible to completely rule out the possibility that apparent failures of capture are the result of an initial orienting to the singleton followed by a rapid disengagement. We have already assessed this possibility by using short SOAs in psychophysical tasks (Gaspelin et al., 2015), by examining the fastest eye movements in oculomotor paradigms (Gaspelin et al., 2017, 2019; Gaspelin & Luck, 2018a), and by using ERPs to assess the continuous processing of information following stimulus onset (Gaspelin & Luck, 2018b; Sawaki & Luck, 2010). In each case, we found no evidence that the singleton attracted attention prior to being suppressed. However, we would reconsider this conclusion if new methods became available that revealed some type of attentional capture that was missed by existing methods.

Unresolved issues

We would like to mention three additional issues that remain unresolved. One important issue is that the evidence for suppression comes primarily from studies of colour singletons. It is not yet known whether abrupt onsets—which may be more powerful (Franconeri & Simons, 2003; Gaspelin et al., 2016; Hollingworth et al., 2010; Jonides & Yantis, 1988; Lamy & Egeth, 2003; Ruthruff et al., 2020; Zivony & Lamy, 2018)—can be suppressed. A key challenge toward testing whether abrupt onsets automatically capture attention will be to definitively rule out any attentional control setting for onsets. This will be challenging because most attentional capture tasks use search displays that suddenly onset and observers may therefore adopt a control setting for that feature (but see Franconeri et al., 2004).

Another unresolved issue is that the apparent suppression of the colour singleton may actually reflect an upweighting of the target colour rather than a downweighting of the singleton colour (Gaspelin & Luck, 2018c). There are some important reasons to doubt that target upweighting can entirely explain the evidence for singleton suppression. First, several experiments have demonstrated that participants are initially vulnerable to capture by a singletons of a new colour and the singletons are eventually suppressed as participants gain experience with this colour (Gaspelin & Luck, 2018a; Vatterott & Vecera, 2012). Given that the target colour was held constant in these studies, these results suggest that participants learn to inhibit the singleton colour (see also Vecera et al., 2014). Second, in a recent study, Chang and Egeth (2019) modified the capture-probe technique to include various colours in the probe display, and they found evidence for both upweighting of the target colour and downweighting of the singleton colour. Finally, recent studies have provided evidence that participants may eventually learn to ignore singletons without knowledge of the specific singleton colour (Vatterott et al., 2018; Won et al., 2019).

A final unresolved issue is the specific learning processes involved in the suppression of attentional capture by salient items (see Vecera et al., 2014 for a detailed discussion). Although suppression builds up over several trials with the same singleton colour, it is unclear how this suppression is learned, especially in laboratory tasks without explicit feedback about whether attention was captured. Some evidence indicates that the learning is implicit (Anderson et al., 2011; Gaspelin et al., 2019; Gaspelin & Luck, 2018c; Stilwell et al., 2019; Vatterott & Vecera, 2012; Wang & Theeuwes, 2018a). Indeed, explicit intentions to avoid a specific feature are often ineffective or counterproductive (Cunningham & Egeth, 2016; de Vries et al., 2019; Gaspelin et al., 2019; Vecera et al., 2014). On the other hand, recent evidence indicates that individuals are aware of attentional capture when it occurs (Adams & Gaspelin, 2020; but see Belopolsky et al., 2008; Theeuwes et al., 1998), and this awareness could potentially allow people to explicitly learn to avoid capture. Understanding the learning processes involved in suppression will be an important step toward developing training programmes designed to prevent visual distraction.

Viewpoint: Folk and Remington

The contingent involuntary orienting hypothesis (also called the *contingent capture* hypothesis) was formulated to account for data from spatial cueing experiments in which attention was only captured by distractors when they shared the finding property of the target, irrespective of physical salience (Folk et al., 1992). According to the theory, attentional capture is a reflexive response that is modifiable (as with many muscular reflexes), similar to a proposal by Posner (1980), in his seminal work on endogenous and exogenous attentional control:

> "Comparisons of exogenous (reflexive) and endogenous (central) control of orienting is made difficult because external signals do no operate completely reflexively but will only summon attention and eye movements if they are important to the subject" (p. 19)

In Contingent Capture the notion of *importance to the subject* is manifested in *attentional control settings* that modify the ability of salient stimuli to capture attention as a function primarily of task goals.

