

Investigating Conscious and Unconscious Processes of Top-down Distractor Suppression

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by

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CERTIFICATE

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1. Mohite, V., Prasad, S., & Mishra, R. K. (2023). Investigating the role of spatial filtering on distractor suppression. *Attention, Perception, & Psychophysics*, 1-12. (ISBN/ISSN Number1943-3921), Chapter of dissertation where this publication appears: **Chapter 5**.

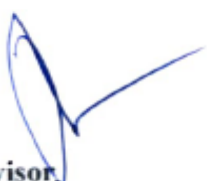
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List of Abbreviation

RT	Reaction Time/ Response Time
CFS	Continuous Flash Suppression
V1	Visual cortex area 1
ERP	Event-related potential
Pd	Distractor positivity
M	Mean
SE	Standard Error
MSD	Mean Standard Deviation
MAD	Median Absolute Deviation
ANOVA	Analysis of variance
IOR	Inhibition of return
CTOA	Cue-target onset asynchrony
PAS	Perceptual awareness scale
ITI	Inter-trial interval
NH	Normal hearing
HI	Hearing impaired
SERR	SEarch via Recursive Rejection
WMR	Working memory resources
HPDL	High probability distractor location
LPDL	Low probability distractor location
MT	Middle temporal
MST	Medial superior temporal
ISL	Indian sign language
DAN	Dorsal attention network

Abstract

Distractors interfere with goals by capturing attention and slowing responses. When distractors are salient, capture can be automatic and instant. Attentional control must spend cognitive resources to suppress such distractors below thresholds of baseline attentional processing, such that they remain unattended. Factors such as task demands, task difficulty, target-distractor similarity, etc. influence the degree of suppression, but conscious awareness of distractor features and locations can significantly alter suppression. The thesis explored various processes of conscious and unconscious distractor suppression using manual RT and eye movement recording, proposing physiological and oculomotor indices of suppression. Suppression of distractor is compared across feature maps and spatial location maps for conscious and unconscious processes using cues preceding search. Studies show evidence for both consciously and unconsciously guided suppression, with better suppression for intermediately unconscious processes (subconscious), indicating a complex interaction of conscious awareness and distractor suppression. Cue-based guidance on conscious and unconscious suppression was based on task goals, such that feature cues guided suppression better when the feature was critical to the task (contingent-suppression hypothesis). Similarly, spatial suppression was seen when utilizing spatial contingencies of a distractor using spatial cues was beneficial to the task. Goal-directed suppression was seen irrespective of learning and intertrial priming. Individual differences in visual capacities also influenced the magnitude and mechanism of distractor suppression.

CHAPTER 1

Introduction

The past decade has shown that goal-relevant and stimulus-driven factors contribute to attentional guidance in a complex interplay. Newer influences on attention such as selection history, value-based learning, etc. have also been shown to influence the control. Not only do they enhance target selection but also facilitate suppression of distractors. While observers are conscious of the goals they pursue, some influences often escape conscious awareness, especially during distractor suppression. The unconscious processes that precede suppression may have significant implications for the suppression of distractors. This poses an important question, does awareness of the features/locations of potential distractors influence suppression? Few studies have investigated this by introducing cues that inform observers of an upcoming distractor, but without perceptual awareness, using continuous flash suppression (CFS) or subliminal primes. While both consciously and unconsciously perceived cues influence the processing of distractors, distractors are not inhibited below baseline filtering thresholds. This suggests that the process of suppression and the conscious awareness of the observer (of items to be suppressed), interact during search. The thesis explores this question through a series of studies with subliminal distractor-matching cues during variations of a feature search task. This chapter discusses the various concepts surrounding distractor suppression, a historical overview of suppression, models of conscious and unconscious suppression, and empirical findings supporting distractor suppression in the absence of conscious awareness.

1.1 Selective attention and distractions

The visual world is a dynamic clutter of objects. Our eyes are bombarded with stimuli faster than our visual processing capacity. While walking down a street, you may encounter trees, pedestrians, vehicles, pets, street signs, and other such things besides the way you need to go. To stay focussed on the current activity, attention must steer away from distractors and towards the potential

targets. But attention has a limited processing capacity (Duncan, 1980), hence every object in the visual stream cannot be processed by attention. As a result of a complex competition between targets and distractors (Desimone & Duncan, 1995), attention is driven towards potential targets and away from potential distractors, thus selective attention (or selection). Selection can be based on the immediate goals of the observer, properties of the visual stimulus (such as salience and contrast) and the history of selection (Liesefeld et al., 2024). Models of visual search capture the various ways in which selection can be guided as a function of some or all of these influences. The classical models such as the guided search theory (Wolfe, 2021, 1994) suggest that these influences alter a priority map for attention and achieve selection. If the goals are clear and the incentive to complete the task is strong, top-down influences take precedence in selection (Anderson, 2014; Remington, Folk & McLean, 2001). But if the visual scene comprises salient stimuli, attention can be directed to them instead of goal-relevant stimuli, suggesting stimulus-driven guidance (Corbetta & Shulman, 2002; Yantis, 2000). Additionally, the selection of a repeated target is often guided by selection history, implicitly during the search (Failing & Theeuwes, 2018; Jiang & Sisk, 2019).

1.2. Dual processes of selection

Recently, distractor suppression has been seen as not just a byproduct of target enhancement but an independent neural process altogether (Noonan et al., 2016). Studies have shown that alpha power increases with target enhancement but decreases with distractor suppression (see figure 1.1)(Fu et al., 2001; Mazaheri et al., 2014), although the evidence for the latter is scarce (Antonov et al., 2020; Foster & Awh, 2019). This dual yet complementary process takes place in the areas V1 to V4. While one pathway is responsible for enhancing target features and location, another is responsible for suppressing the distractors. Efficient target enhancement as well as distractor suppression benefits search, however, observers often demonstrate a bias to one or other of these processes as their dominant search strategy. Distractor suppression, thus, is not observed in all search

contexts. The necessary conditions for suppression vary from that for target enhancement. This makes it interesting to know when a distractor can be suppressed and when it cannot, since, the degree of suppression may also vary with the process of suppression it goes through. The upcoming sections elaborate on various processes that enable an inhibitory influence on distractors.

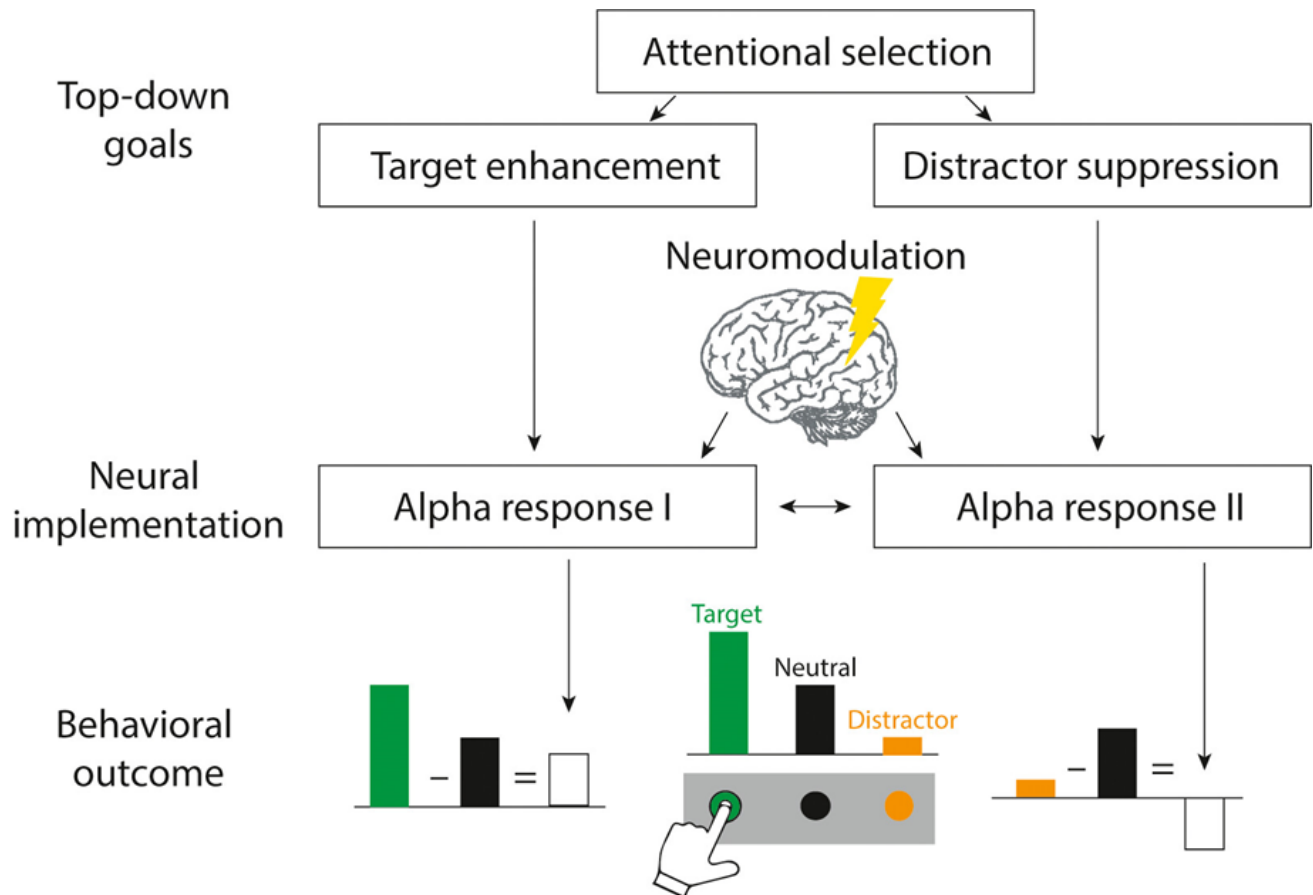


Figure 1.1. Alpha modulation during search. Schneider et al. (2022) showed differential alpha response to target enhancement and distractor suppression and corresponding behavioral outcomes.

1.3. Distractor suppression

Objects that do not concern our goals are distractors. Broadly defined, they are all items that spatially surround the target, resemble some of its features, or may even appear where the target is expected. Since attention is prone to be directed to distractors instead of the target, processes guiding

selection have ways of suppressing them. Suppression is a result of below-threshold prioritization of objects that are distractors (Gaspelin, Leonard & Luck, 2017; Richter, Ekman & de Lange, 2018; St. John-Saaltink et al., 2015). If targets receive the highest priority for attention, non-targets (items other than the target) receive low priority for attention, and distractors receive even lower priority and are hence suppressed (Falkner, Krishna & Goldberg, 2010; Ferrante et al., 2018; Zhang et al., 2019). This implies that activation of the target will require minimal cognitive effort, whereas activation of the distractor will require substantial cognitive effort. Suppression is always relative (Liesefeld et al., 2024) hence baselines are critical for understanding suppression. Many studies show that the salient feature allows suppression of the singleton distractor more than other non-singleton distractors. This distractor can be a unique-colored object in a homogeneously colored array of objects, or a unique shape among homogenous-shaped objects (Gaspar & McDonald, 2014; Gaspelin & Luck, 2018).

Suppression leads to graded prioritization of attention among targets, non-targets, and distractors (here the singletons). This results in faster RTs to the target in the presence of the singleton compared to its absence (Stilwell & Gaspelin, 2021). When studies measured eye movements during suppression, they found faster SRTs to the target in a singleton's presence. Eye movements towards the singleton are inhibited (depending upon task difficulty). The percentage of first saccades, which is an index of attention capture, is also significantly lower on singleton distractors compared to other distractors (Gaspelin, Leonard & Luck, 2017). Many studies have shown these effects when the singleton distractor is repeated across trials at a given location (statistical learning) or when participants are explicitly aware of its features or locations (goal-directed guidance), suggesting top-down control over distractor suppression (Britton & Anderson, 2020; Wang & Theeuwes, 2018a). However, participants are often unaware of learning such contingencies about the distractor (implicit learning) and show less suppression when they are made more aware (Adams & Gaspelin, 2020,2021), suggesting that perceptual or conscious

awareness of the distractor and its features critically influence the forces guiding suppression. The section below discusses the development in the understanding of attention and awareness in models of selection concerning suppression.

1.4. Influences on distractor suppression

1.4.1. Goal-driven influences

Goal-directed suppression refers to the intentional process that guides the suppression of stimuli that are irrelevant to the task. Goals are established through prior knowledge or with the help of cues that inform observers of task-relevant information. The clearer the observer's intentions are in the task, goal-directed control processes are as efficient. A lapse in intentions or goals can lead other influences (such as stimulus-driven influences) to take over goal-directed control (Simons et al., 2000). Thus, goal-maintenance is critical for suppression. Further, the incentive to use prior knowledge in a task also influences goal-directed suppression such that individuals differ in their ability to exert goal-directed control (Ashinoff, Geng & Mevorach, 2019; Levy & Anderson, 2008; Mevorach et al., 2016). For instance, the load theory of attention suggests that under a high perceptual load irrelevant information is automatically suppressed, but a low perceptual load leaves spare attentional resources for irrelevant information to be processed (Lavie et al., 2004). Thus, irrelevant distractors are suppressed better when the task conditions simulate a high load context. The prefrontal cortex and anterior cingulate cortex play a crucial role regulating goal-directed distractor suppression (Kuhl et al., 2008).

1.4.2. Stimulus-driven influences

Stimuli can capture attention based on its own attention-grabbing properties, irrespective of task goals. For instance, stimuli that are highly salient in features (brightness, contrast, movement pattern, luminosity, etc.), or novel stimuli tend to capture attention automatically. Many studies have

suggested that attention is directed to stimulus with such properties within the first few milliseconds of search (Yantis & Egeth, 1999). Moreover, stimuli closer to the locus of attention also capture attention instantly compared to stimuli that are spatially distant (spatially salient). These properties of a stimulus that are irrelevant to the task, yet make them pop-out, contribute to attention capture. Naturally, stimuli that are non-target but resemble them also capture attention albeit more than completely irrelevant stimuli (contingent capture), as they match the attentional set at least in parts (Gibson & Kelsey, 1998). For instance, during a typical feature search, participants find a green circle among distractors that are also green but different in shape, while any one distractor is presented in the non-dominant color (say red) It is difficult to discern which of them capture attention more strongly. One theory would predict stronger signal from salient stimuli due to greater absolute salience, but another will predict greater interference from non-targets as they share features with the target (Liao & Yeh, 2013; Theeuwes, Olivers & Belopolsky, 2010).

1.4.3. Influences from selection history

We learn from experience during search (Bichot & Schall, 1999). If a target is encountered more often at a location, or in a quadrant, finding a target there becomes subsequently easy (Anderson et al., 2021; Wolfe, Cain & Aizenman, 2019). Similarly, repetitive distractors can be suppressed better. Frequent exposure to a distractor appearing at one location, creates a probabilistic expectation about it. Observers learn contingencies of the distractor, ‘statistical learning’. Thus, other locations automatically become low-probability distractor locations. Studies have found that search RTs are faster when a distractor appears at high probability locations compared to low probability locations (Anderson & Kim, 2020; Kim, Ogden & Anderson, 2023). Interestingly, such statistical learning can happen even without the explicit knowledge of the observer, implicitly through passive exposure with a distractor (Di Caro, Theeuwes & Della Libera, 2019) and not just through active suppression of a singleton distractor (Tseng et al., 2014). The priority for attention is strengthened if

a target is repeatedly presented in a certain color or at a certain location and such locations and features are weighed higher on the priority map (Chetverikov & Kristjansson, 2015; Di Caro & Della Libera, 2021). But when a distractor is suppressed over and over again, the features and locations of the critical distractor obtain consistently lesser weights for priority computation. This is also why practice with a distractor makes suppression easier and faster, whereas every new exposure to a novel distractor takes time for suppression to set in (Stilwell, Bahle & Vecera, 2019). The effects of such learning persists over trials, and can transfer across task conditions (de Waard et al., 2023).

1.5. Mechanisms of distractor inhibition

1.5.1 Classical Models

The feature inhibition hypothesis, proposed by Treisman and Sato (1990) in studying diverse conjunction search and search mechanisms, proposed that features of stimuli which are not part of the attentional set (distractors) can be ignored by inhibiting the feature maps corresponding to them. Thus, if the color feature map was inhibited, it would prevent the processing of not only one but many distractors with that color. As a result, a group of distractors could be suppressed altogether, making selection more efficient. This hypothesis also predicts that suppression of a ‘red’ feature on the feature map would result in efficient suppression of ‘reddish’ features of other distractors more effectively than, say, greenish or bluish features. A recent revival of this idea was seen in experiments by Won and Geng (2018) who suggested a template for rejection comprising features of distractors to be suppressed. As observers learn upcoming distractor features, the template is revised and matched against visual stimuli for active suppression. Such learning creates a suppression template of a range of distractor features and makes the search easier (Won & Geng, 2018). Suppression becomes difficult, however, when the distractor shares features with the target. To suppress such distractors, more inhibition is needed to overcome the activation of (target-related)

features in the target template and relative inhibition in the distractor template. Thus, if a search array contains more distractors that resemble the target, the search is difficult.

A later account by Desimon and Duncan (1995) is the most popular model of attention selection. They proposed that the filtering of information takes place in two distinct pathways, the ventral and the dorsal pathway, situated in the parieto-occipital network of visual processing. The neurons along this pathway become increasingly specialized in processing information (such as shapes, colors, orientation, etc.) and hence restrict the number of stimuli moving up the pathway. The stimuli that reach the end of this pathway get selected for attentional allocation. Influences such as, current task goals, rewards associated with stimuli, perceptual salience, selection history of a target/distractor and learned contingencies about the stimuli, bias the flow of information across the pathway influencing the outcome of selection. They form what current theories call the attentional template. Such a rigorous screening process creates a competition among stimuli to be selected and hence the stimuli that are favored by most influences get selected, which is most often the target stimulus and sometimes a singleton distractor. The stimuli that do not get selected get filtered out from the visual processing stream, and hence no more competes for attention. During selection, perceptual features of the visual stimuli are matched against the attentional template. If a distractor has a feature in common with the target, it moves ahead in the competition compared to distractors that do not match the target in any features. Further, the perceptual processing of the stimuli refines the attentional template and distractors irrelevant to the task are filtered out as a group.

What does suppression of one distractor imply for suppression of another? Houghton and Tipper (1996) further explored how suppression propagates (or spreads) across distractors during search and called it spreading suppression. In their neural networks model, they showed that neurons keep on activating other neurons until suppressed by the activity of a different neuron. This suppression controls selection processes. For instance, the processing of a color by a group of

neurons might allow the processing of another color by another group of neurons, cascade effect—unless the second group of neurons is inhibited and the color they process is suppressed. In this, target selection happens simultaneously as distraction deselection, while working memory representations guide both processes and influence representations of stimuli as active percepts (Tipper, Weaver & Houghton, 1994). Working memory facilitates suppression to spread from one distractor to another by allowing a workspace to match the perceived distractor against representations of the target. Thus, active perception is affected by feedback from working memory during the search and can be dynamically adjusted to the task context. Such inhibition leads to a phenomenon called ‘negative priming’, which results in slower RTs when previously suppressed distractors become targets on an upcoming trial. The residual inhibition of the distractor features during its initial encounter makes its selection on later trials difficult, and hence search slows down. Subsequently, longer exposure with distractors would thus increase the strength of negative priming. As the number of prime trials decreases, the inhibition over repeated distractors decays.

Most previous models rely on prior knowledge of distractor features from either task instruction or experience, the predictive coding model explains expectations suppression—repeated occurrence of a specific distractor. Predictive coding emphasizes reducing errors in predicting the target, and consequently results in the suppression of distractors. According to this model, suppression of stimuli is active at a baseline level at all times during a task, especially when no novel conditions are introduced to the task. Expectations about the distractor build through passive exposure to them. This model differs from all previous models in suggesting that working memory updating is not necessary for learning contingencies of distractors as they build over time. Thus, observers can implicitly learn if a distractor is expected more often at one location and suppress that location better than another location at which the distractor is less frequent (Lin et al., 2021; Noonan et al., 2016). The model proposes that errors in detecting the target, such as selecting a distractor, trigger a prediction error which releases feedback to the predictive process about ‘what is not the

target’. This process fine-tunes the information about the target and in turn about the expectations of the distractors. Such learning of distractor features is hence implicit and does not involve working memory representations of distractor features or their active suppression. Predictive coding explains selection as a process of minimizing prediction errors during target detection and not explicit suppression of distractors, during search.

1.5.2 Current Models

The current models differ from classical ones in the view that certain distractors that are more salient can be suppressed more than those that are not, unlike the assumption that suppression is generalized across distractors. The signal suppression hypothesis posits that singleton distractors capture attention almost instantly, but they can be suppressed by top-down attentional control, if they are proven to be completely task-irrelevant (Gaspelin, Leonard & Luck, 2015). Unlike other models, that suggest suppression of low-level features, the signal suppression hypothesis proposes suppression of attention-grabbing signals by top-down control processes. This effect is demonstrated during feature search, where a unique shape (feature) target is presented among an array of other heterogeneous shape distractors and a color singleton distractor. Typically, the distractor presented in the unique color captures attention and slows RTs, during the singleton search paradigm. However, during feature search, RTs are faster on trials that contain the singleton distractor compared to trials that do not. The signal suppression hypothesis explains this effect by assuming goal-directed control of the search for a target is based on the shape feature. Thus, the color feature is task-irrelevant and hence the color singleton distractor is task-irrelevant too. Participants use feature search mode, to suppress the singleton distractor (as shown in Figure 1.2). In a singleton search task, the target is defined by a shape while all distractors have another shape (homogenous), hence the search template is presumably set to find the ‘unique’ shape and not a specific shape feature (singleton-search mode).

A unique color singleton here fits the attentional set and hence captures attention as if it were the target of the search. The signal suppression hypothesis thus supposed top-down control of attention, overriding stimulus-driven capture by singleton distractors.

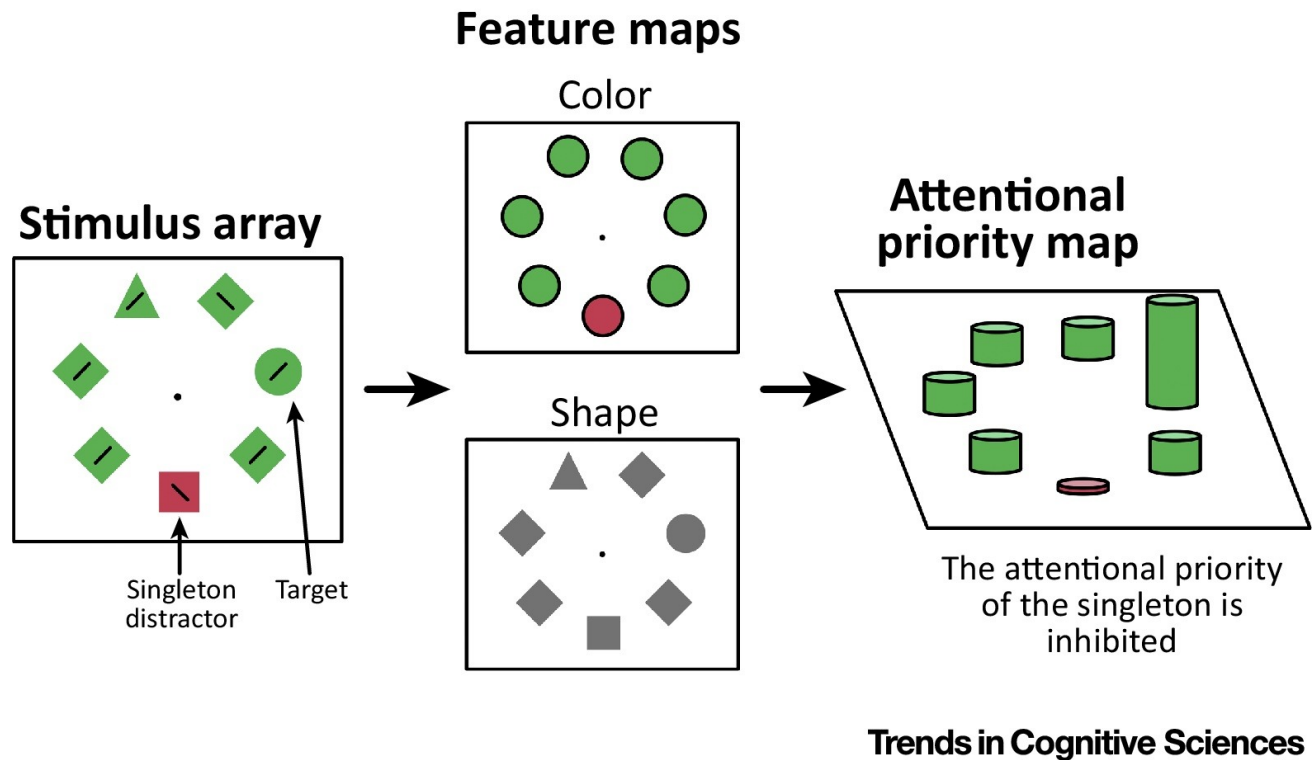


Figure 1.2. Distractor suppression during feature search. Gaspelin and Luck (2018) proposed the signal suppression hypothesis, suggesting that stimulus-driven capture by salient singletons can be prevented by top-down control. The figure shows reduced priority of the red singleton distractor on the attentional priority map.

The conditions that allow suppression and the mechanisms of suppression were discussed in the previous models, but the question remains—what gets suppressed? During search, an object is made up of many features and the task might have one or more relevant features. When a distractor is suppressed, do participants suppress the entire object (all its features and location) or suppression of any feature/location of the distractor is sufficient to prevent capture? First-order suppression suggests inhibition of a distractor by suppressing its critical feature or location. On a feature map, the

feature of the distractor is suppressed below thresholds of baseline attentional processing (Gaspelin & Luck, 2018). This first-order suppression is only possible if the critical feature (color, orientation, vibrancy, movement pattern, etc.) of the distractor is known or learned with experience. According to feature integration theory, until features are combined into an object with the help of attention, they are processed unconsciously. Thus, first-order suppression must operate below the levels of conscious awareness (Treisman & Gelade, 1980). This makes first-order suppression a cognitively efficient process, as fewer cognitive resources are needed to achieve early perceptual suppression compared to attentional suppression. However, unexpected distractors cannot be suppressed using first-order mechanisms.

Second-order suppression allows more flexibility during search. This alternative account suggests that feature discontinuities on first-order feature maps can be used to suppress distractors. Hence, knowing the specific feature of the distractor is not necessary for second-order suppression. For instance, if the task is to find a green target between all green but one red distractor, the red distractor must be suppressed. Suppression of any color singleton will yield suppression of the red singleton. Hence, discontinuities in the color feature map will be used to guide suppression. Furthermore, a distractor need not be salient for second-order suppression to take place. Any distractor which fits into the spectrum of feature discontinuities is suppressed. This happens when a singleton distractor appears at a location of a previous singleton distractor; prior suppression at that location allows better suppression of the singleton re-appearing at that location, compared to a singleton appearing at a new location. Such effects can also be seen for long stretches of trials. For instance, the frequency of appearance of a distractor can be used to suppress it rather than its critical feature. Statistical learning of the high-probability distractor locations creates a contrast in distractor location probabilities and guides suppression using second-order processes (Won et al. 2019). Similar predictions are made by the dimensional weighing account, which suggests that suppression operates on dimensional maps instead of feature maps. Suppression of a dimension depends on the

weights it is assigned; assignment of weights depends upon task relevance (Found & Müller, 1996; Müller, Heller, & Ziegler, 1995; Müller, Reimann, & Krummenacher, 2003). Thus, distractors that share features with the target on dimensions with maximal weight have a greater propensity to be suppressed, even if the distractors are not salient in features. For instance, if you are searching for a red hatchback car among gray and black hatchbacks, the weights will be greater on color dimension rather than shape dimension. Hence, a red sedan might be more distracting than a gray hatchback.

Another form of suppression is called feature-blind attentional suppression. This allows suppression of anything which is not the target (Ma & Abrams, 2023). For instance, while looking for a green target, all blue items in the display will be suppressed, even if some blue items share the target shape. Such suppression is considered to take place automatically and quickly with limited flexibility or control. The benefit of such suppression can be seen in large sample searches when a target is one in a hundred items. Mass suppression of non-targets is necessary for efficient search. Hence, the criteria for suppression must be as broad as possible. The limitation of this process, however, is that it may lead to the suppression of relevant information along with distracting information, and prevent critical learning during search. No prior knowledge is needed for feature-blind suppression suggesting that top-down processes are not influencing this process, hence it can take place almost instantly with exposure to stimuli. Taken together, top-down attentional processes are capable of inhibiting distractors with known specific features as well as distractors anticipated from experience. Moreover, experiential knowledge of feature/location discontinuities guides suppression. Finally, all non-targets can be suppressed in a feature-blind manner in a quick, automatic fashion. All models convergently suggest that the representation of distractor or distractor-like items during the search is used and updated for suppression (Gao & Theeuwes, 2020) and such updating takes place pre-attentively (Donnelly, Humphreys & Riddoch, 1991; Treisman,

1992). This opens the discussion to an interesting question of the role of perceptual awareness in suppression (Chisholm & Kingstone, 2014; Prasad & Mishra, 2019).