It is important to note that contingent capture theory began as a statement of the necessary conditions for attentional capture. It has remained relatively agnostic with respect to underlying mechanisms that instantiate attentional control settings, as long as those mechanisms are consistent with the control state as described above. Nonetheless, the original formulation held that contingent capture was accomplished by up-weighting or down-weighting signals feeding into the priority map according to relevance associated with current task goals (Folk et al., 1992; Folk & Remington, 1998). The EEG work of Gaspelin and Luck (2018b) has shown proactive suppression of attentional shifts to salient singletons in the additional singleton paradigm, providing clear evidence for *proactive* inhibitory control that modulates priority map input from sensory representations encoded in the feedforward sweep of information processing (Zhang & Luck, 2009). Work by Schall and colleagues (Bichot & Schall, 2002) has provided evidence of how neural mechanisms implement proactive suppression as well as enhancement. Recording from single cells in the frontal eye field (FEF) of macaques while the animals performed the additional singleton search task, they found enhanced firing rates to stimuli possessing target properties, the same properties that, when not a target, produce no enhanced firing. Critically, these same FEF neurons also show *suppressed* firing rates for salient distractors falling within their receptive field. These changes in FEF firing rates were correlated with, and temporally preceded, ERP responses in extrastriate regions associated with attentional allocation and suppression (e.g., N2pc and P_D; Cosman et al., 2018a).

Updates to contingent capture theory

Since the original publication, the contingent capture theory has retained its core assertion that cognitive state, not stimulus salience alone, determines whether or not attention will be captured. Nonetheless, some adjustments have been made. One important modification of the original formulation was to allow that attention could be captured by salient stimuli when no control setting was in place. Yantis (1993) suggested that attention would be captured automatically by salient stimuli when the system was in a neutral state. Consistent with this, an fMRI study by Leber (2010) using the additional singleton paradigm found that capture from the salient distractor occurred only with low levels of activation in prefrontal cortex prior to trial onset. Assuming that this pre-trial activity is involved in establishing attentional control settings for the target property, the results provide evidence that salient stimuli will not capture attention when a set has been established, but can do so when no set, or a weak set, exists. The current view of contingent capture is consistent with this position, as noted in Statement 1 in the introduction.

Empirical investigations of Contingent Capture theory have focused largely on the role of current goals in the configuration of the attentional control system. Nonetheless, we left open the possibility that factors other than task demands could affect attentional control settings:

> "These control settings, in turn, are a function of current behavioral goals, as well as past experience or enduring biases of the organism." (Folk et al., 1992, p. 1043)

The recent work on the influence of selection history (see Theeuwes, 2018 for a review) confirms these speculations about the potential influence of past experience and enduring biases. The statistics of past experience also determine the likelihood that a salient stimulus will capture attention. Folk and Remington (2015) found that abrupt onset stimuli would not capture attention when they occurred frequently, but would when they were rare. This was attributed to underlying brain mechanisms that respond to novelty, but that habituate rapidly, an idea which has been worked out more fully by Turatto et al. (2018). This led to a consideration of internal models of the world that determined the control state for attention, leading to the explicit incorporation of the idea of a *control state* to account for this and other selection history influences.

Finally, the theory has expanded the specific attentional control settings that operate to control capture. Originally attentional control settings were posited to act on feature values (e.g., red, moving) within feature dimensions corresponding to dynamic (e.g., onsets, motion) or static (e.g., colour, shape). The theory has discarded the static-dynamic distinction. Subsequent behavioural studies exploring the functional properties for which the allocation system could be configured have revealed evidence of attentional control settings for specific feature values (Folk et al., 1992; Folk & Remington, 1998), feature singletons (Folk et al., 2002; Folk & Anderson, 2010), dimensional singletons (Harris et al., 2015), feature relations (Becker et al., 2010), and even semantic content (Wyble et al., 2013)

Unresolved issues

The control structure for contingent capture depicted in Figure 2 differs in important respects from those for the stimulus-driven capture account of Theeuwes and the inhibitory account proposed by Gaspelin and Luck.