Table 1.1 Describes the various processes of distractor suppression.

Type of suppression	What is suppressed?
First-order suppression	Critical feature (or location) on feature maps
Second-order suppression	Feature discontinuities on first-order maps
Dimensional suppression	Critical dimension on dimensional map
Feature-bling suppression	Task irrelevant features and locations

1.6. Awareness and suppression

In a seminal article, Dehaene et al. (2006) proposed a relationship between conscious perception and top-down attention. Using neuroimaging studies, they suggested separate brain areas for processing stimuli at varying levels of perceptual awareness. For instance, the parieto-frontal is responsible for conscious processing whereas the occipital cortex alone can facilitate preconscious processing. However, areas associated with subliminal processing could not be detected using neuroimaging methods. The figure 1.3 explains how top-down attention and bottom-up stimulus strength influences conscious perception. When top-down attention is oriented to a stimulus which itself has a strong bottom-up signal, the stimulus is perceived consciously, for instance the target of a search. Diverse brain areas contribute to such perception, from frontal regions to the parietal regions. Observers can maintain such stimuli in attentional focus at will, and also report their perception consciously. When top-down attention is not oriented to a stimuli, such as unattended stimuli, yet they have a strong bottom-up signal, they are perceived pre consciously. This could imply that distractors are perceived pre consciously during search. Only when attention is directed to such stimuli can they be reported. They can still prime responses in favor of the distractors, as neural

activations are permeable to the sensorimotor processes. When the bottom-up signal of stimulus is weak, regardless of top-down attention, they are perceived subliminally. However, when attended the activation of such stimuli is relatively enhanced, and they can also cause priming during search (Dehaene et al., 2006).

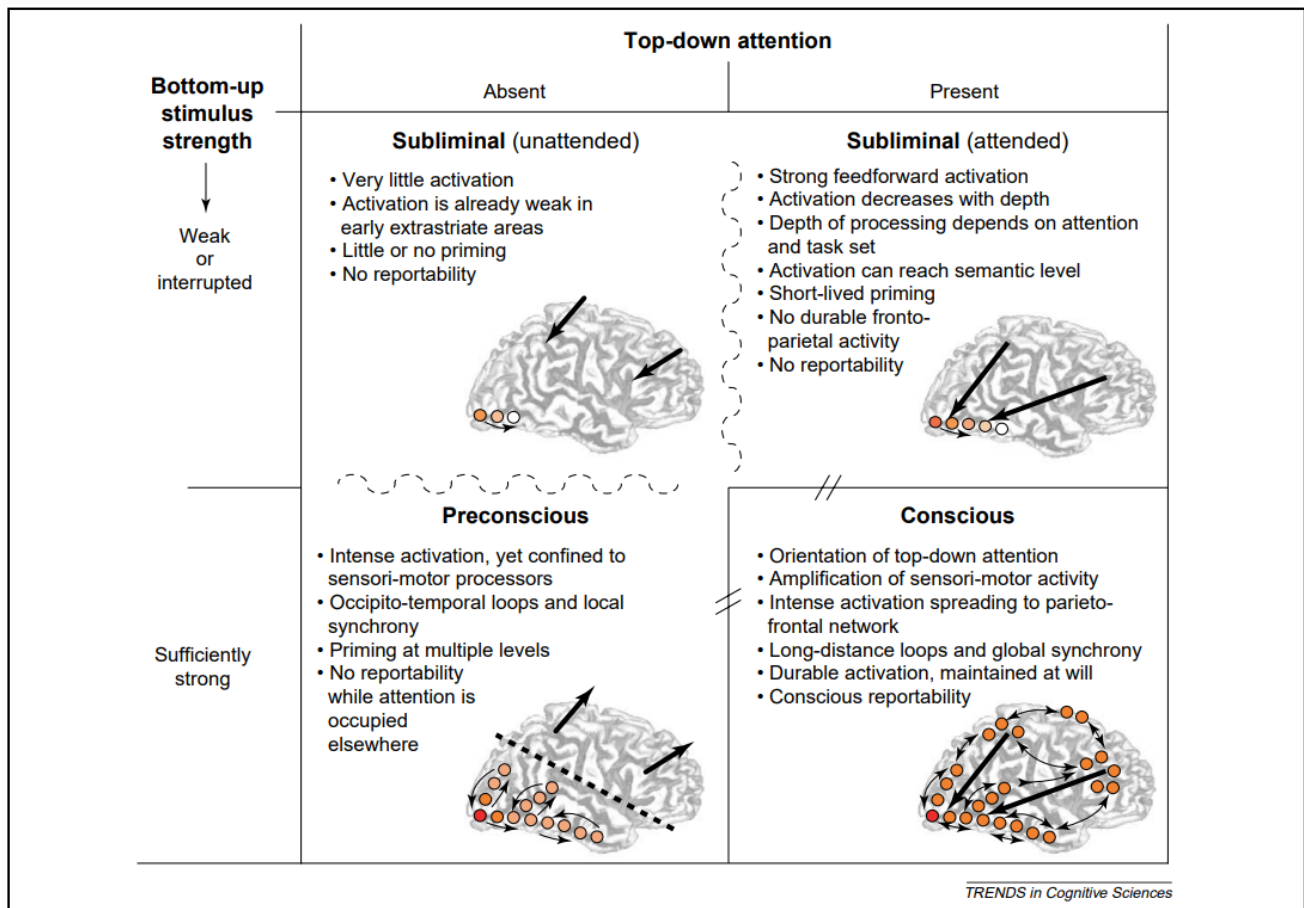


Figure 1.3. Relationship between attention and conscious awareness. Dehaene et al. (2006) explained how access to conscious awareness is controlled by top-down attention and bottom-up salience.

Similarly, in the Biased Competition Theory, attention was necessary for awareness; attention was directed to the target and hence participants were aware of perceiving them; distractors were filtered out, and hence participants were unaware of them. This implied that the filtering process that involved the deselection of distractors took place without conscious awareness of the observer. Most

models of suppression suggest that computations over the distractor take place in memory, such that memory representations of distractors change priority, and are degraded for suppression. According to Colheart (1983), early visual processes were coded in large pockets of iconic memory, which has a short decay time. This can explain why unconscious processes typically occur fast and without top-down control. Further investigations of iconic memory proposed that features such as color, orientation, letters, or numerals could be stored without conscious access to the observer (Allport, 1989). Thus, search displays with distractors that varied in a range of features from each other and the target could be clustered and suppressed in iconic memory (also called spreading suppression) (Houghton & Tipper, 1996). In an influential article, Crick and Koch (1990) proposed that iconic memory is stored through dynamic yet transient changes in the intensity of neuronal connections in the visual cortex (areas V1 and V2) that decayed on their own. Thus, very few resources were required to maintain representations in iconic memory. Since attentional processes cannot take place in a fast timeline, most of the processes that take place in iconic memory are intentional and unconscious, such as distractor suppression.

Studies in the past have suggested a critical role of conscious perception in attention and maintenance of attended stimuli in working memory (Baars, 1997; Noah & Mangun, 2020; Prinz, 2010). In a critical study, Lamy et al. (2015) investigated the role of conscious perception in attention capture in a series of three experiments. People searched for a target letter along with distracting letters when the cue displayed before search either matched or mismatched the target color (Experiment 1). The cue was precluded from perceptual awareness using continuous flash suppression. After reporting the target, participants reported the visibility of the cue using the perceptual awareness scale (0-not visible at all to 3-clearly visible). Task-relevant cues captured attention regardless of their perceptual awareness. Task-irrelevant colors cues perceived below conscious awareness did not result in a cueing effect, i.e., they did not influence attention. Thus, perceptual awareness of cues plays a critical role for attention, when they cue task-irrelevant

(distracting) information. In Experiment 3 when instead of CFS, subliminal cues were used, irrelevant cues produced cueing effects, thus pointing to a complex relationship between task-irrelevant unconscious information and attention capture. Mean RTs were faster when participants were unaware of the cues than when they reported having seen the cueing consciously, suggesting the conscious perception has influences on search beyond selection (Lamy et al., 2015).

1.7. Aim of the thesis

Given this, current thesis aimed at investigating the nature of unconscious goal-directed distractor suppression. This was achieved by contrasting cues perceived subliminally to cues perceived consciously during suppression, while they provided information about the critical distractor. As cues informed participants about a task-irrelevant distractor before search starts, they could use this information to suppress it. We asked, just like conscious cues, can unconscious cues guide search and allow goal-directed singleton inhibition? This would imply that cuing a task relevant feature would enhance search but cueing a task irrelevant feature would enhance suppression. We distinguish goal-directed suppression from learned suppression. The studies were designed to encourage dynamic goal-directed control rather than experiential learning. The paradigm was selected after sufficient testing for the effect of suppression. Further, the cues provided information of an upcoming singleton distractor feature, or location or both. Thus, we could explain a complex relationship between perceptual awareness of the cues at the feature and spatial level during suppression and how it influences search. The thesis examined if suppression across a feature temporal window is comparable to feature suppression in space by identifying oculomotor and manual response indexes of suppression. By contrasting the covert and overt orienting responses, we aimed to explore how suppression as a combination of the two attentional processes takes place with conscious and conscious cues. The final aim was to see variation in suppression as a result of differential vision. We did that by contrasting hearing impaired individuals to people with normal

vision, tapping into domains of neuroplasticity. The objective was to underpin changes in suppression as visual processing capacities differ among individuals, which provided an added layer in the enquiry of distractor suppression.

1.8. Overview of the chapters

The thesis can be grouped into three-subsections. Section one contains Chapter 2, where we study necessary conditions for distractor suppression and explore oculomotor indexes of suppression. In section two, we compare conscious and unconscious processes of distractor suppression. In Chapter 3, we study the effect of location and/or feature cues on distractor suppression with and without the conscious awareness of the observers. Chapter 4 further explores whether unconscious feature suppression can be strategically motivated (top-down) while incorporating subjective assessments of unconscious perceptual experience. Chapter 5 investigates the nature of top-down spatial suppression irrespective of learned suppression of singleton distractors in a registered report. The final section explored individual differences in distractor suppression. In Chapter 6 hearing impaired individuals were compared to normal hearing individuals during search, to investigate changes in distractor suppression mechanisms with hearing-impairment-induced neuroplasticity.

CHAPTER 2

Calibrating Feature Search Paradigm for Goal-directed Distractor Suppression

Attentional selection during visual search is sensitive to probabilistic changes in target and distractor frequency, as well as target indistinguishability. While predictable target appearance enhances search performance, studies have also found reduced capture with repeated exposure to singleton distractors. Whereas, search is perceived to be more difficult when distractors resemble the target more closely. We aimed to find suitable conditions for distractor suppression using two manipulations. In two experiments, we varied distractor frequency and target-distractor similarity to see its influence on active distractor suppression using eye-tracking. By varying the frequency of appearance of a color singleton distractor across easy (experiment 1) and difficult (experiment 2), we measured manual RTs and eye movements. RTs were faster on singleton present vs. absent trials in experiment 2, but in experiment 1. Also, latency on first target saccades were faster in presence of the singleton distractor (experiment 2). Fixation dwell time on the singleton was lower than other distractors and the target, indicating rapid disengagement at the singleton distractor location (experiment 1 and 2). Finally, changing frequency of singleton distractor present trials influenced relative suppression of oculomotor responses towards them, more so during a difficult search task (experiment 2). The frequency manipulation led to probabilistic learning of singleton expectancies, influencing its suppression as per task difficulty.

2.1 Introduction

Visual search is ubiquitous in everyday life. However, the presence of singleton distractors makes this process difficult. Studies show that singleton distractors capture attention reflexively (Forster & Lavie, 2008; Theeuwes, Reimann & Mortier, 2006). Since visual search is attention demanding and attention is a limited capacity resource, one must develop strategies to avoid capture. Bacon & Egeth (1994), showed that it is possible to suppress capture by singleton distractors if the search is for a target feature and not for a target singleton, using the feature search paradigm. Multiple studies have replicated these findings using variations of the feature search paradigm (Barras & Kerzel, 2016; Hickey, Di Lollo & McDonald, 2009; Lamy & Egeth, 2003; Suzuki & Gottlieb, 2013). More recently some have proposed that target searches can in fact improve in the presence of singleton distractors through active suppression (Gaspelin, Leonard & Luck, 2017; Kerzel & Burra, 2020). Few studies have been trying to test the influence of learning through experience on distractor suppression (Won & Geng, 2018). For instance, recent accounts suggest learning of distractor expectancies that are not task relevant (Müller et al., 2009) such that increased exposure to the irrelevant distractors *reduces capture*. In two experiments, we further examine the hypothesis that changing singleton distractor frequency induces varying expectancies and *modulates suppression of the singleton distractor*. Furthermore, we increased incentive for suppression by making the task more difficult, thus calibrating conditions suitable for suppression.

Current studies on distractor interference support three possible mechanisms of distractor avoidance, a) through strategic top-down mechanisms that enable proactive distractor suppression, b) by learning to avoid irrelevant distractors over time and c) by passive attenuation of capture by irrelevant distractors (see Geng, Won & Carlisle, 2019 for a brief review). A strategic ignoring mechanism predicts immediate suppression after encountering singleton distractors, like observed by Gaspelin et al. (2017), (see experiment 2 and 3) using eye tracking. People in this task searched for a

circle/diamond target. A unique color distractor sometimes appeared, along with other distractors, randomly during search. Presence of the singleton benefited search RTs. Lesser percentage of first saccades were directed to the singleton distractor compared to other distractors. Also, the gaze position was directed towards all shapes except the singleton. This study offered clear proof for oculomotor suppression. To explain the findings, they proposed the signal suppression hypothesis which suggests that singleton distractors can automatically capture attention, however top-down control can prevent this capture through proactive suppression (Gaspelin, Leonard & Luck, 2015, 2017). These results are consistent with a further ERP study showing an early Pd component on singleton distractor present trials compared to singleton distractor absent trials (Gaspelin & Luck, 2018a) implying singleton distractor related inhibitory activity. This Pd component has been suggested to indicate lowering of attentional prioritization or distractor suppression (Burra & Kerzel, 2014).

Learning that a distractor is a task irrelevant can also significantly reduce attention captured by it (Töllner, Müller & Zehetleitner, 2012). For instance, mixing singleton distractor present and absent trials in varying frequencies across trial blocks induces varying expectancies of the singleton distractor. In Geyer et al. (2008) the participant encountered a high (80 %), an intermediate (50 %) and a low (20 %) singleton distractor present block. Blocks influenced singleton presence cost. Interestingly, statistical analysis of fixation durations on the singleton distractor vs. neutral distractors showed relatively shorter fixations on the singleton distractor. This suggested that attention was disengaged faster from the singleton distractor (disengagement hypothesis). This pattern was observed in the low frequency distractor block alone. In the blocks of higher frequencies, the opposite trend was observed, suggesting that a higher exposure to singleton distractors makes disengagement difficult. Although these results were not significant in the study, the disengagement hypothesis raises important implications to the suppression literature. If singleton distractors are to be suppressed successfully, the eventual engagement with them must be avoided through rapid

disengagement (Geng & DiQuattro, 2010; Theeuwes, 2010). Since frequency manipulation can influence capture during singleton search, we expected it to influence active suppression during feature search (Won, Kosoyan & Geng, 2019; Lahav & Tsal, 2013) albeit weakly.

Given the premise, we wanted to replicate the findings of Gaspelin et al. (2017), in a similar feature search task by recording eye movements in addition to manual responses. They found proof for proactive goal-directed inhibition of distractor that was completely task irrelevant. Our aim was to extend those findings with additional modifications of varying singleton distractor expectancy. This would allow us to identify the condition when maximal suppression can be achieved. We also know that expectancies influenced attentional engagement by singleton distractors in Geyer et al. (2008). Hence, eye movement data can inform us if participants were capable of biasing their attention away from distractors without making any eye movements towards them (proactive suppression) or they consider the distractors before rejection (rapid disengagement). A proactive suppression account suggests that fewer saccades end at the singleton relative to other distractors. Additionally, latencies of the saccades that ended at singletons are faster relative to other distractors, implying reflexive shifts of attention. The disengagement account predicts shorter fixation duration on singleton distractors than other distractors. In the current experiments, we could expect results supporting either proactive suppression or rapid disengagement. We measured both saccades and fixations to find evidence in support of one or both the hypotheses. Additionally, assuming the disengagement hypothesis to be true, similar to Geyer et al., (2008), we expected better disengagement from singleton distractors with increasing experience across trial blocks. It is also possible that blocks with higher singleton distractor predictability display proactive suppression and hence better suppression in the 20 and the 80 blocks. And the block with lower singleton distractor predictability displays reactive suppression and hence less suppression in the 50 block (Marini et al., 2016).

2.2 Experiment 1

Random grouping of people to search for circle or diamond target was done. People searched for the target among square, hexagon, and diamond shaped distractors. Since the distractors could be easily differentiated from the target, we expected the search to be relatively easy. On some trials, one of the distractors was salient, hereafter referred to as singleton distractor present trials. The percentage of these trials were varied across three blocks of 20%, 50% and 80% singleton distractor present trials, respectively. We expected that varying the occurrence of singleton distractor present trials would influence relative suppression of singleton distractors in the respective block. However, the easy search task provided minimal incentive for suppression.

2.2.1 Methods

2.2.1.1 Participants

Twenty-seven people registered at the University of Hyderabad (19 males, $M_{\text{age}} = 25.3$ years, $SD = 3.4$ years) having normal visual acuity performed the study. Participants signed a consent form prior to practice session. The methods, data collection procedure and design of the study were approved by the Institutional Ethics Committee of the University of Hyderabad.

2.2.1.2 Apparatus

Stimuli were designed using SR Research Experiment Builder software (SR Research Ltd., Ontario, Canada) and were presented on a 15-inch Dell monitor (1280 x 1024 pixels, 60 Hz), 70 cm away from the participant. The SR Research Eye link 1000 Desktop Mount eye tracking system (SR Research Ltd., Ontario, Canada) recorded eye movements with the refresh rate of 1000 Hz. Responses were recorded using a Cedrus RB-844 (Cedrus Corporation, San Pedro, California, USA) response pad that recorded RTs with the precision of 2-3 ms.

2.2.1.3 Stimuli

All stimuli were presented on a gray background rgb (153, 153, 153). A fixation ($0.52^\circ \times 0.52^\circ$) appeared in the middle of the screen. The search display comprised six items ($1.02^\circ \times 1.19^\circ$) each, randomly placed on the circumference of an imaginary circle subtending 4.5° from the center. Every item was placed at 60° from the adjacent item along the circle. The target and all the distractors were dark gray colored rgb (130, 130, 130), (contrast ratio: 1.35) on trials with no singleton. Other trials had one of the distractor shapes in light gray rgb (240, 240, 240) (contrast ratio: 2.50) in color. Since light gray contrasted more with the background than dark gray, we called it the *singleton distractor* (similar to Geng & DiQuattro, 2010). A black dot rgb (0, 0, 0) was randomly present on each search item for the localization task.

2.2.1.4 Procedure

The procedure was partially adopted from Gaspelin et al. (2017). Participants completed a total of 40 practice trials, 1080 experimental trials interspersed by 2 minute breaks. As shown in figure 2.1, the trial began with a 500 ms an empty display and a 100 ms fixation at the center. The search screen lasted 2000 ms or until a manual button press. It consisted of one target shape and five distractor shapes, equally probable at all positions. Participants reported a dot superimposed on the target (right/left) (response keys were counterbalanced between participants). Since the search items were relatively small, fixating the target was necessary for responding correctly.

The search display either lacked the salient (singleton distractor absent trial) or had a singleton distractor (singleton distractor present trial). The singleton distractor could be of anyone among all distractor shapes, on a given trial. Of the 360 trials, one block had 20% singleton distractor present trials i.e. 72 present trials and 288 absent trials. The other blocks had 50% and 80% singleton distractor present trials, respectively. Participants were given warning messages for 500 ms on

making incorrect as well as slow responses.

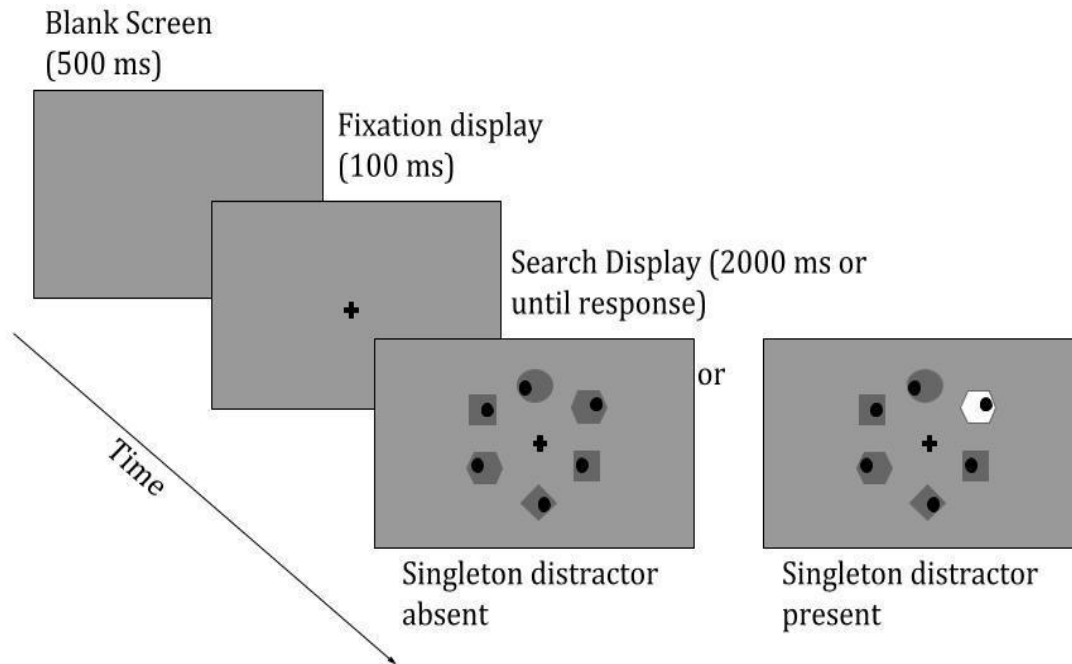


Figure 2.1. Sample trial in Experiment 1 (not to scale). A blank screen, fixation, and search display comprised one trial. Participants encountered either a singleton present or singleton absent trial in randomized fashion and discriminated the location of the dot on the circle (or diamond). Note that both experiment 1 and 2 followed similar trials, except in Experiment 2 the search was difficult.

2.2.2 Analysis

We excluded missing responses and incorrect manual responses from RT analysis, resulting in 1.8% data loss. We also discarded very fast and very slow responses (< 200 ms and > 2000 ms). Additionally, RTs were discarded using Median Absolute Deviation (MAD) since median is insensitive to extreme values unlike the mean (Leys et al., 2013). RTs falling outside 2.5 MAD (moderately conservative exclusion criteria) were considered as outliers (Eng et al., 2018; Lim et al., 2019), removing a total of 5.3% trials from the RT analysis. Using SR Eye link 1000's default configuration, saccades composed eye gaze greater than $30^\circ/s$ and $8000^\circ/s^2$. Only the first saccade

on every trial was selected for saccade latency and proportion analysis. Saccades with latencies other than 2.5 MAD were discarded as outlier saccades removing 8.4 % data from first target saccades and 10.3% data from all first saccades.

Fixation dwell time analysis took into consideration fixations only on the target, singleton distractor and non-singleton distractors. We similarly discarded dwell times other than 2.5 MAD causing 4.6% data loss. Statistical analysis was performed on the filtered data using RStudio Version 1.2.5003 (2009-2019 RStudio, Inc). To account for the large individual variance in attentional control, we analyzed the data using Linear Mixed Model for mean RT, latency on first target saccades, percentage of first saccades, fixation dwell time and percentage of fixations. We used Generalized Linear Mixed Models for accuracy data, since it required comparing proportions of correct responses. lme4 and lmerTest packages were used for the analysis (Bates et al., 2014). All results were reported in the appendix using the package stargazer (Hlavac, 2018).

2.2.3 Results

2.2.3.1 Manual RT

A linear mixed effect model was fit for RT data with singleton distractor (present vs absent) and block (20, 50, 80) interaction as fixed effects and participants as random effects factor. For this model, distractor was coded using sum coding (i.e., present = 1, absent = -1) and blocks were coded using contrast coding, creating a factor block 2050 (20 = -1, 50 = 1, 80 = 0) for comparing blocks 20 and 50, and factor block 2080 (20 = -1, 50 = 0, 80 = 1) for comparing blocks 20 and 80. As shown in figure 2.2(a), RTs on singleton present and absent trials were similar ($t = 0.28$, $p = 0.778$), suggesting that singleton distractors were not suppressed. Mean RTs were significantly slower in the 50 block ($t = 3.36$, $p < 0.001$) and in the 80 block ($t = 3.31$, $p < 0.001$) compared to the 20 block. However,

singleton presence benefit did not differ across blocks (distractor*block2050: $t = -0.39$, $p = 0.690$; distractor*block2080: $t = -0.22$, $p = 0.825$).

2.2.3.2 Accuracy

The GLM with distractor and blocks as fixed factors and participants as random factors was fit to filtered accuracy data, coding correct responses as 1 and incorrect responses as 0. As shown in figure 2.2(b) accuracy was similar across singleton present and absent trials ($z = 0.39$, $p = 0.694$), neither did the individual blocks influence accuracy, block2050 ($z = -0.82$, $p = 0.412$) and block 2080 ($z = 1.00$, $p = 0.316$). Distractor and block did not interact significantly (distractor*block2050: $z = -0.69$, $p = 0.486$; distractor*block2080: $z = -0.80$, $p = 0.423$).

2.2.3.3 Saccade latency on first target saccades

We compared first target saccade latencies across all conditions. Main effect of the singleton distractor was not significant ($t = -1.10$, $p = 0.269$), see figure 2.2(c). The main effect of block 2050 ($t = -3.40$, $p < 0.001$) and block 2080 ($t = 2.49$, $p < 0.001$) was significant such that saccades were overall slower in the 20 block compared to the 50 block and slower in the 80 block compared to the 20 block. The interaction of singleton distractor and blocks 2050 as well as block 2080 was not significant (distractor*block2050: $t = -1.28$, $p = 0.200$; distractor*block2080: $t = 0.85$, $p = 0.393$).

2.2.3.4 Percentage of first saccades

The model fit first saccade percentages across blocks (singleton distractor = -1, non-singleton distractor = 1 and target = 0). No difference was observed between distractors (singleton vs others) ($t = 0.25$, $p = 0.799$). Blocks did not influence the overall percentage of first saccades (block2050: $t = -0.07$, $p = 0.943$; block2080: $t = -0.07$, $p = 0.943$). The interaction of saccade location with block was also not significant (saccade location*block2050: $t = 0.17$, $p = 0.861$; saccade location*block2080: $t = 0.03$, $p = 0.974$). The second model comparing percentage of first saccades to target, and all

distractors combined (singleton distractor = -1, non-singleton distractor = -1 and target = 1), showed a main effect of saccade location ($t = 31.43, p < 0.001$), suggesting more first saccades landed on the target than on any distractor. However, the main effect of block (block2050: $t = -0.21, p = 0.831$; block2080: $t = -0.15, p = 0.876$) and the interaction of saccade location and block (saccade location*block2050: $t = -0.38, p = 0.704$; saccade location*block2080: $t = -0.20, p = 0.836$) was not significant.

2.2.3.5 Fixation dwell time

Participants were faster in disengaging attention from the singleton, but not from the non-singletons ($t = -25.31, p < 0.001$). However, blocks did not influence attentional disengagement (block2050: $t = 0.24, p = 0.804$; block2080: $t = 0.40, p = 0.689$) such that the difference between dwell time on non-salient and singleton distractors also did not vary across blocks 20 and 50 (fixation location*block 2050: $t = 0.37, p = 0.712$) but it was significantly greater in block 80 than block 20 (fixation location*block2080: $t = 2.06, p < 0.050$). Also, we found longer dwell time on the target than any distractor ($t = 93.20, p < 0.001$) which suggested stronger attentional focus at the target location, see Figure 2.2(d). Overall dwell times in the 50 block were significantly longer than the 20 block ($t = 2.10, p < 0.001$), however 20 and 80 blocks did not differ significantly ($t = 1.35, p = 0.176$). The difference in dwell time on target and distractors did not differ between different blocks (fixation location*block2050: $t = 0.52, p = 0.600$; fixation location*block2080: $t = 0.96, p < 0.335$).