First, in stimulus-driven accounts, and the inhibitory account, selection history is assumed to act directly on a salience map in which its activations pool with those of goals and salience (Awh et al., 2012). Were that the case, however, there should be greater correspondence between goal-driven attention and attention biases in response to selection history than is generally observed. For example, Jiang (2018) lists seven critical differences between goal-driven and selection-driven attention, including the role of working memory, response to aging, and flexibility. She proposes a multi-level framework in which separate neural systems engage attention both in reference to where to attend and to habits that dictate how to attend (Jiang, 2018). Jiang's multi-level approach is consistent with the modification to Contingent Capture noted above, in which selection history, task goals, and enduring biases are seen as influencing the *control state* of the allocation system, which encompasses separate neural systems (see Figure 2). The Control State integrates multiple separate inputs into a set of context-specific control signals in place at the time of stimulus presentation.

The control state is not localised, but describes the state of the cognitive set across regions. This allows for biases within specific systems, not system-wide, or pooled, effects. The control state is constantly being tuned by virtue of experience *within* a task to yield optimal overall performance (Folk & Remington, 2015; Vatterott & Vecera, 2012). Accordingly, capture depends on the interaction between the stimulus and current control state. Contingent Capture does support the idea that salient singletons can generate a strong attend-to-me signal. However, a salient stimulus will capture attention only if the control state establishes a setting for its properties, or fails to establish the mechanisms needed to prevent capture. Studies show that such is the case when participants fail to establish any set or the "right" set (Bacon & Egeth, 1994; Folk & Remington, 2006, 2008; Wu et al., 2014; Wu & Remington, 2003). This could reflect lack of experience with the task context (Vatterott & Vecera, 2012) or contextual tuning that allows capture in order to optimise overall task performance (Folk & Remington, 2015). It might also result from a control state in which control mechanisms vary in fidelity across trials (Leber, 2010).

Also depicted in the control flow for Contingent Capture in Figure 2 is that the Control State achieves proactive control by a context-sensitive pattern of excitatory and inhibitory inputs across feature maps that alters the computation of salience across locations in the priority map. One particular feature that distinguishes it from the other accounts is that Contingent Capture leaves open the possibility that the Control State can operate at multiple stages of processing. For example, rather than assume that all inhibitory or facilitatory activity is directed at early feature maps, the control state can also set the threshold for executing a shift of attention when more or less caution is required, akin to an overt motor response. Such changes in threshold are consistent with observations that error saccades to distractors are generally faster than correct target saccades (Wu & Remington, 2003).

The depiction of Contingent Capture in Figure 2 also differs from the other accounts in asserting that both implicit biases and task goals can act proactively to prevent attention shifts from occurring. Evidence for goal-driven proactive inhibition comes from studies that have found contingent capture when target properties change from trial-to-trial (Lien et al., 2010; Moher et al., 2011), consistent with goal-driven proactive inhibition. The conflicting empirical findings with respect to trial-by-trial manipulations point to an area in need of further research. Additional support for goal-driven proactive control comes from the fMRI experiment of Leber (2010), who showed that capture by an irrelevant singleton was associated with low levels of pre-trial frontal activation. This finding suggests that some form of deliberate preparation is required to instantiate the appropriate control settings, though it is not clear if such proactive control is accomplished by excitation or suppression.

Note that this goal-driven proactive control is independent of *reactive* suppression that is applied after attention has already been allocated (i.e., the rapid disengagement account). Rapid disengagement has received little empirical support (Folk & Remington, 2010). Indeed, Cosman et al. (2018a) have argued that their work with macaques effectively disconfirms the rapid disengagement account, as the presence of a salient distractor had no effect on the latency of target selection by FEF neurons. Similar arguments against rapid disengagement have been made by Gaspelin and Luck on the basis of EEG data (Gaspelin & Luck, 2018b). As noted earlier, the assertion of proactive inhibition in response to task goals, not selection history, sets contingent capture apart.

Summary

The central assertion of Contingent Capture is that capture of attention by a salient stimulus is dependent on the current *control state* of the attention allocation system, consisting of control mechanisms customised by task goals and selection history, compiled off-line, and then activated by stimulus presentation. The control mechanisms include proactive suppression/enhancement of salience, as well as reactive suppression/enhancement after attention has been shifted to a location. The contents of the control state of the system become tuned within a given experimental context, such that with task experience, various control mechanisms are brought on or offline to yield optimal overall task performance.

The capture debate has furthered our understanding of the attention allocation system. In a classic example of forward engineering, relatively high-level constructs such as attentional control settings were proposed to account for patterns of behaviour (contingent capture), and were subsequently decomposed into constructs such as singleton search mode and feature search mode, followed by the specification of basic mechanisms in the functional architecture such as proactive/reactive suppression/enhancement. Recent work (Cosman et al., 2018a) has shown how these control mechanisms are implemented in the brain. The introduction of the *control state* in the updated version of Contingent Capture provides a useful framework within which to investigate the functional architecture of attentional control and the various means by which the attention system is able to adapt in ways that yield optimal performance for a given task environment.

Viewpoint: Theeuwes

According to the original stimulus-driven selection account (Theeuwes, 2010), salience computations take place automatically, independently of task set. This idea dates back to the initial conceptualisation of a salience map (Koch & Ullman, 1985), which is assumed to represent a two-dimensional spatial map that encodes the saliency of objects in their visual environment. Neurons in this map compete among each other, giving rise to a single winning location (cf. winner take all) that contains the most salient element. It is assumed that the initial shift of attention to the most salient singleton (i.e., attentional capture) is the result of this automatic mechanism triggered by the presence of feature difference signal interrupt. As noted, the area within which salience computations take place can be limited: "One of the premises of the stimulus-driven capture approach is that salience computations are restricted to the attentional window of the observer" (Theeuwes, 2010, p. 91). The overall claim is that within the attended area, and independent of task set, salience computations always take place, followed by a shift of spatial attention to the location having the highest interrupt signal.

Adjustments to the stimulus-driven account

Spatial attention plays a crucial role in the stimulus-driven account. Recently, the Theeuwes lab showed that through statistical learning, locations that are likely to contain a distractor become suppressed such that such a location competes less for attention than other locations (see Figure 4) (Ferrante et al., 2018; Wang & Theeuwes, 2018a, 2018b, 2018c). Because the location is suppressed, the salience signal of the object presented at that location becomes attenuated. A distractor presented at this location gives a smaller saliency signal and because the saliency signal is reduced, attentional capture by a distractor presented at this location is reduced as well relative to distractors presented at other locations (see Figure 4B)

When suppression is location based, it is implemented as a spatial filtering map which is feature-blind (see Wang & Theeuwes, 2018c Exp. 3 and 4; but see Stilwell et al., 2019, for conditions in which suppression can be feature-based). Through spatial filtering, the weights within the attentional spatial priority map change as well. There are two important findings to support this notion. First, because this spatial filtering map is feature blind, the saliency of any object presented at this suppressed location becomes attenuated. This explains why not only distractors presented at this location give less attentional capture, it also explains why it is harder to select the target singleton when it happens to be presented at this suppressed location (see Figure 4C). If suppression would be feature specific, one would have expected that the target singleton would not be affected by this suppression. Second, in all experiments, there was a spatial gradient of attentional suppression for target and distractor that extended with the distance from the suppressed location. Finding such a spatial gradient signifies the spatial nature of the suppression.

In addition to showing suppression of likely distractor locations, it was also shown that through statistical learning, locations that are likely to contain a target are enhanced (Ferrante et al., 2018; Gao & Theeuwes, 2020). This suggests that through statistical learning the weights of the spatial filtering map are adjusted such that weights are increased for locations that that observers have experienced to be relevant and weights are reduced for locations have experienced to be irrelevant. This spatial filtering mechanism ensures that the priority map is flexible, allowing an optimal adaptation to the statistics present in the environment.

Figure 2 presents the adjusted account. There is bottom-up input from the sensory register.