2.2.3.6 Percentage of fixations

Fixation percentage on the singleton and non-singletons were alike ($t = 0.34, p = 0.734$). Moreover, blocks did not influence the overall percentage of fixations (block2050: $t = 0.06, p = 0.951$; block2080: $t = -0.11, p = 0.907$). The interaction of fixation location and blocks was also no significant (fixation location*block2050: $t = -0.16, p = 0.867$; fixation location*block2080: $t = -0.04, p = 0.963$). On comparing the target and all distractors, we found that the percentage of fixation was

significantly greater on the target ($t = 38.41, p < 0.001$). However, percentage of fixations did not get affected by blocks (block2050: $t = 0.00, p = 0.996$; block2080: $t = 0.08, p = 0.932$) or the interaction of fixation location and blocks (fixation location*block2050: $t = -0.20, p = 0.840$; fixation location*block2080: $t = 0.70, p = 0.483$).

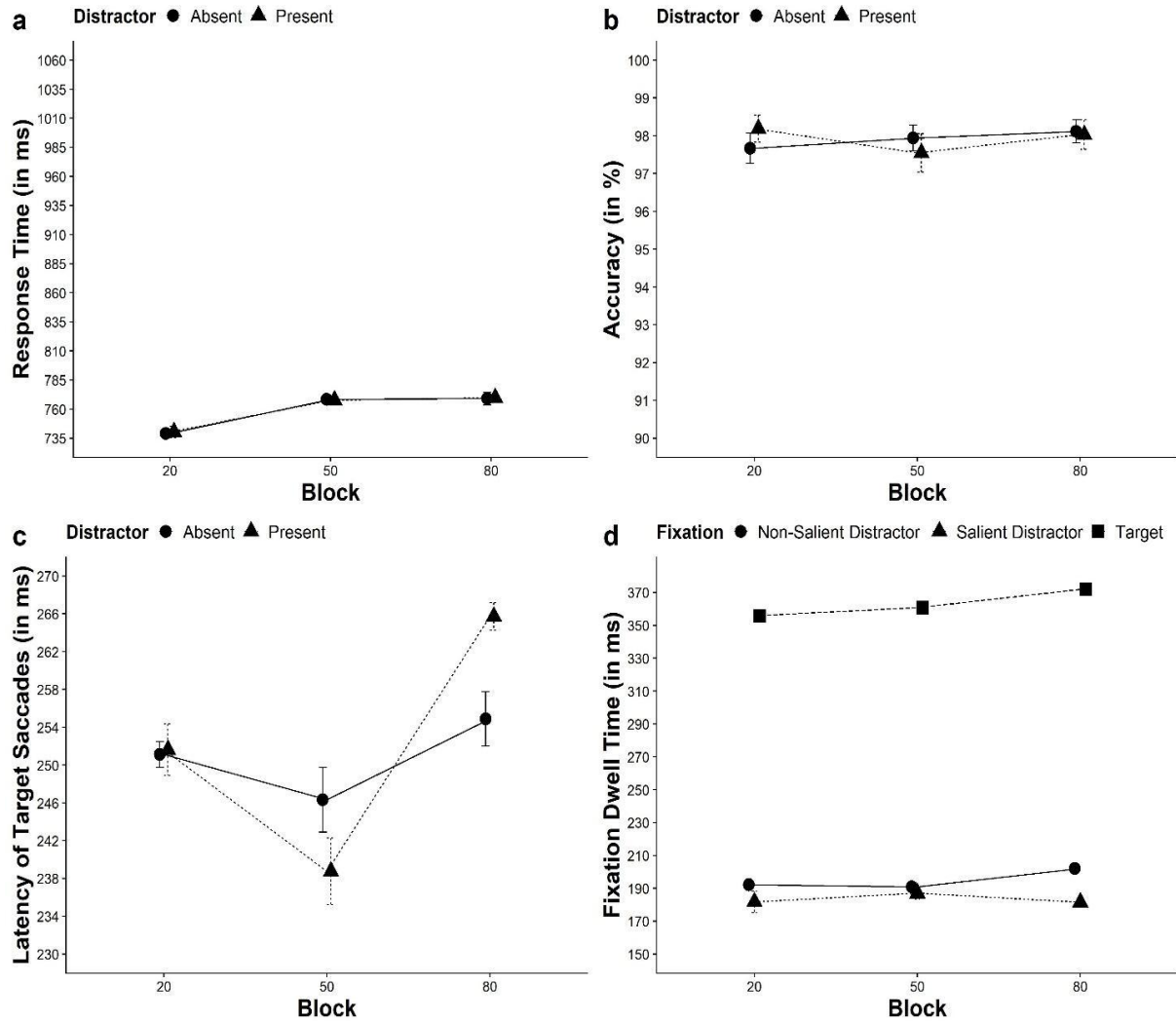


Figure 2.2. Experiment 1 Results (a) Average RT, (b) average accuracy, (c) average saccade latencies of first target saccade (d) fixation dwell time, on singleton present and absent trials, during 20%, 50% and 80% singleton present blocks in experiment 1.

Table 2.1 Mean, standard error (SE) of manual response time, accuracy, and first target saccade latency on singleton absent and present trials in Experiment 1.

Singleton distractor	Block	RT		Accuracy		Saccade Latency	
		Mean	SE	Mean	SE	Mean	SE
Present	20	740.44	4.81	98.19	0.36	251.63	2.72
Absent	20	739.10	2.42	97.67	0.40	251.13	1.36
Present	50	767.61	3.20	97.55	0.50	238.76	3.51
Absent	50	768.38	3.26	97.94	0.34	246.34	3.42
Present	80	769.67	2.76	98.03	0.39	256.71	1.46
Absent	80	769.07	5.59	98.12	0.30	254.89	2.88

Table. 2.2 Mean and standard error (SE) of percentage of first saccades, average fixation dwell time and average percentage of fixations in the presence of the singleton distractor across blocks, and saccade and fixation end locations in Experiment 1

End location	Block	% First Saccades		Dwell Time		% Fixations	
		Mean	SE	Mean	SE	Mean	SE
Target	20	66.70	2.73	355.81	3.35	71.77	3.47
Singleton distractor	20	16.72	2.00	181.69	6.45	12.15	2.03
Non-singleton distractor	20	17.40	1.77	192.13	3.47	16.67	2.41
Target	50	65.01	3.10	360.73	2.12	72.19	2.67
Singleton distractor	50	16.33	2.02	187.02	3.59	13.45	1.52
Non-singleton distractor	50	18.65	1.65	190.90	1.97	15.02	2.06
Target	80	65.27	2.64	371.94	1.60	73.25	1.92
Singleton distractor	80	16.66	1.73	181.53	2.61	12.62	1.06
Non-singleton distractor	80	18.06	1.43	201.99	1.63	14.12	0.97

2.2.4 Discussion

In Experiment 1 we wanted to replicate singleton distractor suppression observed by Gaspelin et al. (2017) and additionally see how varying frequency of singleton distractors influences eventual suppression (Geyer et al., 2008). Unlike them, we did not find evidence for suppression in manual RT. Also, accuracy did not vary on singleton distractor absent and present trials. While blocks influenced overall RTs, they did not alter the relative difference in singleton distractor absent and present RTs (index of response suppression). Saccade latency to first target saccades and the overall percentage of first saccades did not show a bias against the singleton distractor, nor was there any influence of the various blocks. Although, greater first saccades landed on the target, suggesting efficient target selection. In line with the disengagement hypothesis dwell time on the singleton distractors was significantly longer than non-singleton distractors. Interestingly, the difference in non-salient and singleton distractor dwell time was significantly greater in the 80 block than the 20 block, while the 20 block and the 50 block did not differ. The dwell time on target was also overall longer than any distractor, with no influence of blocks on relative target engagement. Fixations on the singleton and other non-targets were comparably equal. While target fixations were significantly greater than non-targets.

While we did not observe a singleton presence (RT) benefit, fixation dwell time showed interesting results. This finding can be interpreted with the help of the attentional dwelling hypothesis which suggests that attention dwells at an object location until it is accepted as a target or rejected as a distractor (Gaspelin, Ruthruff & Lien, 2016; Lamy et al., 2019). Since singleton distractors were (never the target shape) irrelevant to the task goals of the participants, they could be easily rejected or suppressed (Theeuwes, Atchley & Kramer, 2000) causing shorter dwell time. We found that engagement with the singleton distractor increased with increasing experience of encountering them, as expected. While we would expect faster disengagement to result in faster responses as well, studies show that weaker suppression often results in a null effect in RT (Gaspelin & Luck, 2018a). Hence, we suspected due to the relatively easy search task the need to effectively

suppress singleton distractors was less, and the resulting suppression was weak. Although some evidence encourages statistical learning of singleton distractor contingencies during features search, the lack of typical findings in RT and saccade latency prevents us from making strong claims.

Recent neuroimaging and behavioral data suggest that learned suppression or working memory based guidance of visual attention (Jones & Berryhill, 2012) becomes active only in a demanding context (Arita, Carlisle & Woodman, 2012; Geng, DiQuattro & Helm, 2017). Additional electrophysiological evidence suggests that given both positive and negative attentional templates, participants store the positive template in working memory to guide search (Rajsic, Carlisle & Woodman, 2020). While positive cues enhance performance on easy as well as difficult searches, negative cues enhance performance mostly during difficult searches (Conci, Deichsel, Müller & Töllner, 2019). Hence, we propose that difficult search tasks would rely strongly on distractor suppression to maintain search efficiency and additionally show enhanced influence of statistical learning. We tested this possibility in experiment 2. A common way of making a task difficult is by introducing distractors closely resembling the target. As a result, search slopes increase with increasing target-distractor features overlap (Wienrich, Heße & Müller-Plath, 2009).

2.3 Experiment 2

We manipulated search difficulty while keeping the remaining parameters constant in Experiment 2. Previous studies suggest that target search becomes difficult when distractors resemble the target closely. Hence, we expected that finding a circle among these polygons would be difficult and RTs would slow down indicating increased effort (Leber, Lechak & Richardi, 2013; Wienrich, Heße & Müller-Plath, 2009). Also, manual RT suppression would improve accompanied by saccadic and fixation de-prioritization of singleton distractors. Additionally, the difficult search task would make more use of statistical learning. Thus, blocks of varying frequency would display varying degrees of suppression.

2.3.1 Methods

Twenty new volunteers (10 males, $M_{age} = 21.95$ years, $SD = 1.76$) participated in this experiment. In the search display, squares and diamonds were replaced with octagons and pentagons and the target was always the circle, see figure 2.3.

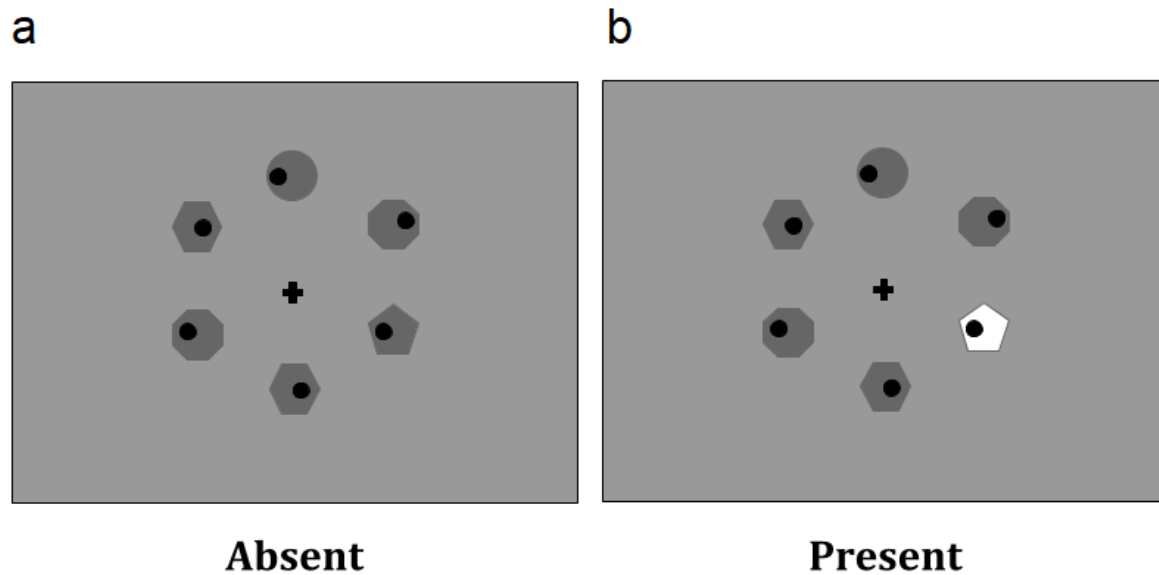


Figure 2.3. A typical search display in Experiment 2 (a) and (b) illustrates a singleton absent and present trials (pentagon), respectively; with circle target, hexagon, octagon, and pentagon distractors.

2.3.2 Analysis

Data exclusion criteria was the same as in experiment 1. Data loss from missing and incorrect key presses (3.5% data loss), RTs < 200 ms and > 2000 ms, and more than 2.5 MAD (1.9%), was incurred. A similar 2.5 MAD criteria led to discarding 7.8% data from first target saccades and 8.5% data from all first saccades. Similarly, we discarded 4.5% fixations from dwell time analysis.

2.3.3 Results

2.3.3.1 Manual RT

Figure 2.4(a) shows a singleton presence benefit ($t = -3.13, p < 0.001$), suggesting that singleton distractor suppression enhanced target search. Blocks influenced overall RTs (block2050: $t = -4.41, p < 0.001$; block2080: $t = 3.99, p < 0.001$) such that 50 block was faster than 20 block and 80 block was faster than 20 block. Singleton presence benefit was not significantly different across blocks (distractor*block2050: $t = 0.82, p = 0.410$; distractor*block2080: $t = -0.18, p = 0.850$). We compared RTs from Experiments 1 and 2 in another model with distractor (presence vs absence) and Experiments (1 vs 2) as fixed factors and participants as random effects factors. RTs slowed significantly in Experiment 2 than Experiment 1 ($t = -8.83, p < 0.001$) due to increased difficulty. We found *suppression in Experiment 2 and capture in Experiment 1*.

2.3.3.2 Accuracy

The GLMM analysis showed that accuracy was significantly greater on singleton present trials compared to singleton absent trials ($z = 3.00, p$ singleton distractor) as shown in figure 2.4(b). Overall accuracy did not differ between blocks (block2050: $z = -0.97, p = 0.331$; block2080: $z = -0.67, p = 0.500$).

2.3.3.3 Saccade latency on first target saccades

Overall, first saccades to the target were significantly faster on singleton present trials ($t = -1.98, p < 0.001$). Blocks did not influence saccade latencies to target (block2050: $t = 1.53, p = 0.125$; block2080: $t = -0.14, p = 0.887$). The relative difference in latencies to target saccades on singleton absent vs. present trials did not differ between block 20 and 50 ($t = 1.67, p = 0.094$) and 20 and 80 ($t = -0.63, p = 0.525$), see figure 2.4(c).