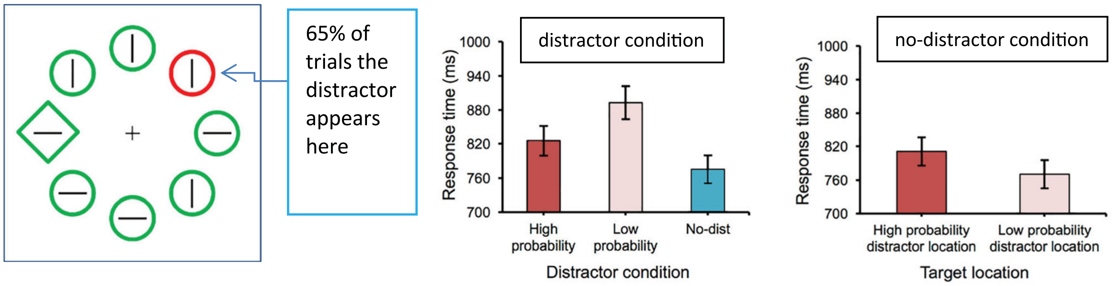

Figure 4. Example display (4a) and results (4b and 4c) from the study of Wang and Theeuwes (2018a). The red distractor could appear at any of the locations but appeared more often in one location (called the high probability location) than in all other locations (low probability location). In half of the trials, the red distractor was absent (no distractor condition). The results showed less attentional capture when the distractor appeared at the high probability location than when it appeared at the low probability location. The no distractor condition (no-dist) gave the fastest RTs (b). In the no-distractor condition, when the target happened to be presented at the location that most frequently had a distractor, participants were slower to select the target than when it appears at any of the other locations (c).

Through statistical learning (labelled as implicit learning in Figure 2), the saliency calculations (spatial gain control) across the visual field can be adjusted. The resulting (spatially filtered) priority map determines the selection priority (e.g., which location is selected first, second, third, etc.). The order in which spatial attention is allocated across the visual field is determined by the adjusted saliency across the visual field. However, there is also a mechanism of reactive control, which allows observers to quickly disengage spatial attention from a location (or feature at a location) which they have experienced through learning to be irrelevant. In this respect, implicit learning that particular locations and features are irrelevant for a task does not allow proactive suppression of these locations or features but does allow a quick and swift disengagement of attention from these locations. In addition, explicit goals may also affect spatial filtering. If observers are explicitly cued to direct spatial attention to a location in space (because the location is likely to contain the target), the weights representing the cued location are enhanced (see Gao & Theeuwes, 2020). Other studies have shown that if attention is explicitly cued to a location in space, very salient events such as abrupt onset transients presented elsewhere in the visual field have no measurable effect on performance anymore (Theeuwes, 1991b). Focusing attention prevents attentional capture by salient events. This fits with the notion that the spatial filtering map attenuates saliency calculations across the visual field.

Implications

According to the adjusted stimulus-driven account there are basically two ways in which suppression of a salient distractor can occur.

(1) *Reactive suppression.* The first way is the traditional way in which suppression of salient singletons occurs (see Theeuwes, 2010). The idea is that attention is captured (even for the briefest moment) by the salient singleton, and if it is not the target, it is immediately suppressed. Through statistical learning, observers may learn that the location or the feature of a distractor is irrelevant giving rise to very fast disengagement of spatial attention such that there is no observable effect of the distractor on the time to find the target. The type of suppression is labelled *reactive suppression* (Won et al., 2019) and is similar to the *search and destroy* hypothesis (Moher & Egeth, 2012), which claims that feature suppression is only possible after attending the location of to-be-ignored feature. It is important to note that this type of suppression is not the same as Luck and Gaspelin (Gaspelin & Luck, 2018c) conceptualise suppression (see above) as they assume that suppression of features can take place without attending to them first. It should be noted that evidence from studies using saccadic eye movements as a dependent measure (Gaspelin et al., 2017) are not always conclusive regarding proactive versus reactive suppression as it is known that capture and subsequent

disengagement can take place without resulting in a saccadic eye movement to the location (Theeuwes et al., 2003). As such the absence of saccadic eye movements to the singleton distractor does not conclusively demonstrate that there was no shift of attention to that location. Thus, although Gaspelin and Luck have argued against the possibility that the singleton captured attention briefly prior to suppression in their experiments (see above), this possibility has not been ruled out with complete certainty.