2.3.3.4 Percentage of first saccades

First saccades were equally biased towards all distractors irrespective of salience ($t = 0.78, p = 0.431$). Also, blocks did not influence the overall percentage of first saccades (block2050: $t = 0.55, p$

= 0.577; block2080: $t = -0.28$, $p = 0.779$). The interaction of saccade location with block was not significant (saccade location*block2050: $t = 1.28$, $p = 0.202$; saccade location*block2080: $t = 0.74$, $p = 0.460$). The target attracted majority of first saccades than any distractor ($t = 6.15$, $p < 0.001$). Blocks did not influence the overall percentage of first saccades (block2050: $t = 1.08$, $p = 0.27$; block2080: $t = -0.00$, $p = 0.997$). However, the difference between target and distractor first saccades was marginally greater in the 50 block than the 20 block ($t = 1.78$, $p = 0.075$) while the 20 block and the 80 block did not differ significantly ($t = 0.73$, $p = 0.464$).

2.3.3.5 Fixation dwell time

We replicated the findings from Experiment1, such that dwell time on non-singletons was longer compared to singletons ($t = -26.93$, $p < 0.001$), suggesting rapid disengagement from the singleton distractor, see figure 2.4(d). Fixations dwelled longer during 80 block than the 20 block ($t = 6.44$, $p < 0.001$), but similar between the 20 block and the 50 block ($t = 1.01$, $p = 0.308$). Relatively shorter dwell times on singleton compared to non-targets was seen in the 20 block than then 50 block ($t = -3.49$, $p < 0.001$) and was also greater in the 80 block than the 20 block ($t = -3.28$, $p < 0.001$). These results suggested that disengagement from singleton distractor was overall faster in the 20 block and 80 block relative to the 50 block. Additionally, dwell time on targets was longer than on any distractor ($t = 114.44$, $p < 0.001$). Overall dwell time was greater in the 50 block than the 20 ($t = -2.71$, $p < 0.001$) and in the 80 block than the 20 block ($t = 6.39$, $p < 0.001$). The difference in target and distractor fixation dwell time was marginally greater in the 50 block than the 20 block but was significantly greater in the 80 block than the 20 block (fixation*block2050: $t = -1.77$, $p = 0.076$; fixation*block2080: $t = 4.73$, $p < 0.001$).

2.3.3.6 Percentage of fixations

Percentage of fixations at the non-singleton distractor were marginally greater than the singleton distractor ($t = 1.90$, $p = 0.058$). Although blocks did not influence overall percentage of fixations

(block2050: $t = 0.15$, $p = 0.878$; block2080: $t = -0.07$, $p = 0.938$), neither did they influence the relative difference in percentage of fixations between distractors (fixation*block2050: $t = 0.29$, $p = 0.770$; fixation*block2080: $t = 0.22$, $p = 0.824$). The percentage of fixations directed to the target were significantly more than the distractors ($t = 55.41$, $p < 0.001$), indicative of effective target selection. Percentage of fixations did not differ between blocks (block2050: $t = 0.76$, $p = 0.444$; block2080: $t = -0.04$, $p = 0.968$). Also, fixation end location did not interact with blocks (fixation*block2050: $t = 1.62$, $p = 0.106$; fixation*block2080: $t = 0.22$, $p = 0.825$), suggesting that blocks did not influence the degree of target selection.

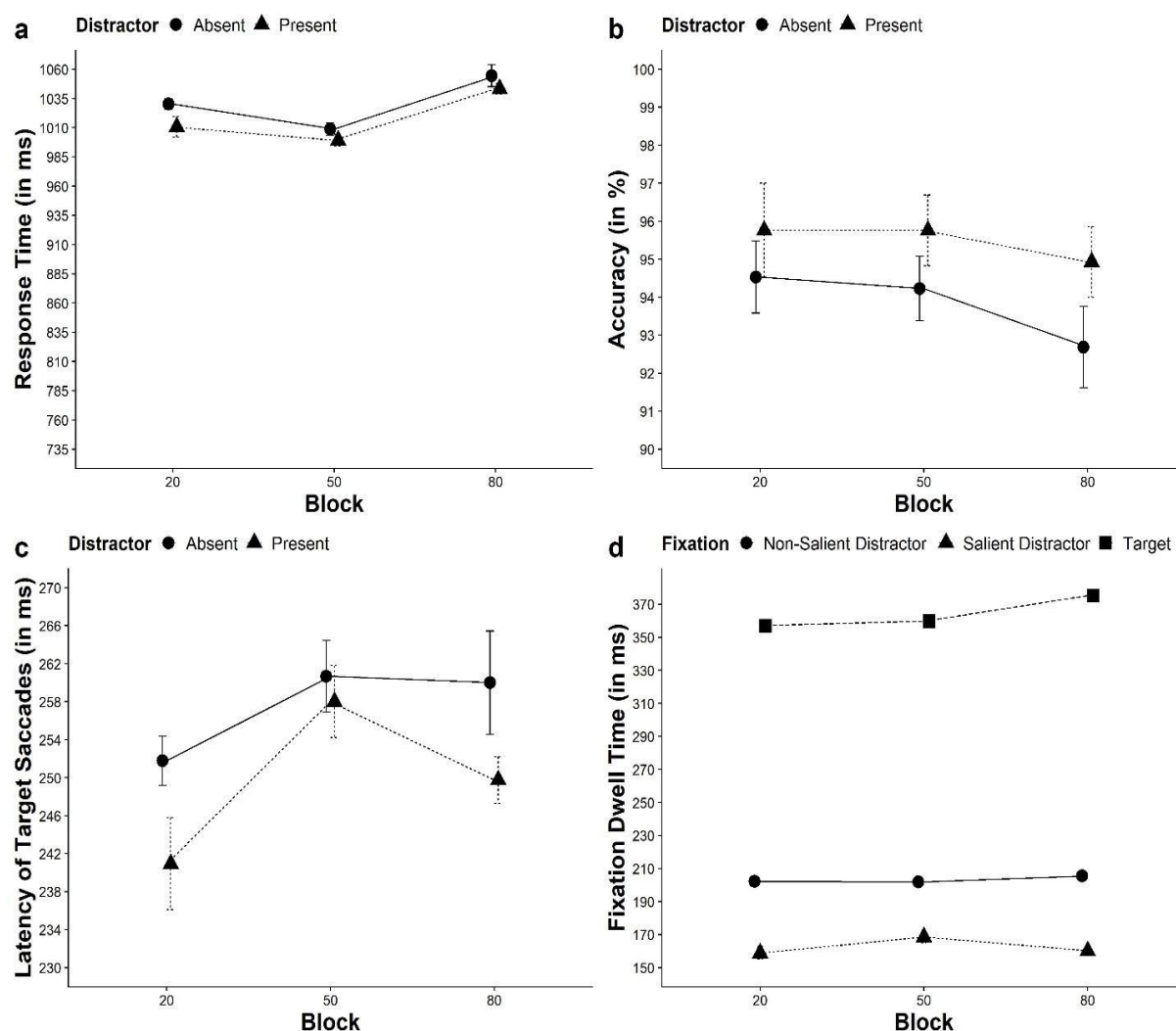


Figure 2.4. Experiment 2 Results (a) Average manual RT on the localization task, **(b)** average accuracy, **(c)** average latency on first target saccades, **(d)** average fixation dwell time in Experiment 2

Table 2.3. Mean and standard error (SE) of manual RT, accuracy and first target saccade latency in Experiment 2

Singleton distractor	Block	RT		Accuracy		Saccade Latency	
		Mean	SE	Mean	SE	Mean	SE
Present	20	1028.54	8.94+	95.76	1.24	240.95	4.85
Absent	20	1047.45	4.74	94.53	0.95	251.78	2.59
Present	50	1018.30	5.47	95.76	0.93	258.00	3.79
Absent	50	1029.61	5.68	94.23	0.85	260.68	3.77
Present	80	1057.29	4.54	94.93	0.93	249.76	2.45
Absent	80	1075.02	9.69	92.69	1.07	260.00	5.45

Table 2.4. Mean and standard error of RT in Experiments 1 and 2

Singleton distractor	Experiment	RT	
		Mean	SE
Present	1	765.06	1.93
Absent	1	752.90	1.85
Present	2	1043.91	3.20
Absent	2	1053.65	3.32

Table 2.5. Mean and SE of percentage of first saccades, average fixation dwell time and average percentage of fixations in Experiment 2

End location	Block	% First Saccades		Dwell Time		% Fixations	
		Mean	SE	Mean	SE	Mean	SE
Target	20	36.35	2.63	357.03	3.20	67.59	1.47
Singleton distractor	20	34.17	3.35	158.81	3.70	13.45	1.30

Non-singleton distractor	20	29.47	1.79	202.28	2.06	18.95	0.92
Target	50	44.46	3.53	359.68	2.09	71.02	1.49
Singleton distractor	50	26.21	2.10	168.54	3.36	9.98	0.82
Non-singleton distractor	50	32.09	1.34	201.82	1.48	19.93	0.74
Target	80	41.77	2.57	375.13	1.56	69.49	1.28
Singleton distractor	80	27.05	2.38	160.14	1.76	10.04	1.00
Non-singleton distractor	80	31.17	1.30	205.48	1.07	20.45	0.76

2.3.4 Discussion

In this experiment, we found significant benefit of overall suppression of singleton distractors in manual RT as well as in accuracy. RTs and first target saccades were faster on singleton present trials. For saccades, this difference was marginally greater in the 20 block than the 50 block, while both the 20 and the 80 block showed a similar trend. The target attracted maximum first saccades, similar to Experiment 1, singleton and non-singleton distractors were equally likely to attract saccades. Dwell time suggested slower disengagement from non-singleton distractors than singleton distractors, and this difference was greater in the 20 block than the 50 block and also greater in the 80 block than the 20 block. Targets had significantly longer dwell times than any distractor and this difference was also greatest in the 80 block than the 20 block and least in the 50 block. Supplementing this finding, the difference in percentage of fixations between non-salient and singleton distractors displayed similar results. Finally, the results show that statistical learning modulates active suppression more when the task demands are high. The influence of blocks showed that when predictability of singleton distractor appearance was higher (in the 20 and the 80 block) suppression was better compared to when the predictability was low (in the 50 block). Also, within the highly predictable blocks, more the experience with the distractors, better was the suppression.

2.4 General discussion

We explored how varying the frequency of a singleton distractor impacts suppression during active feature search. There was a singleton presence benefit in Experiment 2. We observed, enhanced suppression and increased accuracy in Experiment 2. This suggested that suppression of irrelevant singleton distractor was an effective strategy for target selection during the difficult feature search. We observed that frequency manipulation influenced overall RTs. Manual RTs in blocks with high singleton distractor predictability (20 and 80 block) were overall faster than the block with low singleton distractor predictability (the 50 block) in experiment 2. This implies that knowing with certainty whether the singleton distractor is most likely or least likely to appear during active search has a similar consequence for attention. Such predictability is suggested to rely on proactive inhibitory mechanisms. Whereas a highly unpredictable appearance of a singleton distractor, likely relies on reactive inhibitory mechanisms (Gonthier, Braver & Bugg, 2016). Previous studies show that proactive inhibition is faster and more effective than reactive inhibition (Mäki-Marttunen, Hagen & Espeseth, 2019), which aligns with the consistent pattern of both manual and eye tracking measures. In opposition to the prediction, frequency of the singleton, did not influence manual response suppression. While we see a similar pattern of this interaction in other measures, we cannot explain the reasons for the lack of statistical significance in RTs. Still, we suggest that the statistical learning observed in these blocks of varying frequency was influenced by the proactive and reactive inhibitory mechanisms during active search. However, more experiments are needed to understand the precise relationship between inhibitory control and statistical learning during visual search.

Since scanning the display and fixating the target was necessary to perform well in this task, we expected saccadic measures to be more informative about the suppression process. First saccade latencies reflect early biases in attentional prioritization (Sogo & Takeda, 2006; Theeuwes & Stigchel, 2009). Typical findings in feature search show that latencies of the first target saccades

become faster if the singleton distractor is suppressed (Gaspelin, Leonard & Luck, 2017). Greater singleton suppression facilitates faster target saccades, as seen in experiment 2. More importantly both the 20 and the 80 block showed enhanced benefit of target latencies than the 50 block, indicating that singleton distractor suppression expedited target search during higher levels of singleton distractor predictability. We similarly expected that the relative suppression of the singleton distractor would limit gaze directed to it. However, we did not observe this in both the experiments. Whereas, the target was mostly looked at first. We speculate that since we asked participants to focus on both the speed and the accuracy of response, it made them overly cautious. Hence, the manual as well as oculomotor responses in this study were relatively slower compared to previous feature search tasks (Gaspelin & Luck, 2018b; Mazza, Turatto & Caramazza, 2009). Since ‘where to look’ was not particularly emphasized, the ‘when to look’ could have taken precedence in this study. Thus, the suppression of singleton distractor mostly affected the temporal properties and not the spatial properties of selective attention (Eriksen & Hoffman, 1972) for example the latency of the saccades and not the percentage of saccades, respectively. Results from the fixation analysis also line up with this speculation.

Dwell time analysis from the two experiments showed that average dwell time on the target was significantly higher than on all distractors, indicating stronger target engagement. Importantly, dwell time on the singleton distractor was significantly less compared to non-singleton distractors, similar to Geyer et al. (2008). Hence, indicating that rejecting singleton distractor as a ‘non-targets’ was faster compared to rejecting non-singleton distractors (Gaspelin, Ruthruff & Lien, 2016). These results complement shorter dwell time during suppression of distractors due to rapid disengagement (Born, Kerzel & Theeuwes, 2011). In a similar search task, Vatterott & Vecera (2012), found a consistent pattern of initial capture followed by suppression as the salient color kept changing across blocks (Stilwell & Vecera, 2019a; Vatterott, Mozer & Vecera, 2018). Hence, we propose that the singleton distractor captured attention reflexively (Makovski, 2019), however attention quickly

moved from its location (Chang, Cunningham & Egeth, 2019) by generating predictions about its appearance through statistical learning (Beck, Luck & Hollingworth, 2018; Gal et al. 2009; Kelley & Yantis, 2009). We also analyzed the percentage of fixations and found higher fixations to the target than any distractor, in both experiments. This confirms that fixating the target was indeed necessary to perform well in both easy and the difficult search task. Experiment 2 also showed lesser fixations on salient items, similar to the dwell time results. However, we did not find a block-wise variation in percentage of fixations on the two types of distractors. Much like saccades, only the temporal properties of fixations were influenced by singleton distractor suppression. This re-confirms our assertion that inhibition over singleton was built gradually and temporally, rather than instantaneously.

Additionally, Muller et al. (2009), during singleton search, found that engagement with a singleton distractor increases with the frequency of encountering it. While they utilized fixation durations to measure attentional engagement, we measured average fixation dwell time in line with the attentional dwelling hypothesis (Lamy, Darnell, Levi & Bublil, 2019). In Experiment 2, we observed better disengagement from singleton distractor in the 20 block and the 80 blocks relative to the 50 block, while both experiments showed larger benefits in the 80 block than the 20 block. We suspected that an unpredictable experience with the singleton distractor in the 50 block discouraged disengagement (Huffman, Rajsic & Pratt, 2019) due to repeated reflexive capture. Such a hypothesis would predict less incentive to disengage from the singleton distractor in an unpredictable block, but not in the predictable blocks. Thus, faster disengagement in the highly predictable 20 and 80 blocks fits the explanation. Moreover, the exact pattern of results was observed while comparing dwell time on the target with all distractors. Overall, singleton distractor suppression was more effective when the certainty of its appearance was high (20 and 80 blocks) than when the certainty was low (50 block). Additionally, during the high certainty appearance of the singleton distractor, suppression benefited more from encountering more frequency of the singleton distractor as well (more in 80

block than 20 block). Hence, singleton distractor suppression through statistical learning is sensitive to both the predictability and the frequency of its appearance. Moreover, we suggest that better suppression also led to better target enhancement in the 20 and the 80 block, than the 50 block. This implies that better distractor suppression can in turn influence target selection, extending our understanding of the dual process.

Finally, task difficulty significantly influenced suppression of the singleton distractor in both manual RTs and eye movements. We observed a slowing down of responses in Experiment 2 as the difficulty increased. However, manual response suppression improved significantly in this experiment. As the connectionist model of visual search suggests, search progresses by rejecting clusters of non-targets or distractors. These distractors are grouped into clusters based on similarity as well as proximity (Humphreys & Muller, 1993; Humphreys, Quinlan & Riddoch, 1989). In the current study, as distractors became more similar to the target in the second experiment, grouping of distractors for rejection must have become more efficient. Hence, an irrelevant distractor stood out in the display (Utochkin & Yurevich, 2016), facilitating its suppression. Studies have also shown that as the task becomes difficult the window of attention shrinks (Ahissar & Hochstein, 2000) resulting in more localized attention. We can expect that a localized attentional focus would prevent any parallel processing and instead encourage a serial search strategy (Tamber-Rosenau, & Marois, 2016). Hence, a more controlled serial search must have reduced the reflexive bottom-up capture by the irrelevant singleton distractor (Lu & Han, 2009), more so in Experiment 2. Studies also suggest that attentional guidance by negative cues is effective only during difficult search while positive cues predominantly guide attention (Zhang, Gapelin & Carlisle, 2019). It likely suggests that distractor guided attentional selection is relatively costly than target facilitation (Marini, Chelazzi & Maravita, 2013) and hence is only preferred when necessary. Alternatively, Barras & Kerzel (2017), found that stimulus driven capture increased with increasing search difficulty. While this seems to contradict the results, a recent study also showed that the more the capture by an irrelevant singleton distractor,

the more it can be suppressed (Failing & Theeuwes, 2020). Overall, our results suggest that task difficulty played a critical role in enhancing singleton distractor suppression.

The purpose of these experiments was to investigate beneficial conditions for suppression. We found that varying singleton distractor experience influenced the eventual attentional engagement and disengagement at that location. And this change in attentional engagement was sensitive to task difficulty. The relative dwell time difference among distractors varied with singleton frequency in both experiments, albeit more in Experiment 2, suggesting that task difficulty has control over attentional engagement. While we did not find block-wise variation of manual response suppression in both experiments, both saccades and fixations were sensitive to the frequency manipulation. Hence, the two experiments showed both typical and novel evidence of oculomotor distractor suppression during active feature search. We finally propose that easy searches do not necessitate suppression of singleton distractors. As a result, learning to suppress singleton distractors through repeated experience is not necessary to perform well on the search task. Instead, when the task is difficult, the relative incentive to suppress the distractor is enhanced and might rely on processes like statistical learning. Previous studies have confirmed the role of frequency of singleton distractor present trials in reducing capture (Britton & Anderson, 2020). However, our study uniquely found evidence of varying oculomotor suppression of singleton distractors with the frequency manipulation due to increased difficulty.

CHAPTER 3

Comparing Conscious and Unconscious Top-down Distractor Suppression

Does awareness of a cue influence how attention is directed to the cued distractor? Whether subliminal spatial or feature cues can influence oculomotor and manual response suppression? If so, do visible cues share the same characteristics? Participants searched for a target in the presence of a unique distractor (experiment 1). Additionally, a visible pre-cue matching the color, location or both color and location of the singleton, in three separate blocks of trials. RTs for target search were compared across singleton distractor present and absent trials which measured interference caused by the singleton distractor during the search, between cue types. In experiment 2, the cues were presented briefly such that it was perceived subliminally. Singleton presence benefit was found in both experiments; the color-matching cue caused the highest suppression compared to other cues. Interestingly, the latency of first target saccades and percentage of all first saccades suggested oculomotor capture with visible cues (experiment 1) and proactive suppression with subliminal cues (experiment 2). These results point towards a potential dissociation between oculomotor and manual response suppression and their interaction with awareness.

3.1 Introduction

Looking up to the night sky, you can only spot a handful of stars, but human vision has far more sophisticated capabilities. We see an abundance of things in a single glance. While it offers a rich visual perception, abundance can challenge goal-directed action. Goals need to be executed with accuracy and precision, hence vision must adapt to task demands. Attentional control systems adapt visual processes to suit task demands, employing conscious and unconscious processes and engaging working memory to support them. Knowledge about tasks becomes the point of reference of attentional control. The representations of this knowledge form what we call the attentional set and guide selection. For instance, if you are asked to look for your friend in a room full of men, you will start by observing signs of physical resemblance, perhaps height. Then move on to looking for other features such as skin color, tone of voice, walking style, etc. These features in the visual, auditory, tactile and olfactory modality form respective representations and a temple of such representations makes up the attentional temple. As objects cloud our visual fields, it can be hard to look for something given a specific goal. Thus, the attentional template can also contain information on distractors that may be suppressed during the search.

Searching involves a complex process of enhancing target-related features/locations in the visual field while disregarding target-unrelated information. If a distractor is capable of capturing attention stronger than the target, it can hamper the search. Distractor suppression mechanisms are activated to ensure that such distractors do not capture attention. It allows attention to completely disregard the suppressed distractor, such that the target is found faster in its presence than in its absence. This was first observed by Bacon and Egeth (2004) in a modified version of a search task called feature search. Here, participants were instructed to find a shape target (circle/diamond) among unique (heterogenous) shape distractors (unlike the additional singleton paradigm where all the distractors were of the same shape), hence the name *feature search*. On some trials, color

singleton distractor was inhibited as it appeared among other distractors. This was because the uniqueness of its color was irrelevant to the task. Contrary to the capture observed during the singleton search, where the target is a shape singleton and the singleton distractor is a color singleton, and hence relevant to task goals (contingent-capture-like phenomenon). Several studies have found support for suppression in versions of the feature search task (Drisdelle & Eimer, 2021; Kerzel & Barras, 2016) and suggested that singleton distractors can be suppressed if they are irrelevant to the task goals.

Models of search propose a preattentive stage, attentive stage and decision-making stage during the search. The preattentive stage does not depend on attention for completion. Rather, cognition in this stage takes place without the awareness of the observer-unconscious perceptual processes. For instance, in the later part of the dorsal stream, the parietal lobe processes object features such as size, shape, position in geocentric coordinates, etc. without conscious awareness and affects actions directly (Goodale & Milner, 1992; Goodale, Westwood & Milner, 2004; Milner & Goodale, 2008). Also, Treisman (1992) in response to Duncan and Humphreys (1992)- the spreading suppression hypothesis, suggested that different feature maps function independently at the preattentive level. Pre-attention is defined as a stage of parallel processing of features and locations that precedes and controls attention (Treisman & Gormican, 1988). Thus, properties of objects of search can be processed unconsciously and influence selection. To say that a process is completely unconscious, it must be proved that the information it computes is not accessible to conscious awareness (Brogaard, 2011). Taking the example above, participants must be unaware of properties of stimuli even after an action has been motivated by them (manual response). We used this principle to test if cues presented before the search were processed unconsciously. We used a visibility test to ask observers objective information about these cues such as their color and location and compared

the accuracy of their responses on various cue conditions. Since perception can be motivated by action too, a certain cue condition might render it more unconscious than another.

Attention to spaces and objects occurs simultaneously according to models of visual search. ‘What to attend?’ influences ‘where to attend?’ and vice versa. What happens when information about objects and locations is insufficient? For instance, preattentive processes offer information about basic features and locations which can guide attention at later stages (Travis, Duex and Mattingley, 2019). However, unconscious stimuli are often weak and weak signals may fail to bias attention. We question whether preattentive spatial and feature processing is arranged hierarchically. Does attentional selection benefit from either spatial or feature unconscious priming more strongly than the other? Few studies have found that subliminal cues that match the target location in upcoming trials help in finding it faster (McCormick, 1997; Posner, 2016). This is also true for cues that match the target feature and not the target location. While these findings suggest that preattentive ‘target enhancement’ processes can be influenced by unconscious spatial and feature cues, we do not know if they also influence ‘distractor suppression’ processes. To test this in two experiments, we used subliminal cues before a search task. They matched an upcoming singleton distractor in only color, only location or in both color and location, in separate blocks of trials. These were compared to ‘no-cue’ trials. If unconscious cues facilitate inhibition of the singleton, singleton presence benefit must be greater for all cued trials than no-cue trials. If there is a greater benefit for suppression by unconscious spatial priming than feature priming, we would expect a greater suppression index for ‘location-matching’ cues than ‘color-matching cues’ and vice versa if the alternative hypothesis is true.

Typically, in feature search tasks, participants encounter two types of trials. These are singleton absent trials that display a target and distractors of the same color and singleton present trials that display a target, same color distractors and one unique color distractor (similar to

experiments in Chapter 2). Time is needed to find the target among distractors serially. If one of these distractors is suppressed, response times can be reduced. Hence, the difference between the singleton distractor absent and present trials indicates the degree of suppression a singleton distractor has experienced (Gaspelin & Luck, 2019). Currently, two processes explain such RT benefits. First, proactive suppression is observed when prior knowledge about an upcoming singleton distractor is available and attention can be prevented from going to it. Second, reactive suppression is observed when the singleton distractor will inevitably capture attention, but a rapid disengagement will reduce the effect of capture. Manual reaction time, however, cannot clarify if one or both of the processes are taking place in a study. Tracking eye movements allows eye gaze to completely avoid or is captured by the singleton distractor, as is suggested in Chapter 2.

Studies have shown that the first saccades land on the target and other non-singleton distractors significantly greater number of times than the singleton distractor (Adams, Ruthruff & Gaspelin, 2023; Stilwell & Vecera, 2022), implying bias against the singleton. When latency of saccades to the singleton are faster than 200 ms, they are termed reflexive saccades, suggesting reflexive shift of attention or attention capture. Proactive suppression may involve an initial few trials wherein attention capture takes place, but participants learn to completely avoid the singleton distractor as trials progress. A slower saccade to the singleton distractor would indicate an intentional attentional bias to it and then rapid disengagement. Since eye-tracking studies on suppression are rare, few studies can compare proactive and reactive suppression in the same study. Saccades are sensitive to unconscious biases (Mulckhuyse & Theeuwes, 2010; Ramey, Yonelinas & Henderson, 2019). It is often observed that saccades to a target are faster if a subliminal cue precedes it. This is because the subliminal cue captures attention unconsciously. If a target follows within 200-300 ms of cue display, it can be directed faster since attention is engaged at the target location by the cue. But if the target appears after 300 ms, inhibition of return (IOR) is observed at the cued location. Hence, reorienting to a target at that location takes time. But what would happen if a cue

preceded a distractor, is unclear as very few studies have looked at the nature of unconscious distractor cueing.

Rationale for the present study

In a recent review, Wöstmann et al. (2022) prescribed three rules for studying distractor suppression. First, ensuring that a non-target object is indeed distracting. Second, manipulating the distractor independently of the target. Third, comparing distractor processing to baseline processing (Wöstmann et al., 2022). By these guidelines, the current study adopted a methodology similar to Gaspelin et al. (2017) and Gaspelin and Luck (2018) such that the singleton distractors were presented on 50% of total trials and the remaining trials contained only non-singleton distractors, apart from the target. Any difference in RTs between the two trial types thus indicated singleton distractor processing time; RT cost for attention capture and RT benefit for distractor suppression. Additionally, the cue presented in the three cued blocks was only related to the singleton distractor. Hence, any differences among the blocks could only arise due to differences in distractor processing. Thus target enhancement, although it could be co-occurring with distractor suppression, did not interfere with the main manipulation of the task (cueing). Finally, eye movement recording during the search allowed for comparing overt attentional shifts to the singleton distractor vs. non-singleton distractors.

3.2 Experiment 1

3.2.1 Methods

3.2.1.1. Participants

GPower analysis suggested a sample size of 20 to obtain a medium effect size of 0.5 for the desired power of 0.5 and a confidence level of 0.05 (Faul, Erdfelder, Lang & Buchner, 2007) which was in accordance to previous studies on distractor suppression (Failing, Wang & Theeuwes, 2019; Mazza,

Turatto & Caramazza, 2009; Noonan et al., 2016; Van Zoest et al., 2021). We administered the experiment to 20 naive volunteers ($M_{age} = 23$ years, 8 females). They performed Ishihara color blindness test with greater than 90% accuracy and normal visual acuity. University of Hyderabad authorized consented participation in the study.

3.2.2. Design and Procedure

On fixating a central plus for 100 ms, a cue appeared for 500 ms. An invisible square at the center (5 degrees) was used as placeholders for the cue, with each cue (square shape) occupying its corners, as shown in Figure 3.1. Three categories of cues were displayed in distinct blocks. The color-matching cue (red/blue, counterbalanced among participants) matched the singleton's color, location-matching cue matched singleton's spatial coordinates and both-matching cue matched singleton's color and spatial coordinates, at the same time. The color-matching cue consisted of four red-colored placeholders presented at the location of the upcoming search array. The location-matching consisted of a white placeholder and the both-matching cue consisted of a red placeholder matching spatial coordinates of the upcoming unique non-target, while the three remaining placeholders were presented in black color. Participants encountered these cues in separate blocks of trials during the experiment. After a 50 ms CTOA (cue-target onset asynchrony) the search could take place until 2000 ms or response, whichever was earlier.