(2) *Proactive suppression*: As described, through statistical learning the spatial filtering map may get altered such that locations that are likely to contain a distractor become suppressed (labelled spatial gain control in Figure 2). This results in a reduced saliency signal for objects presented at this suppressed location (Ferrante et al., 2018; Wang & Theeuwes, 2018a, 2018b, 2018c). It was shown that this adjustment of the spatial filtering map can only occur through statistical learning; actively trying to suppress a distractor in this way is impossible (Wang & Theeuwes, 2018b). A recent study provided direct evidence that this suppression was indeed *proactive*. In this study, similar to the previous experiments (Wang & Theeuwes, 2018a), the distractor was again presented more often in one location than in all other locations, and critically for this likely distractor location, about 1200 ms before display onset, there was increased alpha power contralateral to this location relative to the ipsilateral location (Wang et al., 2019). These type of alpha-band oscillations have been associated with neural inhibition (Jensen & Mazaheri, 2010) serving as a attentional gating mechanism.

Unresolved issues

The question that is addressed here is the extent to which salient singletons that are known to automatically generate a priority signal can be ignored (contingent capture hypothesis) or suppressed (signal suppression hypothesis). As noted according to the stimulus driven account, only (proactive) spatial filtering (c.f. the attentional window, Belopolsky et al., 2007) allows the attenuation of the saliency signal such that capture is reduced or even eliminated. One critical aspect that has been overlooked in studies that claim to demonstrate the suppression of saliency signals is that in most of these studies the displays that were used did not contain a salient attend-to-me signal. Obviously, when there is no salient signal present in the display there is no need for any signal suppression.

The reason that these displays typically do not contain a salient signal is that the experiment is usually designed to induce the feature search mode (c.f. Bacon & Egeth, 1994) to force participants to search for a specific feature of the target instead of relying on the detection of a pop-out singleton (the singleton detection mode). The idea is that when applying the feature search mode, top-down proactive feature-based control is possible, a result that has been shown in many studies (Bacon & Egeth, 1994; Chang & Egeth, 2019; Gaspelin et al., 2015; Gaspelin & Luck, 2018c). The typical way to enforce the feature search mode is to let participants search for a specific shape (for example a diamond) among various other shapes (e.g., squares, hexagons and circles). With these displays, participants have to search for a specific shape feature and cannot rely anymore on the shape singleton popping out from the background. Even though these findings are convincing there is one caveat when inducing the feature search mode. Because several different shapes are introduced (diamond, squares, hexagons and circles) the target and distractor singleton become less salient and no longer stand out from the background.

There are two factors that affect target and distractor saliency in displays that are assumed to induce feature search. First, saliency depends on local feature contrast, which refers to how different a display element is from nearby surrounding elements (Nothdurft, 1993). Second, saliency is affected by distractor-distractor similarity which refers to the homogeneity of the distractor elements in the display (Duncan & Humphreys, 1989). Critically, it was shown that when distractor-distractor similarity was low (i.e., in heterogeneous displays) search efficiency was low resulting is serial or partly serial search (Duncan & Humphreys, 1989)

Bacon and Egeth (1994) were the first to show that when participants employ the feature search mode, the assumed top-down set prevented attentional capture by salient colour singleton, a finding that is inconsistent with the stimulus-driven account. Yet, while many adhere to the position that the top-down set to search for a specific shape (feature search mode) prevented attentional capture, Theeuwes (2004) showed that it had nothing to do with a top-down search mode but instead was the results of the display characteristics that were used to induce such a search mode. Indeed, Bacon and Egeth used heterogeneous displays to force participants to use feature search but by doing this they rendered both target and distractor singleton as non-salient. Theeuwes (2004) simply added a number of circles to the displays used by Bacon and Egeth (1994) which increased distractor-distractor similarity and made the target and distractor stand out from their local backgrounds (increasing local feature contrast). Even though participants still had to search for a specific shape (a diamond among squares and hexagons) the addition of the extra circles resulted in strong attentional capture by the singleton distractor.

Along similar lines, the most compelling result in favour of the feature suppression account was provided by Gaspelin et al. (2015) and Gaspelin and Luck (2018b) using the additional singleton task in combination with a letter probe task. Their critical finding was that when participants used the feature mode, they were less likely to report the letter inside the colour distractor singleton than in the neutral non-salient element suggesting that the feature search mode induced sub-baseline suppression of the colour distractor singleton. Yet, similar to Bacon and Egeth, in order to induce feature search, Gaspelin et al. (2015) added various shapes to the display making the displays less homogenous without much local feature contrast. Also, in the critical condition which sub-baseline suppression was shown there were only 4 display elements equally spaced around the fixation point which even further reduced local feature contrast and increased heterogeneity in the display

Recently, Wang and Theeuwes (2020) provided evidence that feature suppression can only occur in heterogeneous displays in which none of the elements are salient. Wang and Theeuwes (2020) employed the very same task as Gaspelin et al. (2015) but instead of only testing 4 display elements, in other conditions (between subjects) there were either 6 and 10 elements in the search arrays. For display size 4, Wang and Theeuwes (2020) perfectly replicated the Gaspelin et al. (2015) suppression effect as participants were less likely to report the letters presented within the colour singleton distractor. Yet with larger search arrays (6 and 10 items) there was no sign of any suppression; instead and consistent with the stimulus-driven account, for display size 10 in which that target and distractor singleton were salient, there was clear evidence that the colour distractor captured attention as participants were more likely to report letters presented within the colour singleton distractor than letters presented within the other non-singleton elements in the display. Also, in this condition the colour distractor singleton interfered with search for the target circle providing additional evidence of attentional capture even though participants had to use the feature search mode.

Wang and Theeuwes (2020) argued that in these type of displays with a limited number of heterogeneous elements, there is no capture by the colour singleton not because of some assumed top-down feature-suppression but simply because there is no salient priority signal to begin with. These studies do not speak to suppression of salient signals because there are simply no salient signals present in the display. For the large display sizes when the colour and target signals were salient, even when searching for a specific feature, there was attentional capture by the colour singleton consistent with the stimulus- driven account. Wang and Theeuwes (2020) argued that feature suppression only occurs in displays in which there are no salient elements inducing a (partly) serial search strategy (see also Barras & Kerzel, 2016; Kerzel & Burra, 2020 for similar arguments). Indeed, consistent with this idea is the finding in most feature search experiments of Gaspelin et al. (2015) and Gaspelin and Luck (2018b) distractor present trials are faster than distractor absent trials. Even though this was considered to be an unexpected result (typically distractor present trials are slower than absent trials), it makes sense if search is indeed serial because then there is one item less to inspect when a distractor is present than when it is absent. Note that a similar result was reported by Chang and Egeth (2019) also using heterogeneous four element displays. As noted, because search is likely to be serial, a reversal of the capture effect is to be expected as observers search in a serial manner three instead of four elements.

Note that saliency of the elements in the display also may play a role in the contingent capture paradigm (Folk et al., 1992). In almost all experiments on contingent capture only four elements were used equally spaced around the fixation point. As noted this renders all element rather non-salient. Yeh and Liao (2008) addressed this issue in a study in which they use the classic contingent capture paradigm (Folk et al., 1992) but had in addition to the classic four element displays also a condition with eight equally spaced display elements. Critically, when the larger display sizes were added, regardless the contingent top-down set of the observer, all salient elements (both abrupt onset and colour singletons) captured attention.

Concluding remarks

Longstanding scientific controversies often fade away without any real resolution, leading to the adage, "Science progresses one funeral at a time." In the present paper, researchers who have taken opposing theoretical positions for many years have joined together to describe progress toward resolving a long-lasting controversy about the nature of attentional control. Specifically, it is now clear that physically salient stimuli automatically generate a priority signal that, in the absence of specific attentional control settings, will automatically capture attention, but there are circumstances under which the actual capture of attention can be prevented. As a result, the current models of the three research groups represented in this paper are quite similar, with only a few remaining areas of disagreement (see Figure 1). Moreover, it is now clear how the remaining disagreements can be resolved by future research.

The biggest disagreement concerns the conditions under which singletons can be proactively suppressed (rather than whether they can *ever* be suppressed). All three theories now agree that singletons can be suppressed at small set sizes, when none of the elements are highly salient. However, a recent study has found a lack of suppression at higher set sizes (Wang & Theeuwes, 2020). As more evidence accumulates, it will become clearer whether suppression is possible for singletons that are unambiguously salient. It also remains to be understood how people learn to suppress salient items (see Vecera et al., 2014 for a detailed discussion). Specifically, it is currently unclear whether the ability to avoid visual distraction is solely the result of implicit learning or whether more explicit forms of learning may also contribute to the ability to avoid distraction.

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