Black placeholders contained shapes that formed the search array—one target shape and three distractors, in all red (or green) colors (counterbalanced between groups). Each location displayed each shape equally often. This means that target was seen at all location with equal probability and so were every distractor. As is typical to the paradigm, one singleton distractor appeared on 50% trials—singleton present trials. The cue was displayed only on singleton present trials. Participants pressed number keys from 1 to 4, reporting the number on target. They were given no prior instruction about the singleton distractor or the cues.

There were 800 experimental and 20 rehearsal trials, which comprised three blocks of 200 trials for each cue type and one block for no-cue trials; they contained each 100 singleton present and absent trials respectively—mixed randomly within the block. Blocks appeared randomly and unpredictably with 2 minutes breaks between each.

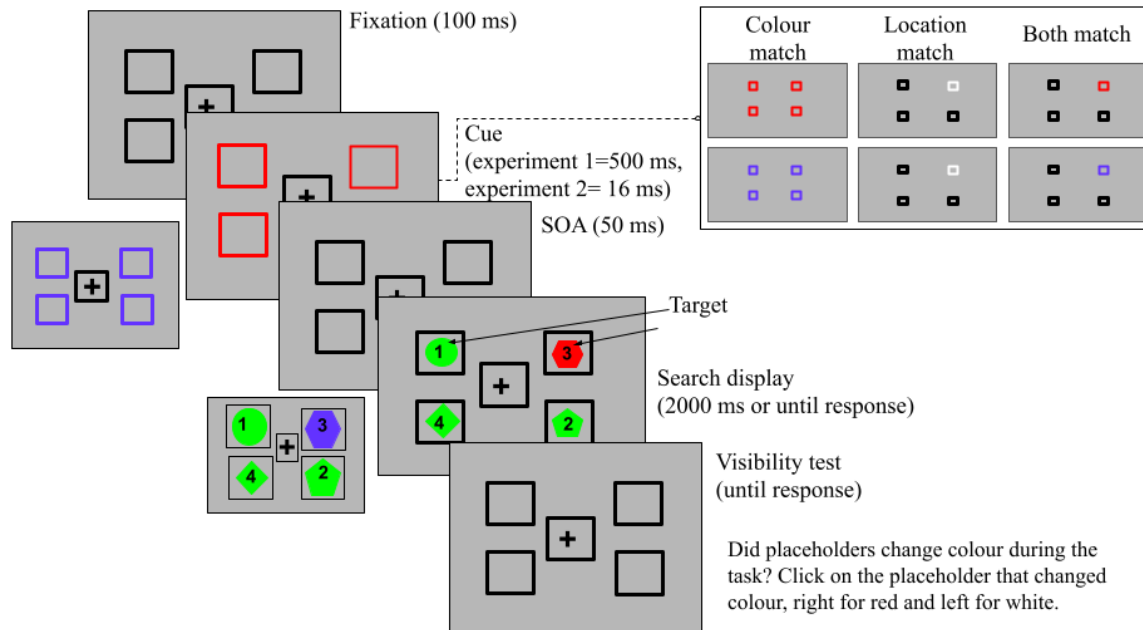


Figure 3.1. Trial in Experiment 1. Search for the target circle is facilitated by a pre-cue by distractor suppression. Cue color and singleton color is counterbalanced across participants (red or blue). All participants complete a visibility test which replicates the design of the main experiment except an additional screen to report cue color and location using mouse click.

3.2.3 Data analysis

The data was filtered on R Studio (Version 2023.09.1+494) using packages dplyr and plotted using ggplot2, cowplot, and tabulated using Rmisc. Statistical tests were performed on JASP (Version 0.16). Outlier removal included incorrect and missing responses besides faster and slower than 200-3000 ms, and 3.5 Median Absolute Deviation (MAD). MAD is more stable against outliers and was hence preferred over Mean Standard Deviation (MSD) (Leys et al., 2013; Montgomery &

Runger, 2020). One participant performed the task poorly (accuracy was less than 50%) and their data were discarded from the analysis. A total 8.75% data loss was encountered post outlier removal and discarding participants. We conducted a Repeated measures ANOVA on trial (singleton present vs. absent) and cue (color, location, both and none) as independent measures on the following dependent measures: a) Mean RTs b) Suppression index (singleton absent RT - singleton present RT).

The saccadic eye movements were analyzed for c) Latency of the first saccade to the target, wherein saccades with latency < 50 ms were discarded as outliers and d) Oculomotor capture index was calculated by subtracting latency of first target saccade on singleton absent and present trials e) The percentage of all first saccades on singleton present trials was compared among saccade end locations (target, singleton distractor, non-singleton distractors). Fixations on target, singleton, and average of non-singleton distractors were plotted for the duration of the search across the condition of cue types using Visual World Package in R.

3.2.4 Results

Manual RT and Suppression Index

Trial type influenced RTs, ($F(1, 18) = 110.890, p < .001, \eta^2 = .860$) such that faster RTs on singleton present trials vs. singleton absent trials (136 ms) ($t(18) = 10.530, p < .001, dz = 2.416$), indexing suppression of the singleton distractor. Cue type did not influence RTs ($F(3, 54) = 1.104, p = .356, \eta^2 = .058$). The interaction of trial and cue was significant, ($F(3, 54) = 6.986, p < .001, \eta^2 = .280$) such that the singleton was suppressed in all cue blocks. When the suppression index was compared between cues, only the color-matching cue showed a significantly higher suppression index compared to the no-cue condition (66 ms) ($t(18) = 3.130, p = .011, dz = 0.718$) and also

compared to the both-matching cue (69 ms) ($t(18) = 3.279, p = .009, dz = 0.752$), and the location-matching cue condition (92 ms) ($t(18) = 4.334, p < .001, dz = 0.994$) see figure 3.2(a).

Latency of the first target saccades

The main effect of the trial was significant, ($F(1, 14) = 7.791, p = .014, \eta^2 = .358$) as is shown in figure 3.2 (c). Latencies were slower on singleton present trials compared to singleton absent trials (178 ms) ($t(14) = 2.791, p = .014, dz = 0.721$), suggesting slower oculomotor orienting to the target in the presence of the singleton. The main effect of the cue was significant ($F(3, 42) = 7.921, p < .001, \eta^2 = .361$). Post-hoc analysis suggested slower latencies to the target in the presence of color-matching cue compared to no-cue (315 ms) ($t(14) = 3.920, p = .002, dz = 1.012$), and also compared to location-matching cue (309 ms) ($t(14) = 3.836, p = .002, dz = 0.990$) and both-matching cue (335 ms) ($t(14) = 4.157, p < .001, dz = 1.073$). The interaction of trial and cue was also significant, ($F(3, 42) = 5.257, p = .004, \eta^2 = .273$) such that only color-matching cues produced significantly delayed orienting to the target in the presence of the singleton ($t(14) = 3.626, p = .005, dz = 0.936$) whereas other cues and the no-cue condition did not let the singleton's presence affect the latency of target saccades. The oculomotor suppression index was a positive value (4 ms) only for the location-matching cue compared to the no-cue trials, suggesting the potential benefit of singleton suppression with the help of location cues, but it was not statistically significant ($t(14) = 0.410, p = 1.000, dz = 0.106$).

Percentage of First Saccades

The main effect of cue was not significant ($F(3, 48) = 1.000, p = .401, \eta^2 = .059$) but the main effect of saccade end location was significant ($F(2, 32) = 27.231, p < .001, \eta^2 = .630$). A higher percentage of first saccades landed on the target compared to both singleton distractor ($t(14) = 7.195, p < .001, dz = 1.745$) and non-singleton distractors ($t(14) = 5.020, p < .001, dz = 1.218$). Importantly, the first saccades to the singleton distractor were significantly lower than saccades to the

non-singleton distractors ($t(14) = 2.174, p = .037, dz = 0.527$), see figure 3.2(e), suggesting suppression of the singleton distractor. The interaction of the cue and saccade end location was not significant ($F(6, 96) = 0.638, p = .699, \eta^2 = .038$).

The time course of gaze shift

Eye gaze trajectory for the no-cue trials at time zero was the time of search display. The bias towards the target and away from the distractors was seen building in the first 250 ms. After which the bias towards the targets increased until the trial ended or a response was made. Figure 3.3(a) shows the time course of gaze for Experiment 1 trials. On no-cue trials, gaze was directed towards target and non-targets but not towards the singleton, from the start of the search. The target and non-singleton competed for attention until 300-400 ms when the competition was won by the target. Importantly, eye gaze remains consistently biased towards the non-singleton distractors compared to the singleton distractor. A similar pattern of eye gaze was seen in color-matching cue trials. On location-matching and both-matching cue trials, however, an initial bias towards the singleton distractor was seen, until approximately 250 ms, indicating bottom-up capture by the singleton and resolution by later disengagement.

Table 3.1. Mean and standard error of RT and latency of first target saccade across the color-matching, location-matching and both-matching cue blocks during singleton present and absent blocks.

Dependent Measure	Trial	Cue	Mean	Standard Error
RT	Singleton present	color-matching	1635.08	59.32
		Location-matching	1727.01	63.87
		Both-matching	1720.28	56.40
		No-cue	1675.48	48.47
	Singleton absent	color-matching	1829.12	53.41
		Location-matching	1828.63	56.52
		Both-matching	1844.41	53.04
		No-cue	1802.79	44.51
First target saccade latency	Singleton present	color-matching	871.30	123.7
		Location-matching	355.88	31.54

Dependent Measure	Trial	Cue	Mean	Standard Error
		Both-matching	460.50	96.69
		No-cue	340.91	79.04
	Singleton absent	color-matching	380.40	100.28
		Location-matching	313.56	69.89
		Both-matching	276.54	45.77
		No-cue	337.51	63.45

Table 3.2. Mean and SE of first saccades % across blocks.

Dependent Measure	Cue	Saccade end location	Mean	Standard Error
Percentage of first saccades	color-matching	Target	52.63	3.62
		Non-singleton distractor	33.50	5.34
		Singleton distractor	28.72	3.00
	Location-matching	Target	47.79	1.80
		Non-singleton distractor	30.36	2.03
		Singleton distractor	24.25	2.33
	Both-matching	Target	44.28	2.37
		Non-singleton distractor	29.55	1.64
		Singleton distractor	26.16	2.61
	No-cue	Target	43.34	1.97
		Non-singleton distractor	32.79	3.77
		Singleton distractor	27.39	2.25

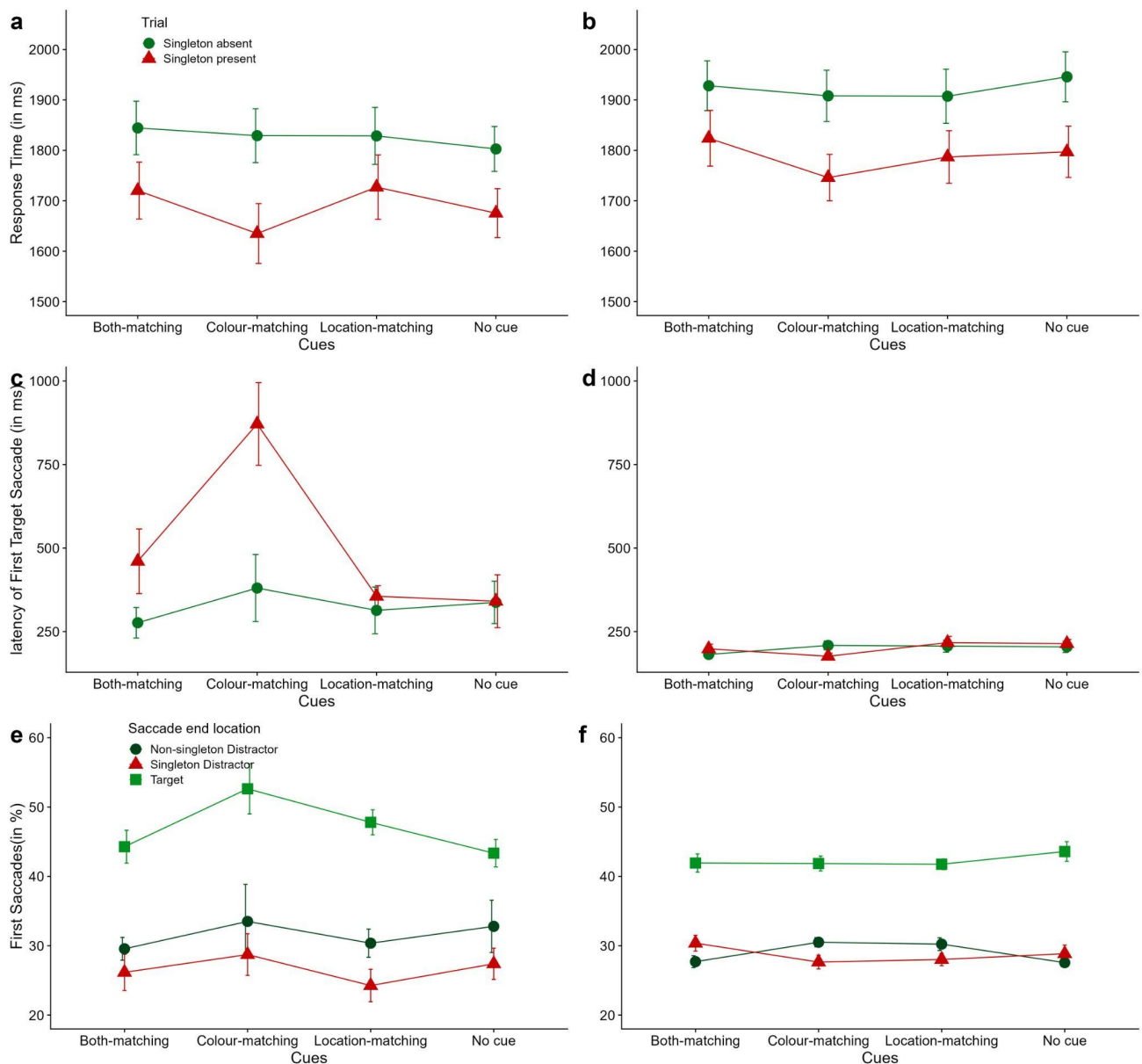


Figure 3.2. Manual response time, the latency of first saccades to the target and percentage of the first saccade in Experiments 1 and 2. Singleton presence benefit reflects the degree of manual response suppression, which can be seen in both Experiments 1 and 2. The time taken to execute the first target saccade reflects how the bias towards the target develops during suppression. Experiment 1 shows slower latencies on singleton present trials whereas Experiment 2 shows comparable latencies. First saccades % was overall greater on target compared to all distractors but significantly greater on non-singleton distractor compared to singleton distractor in Experiment 1.

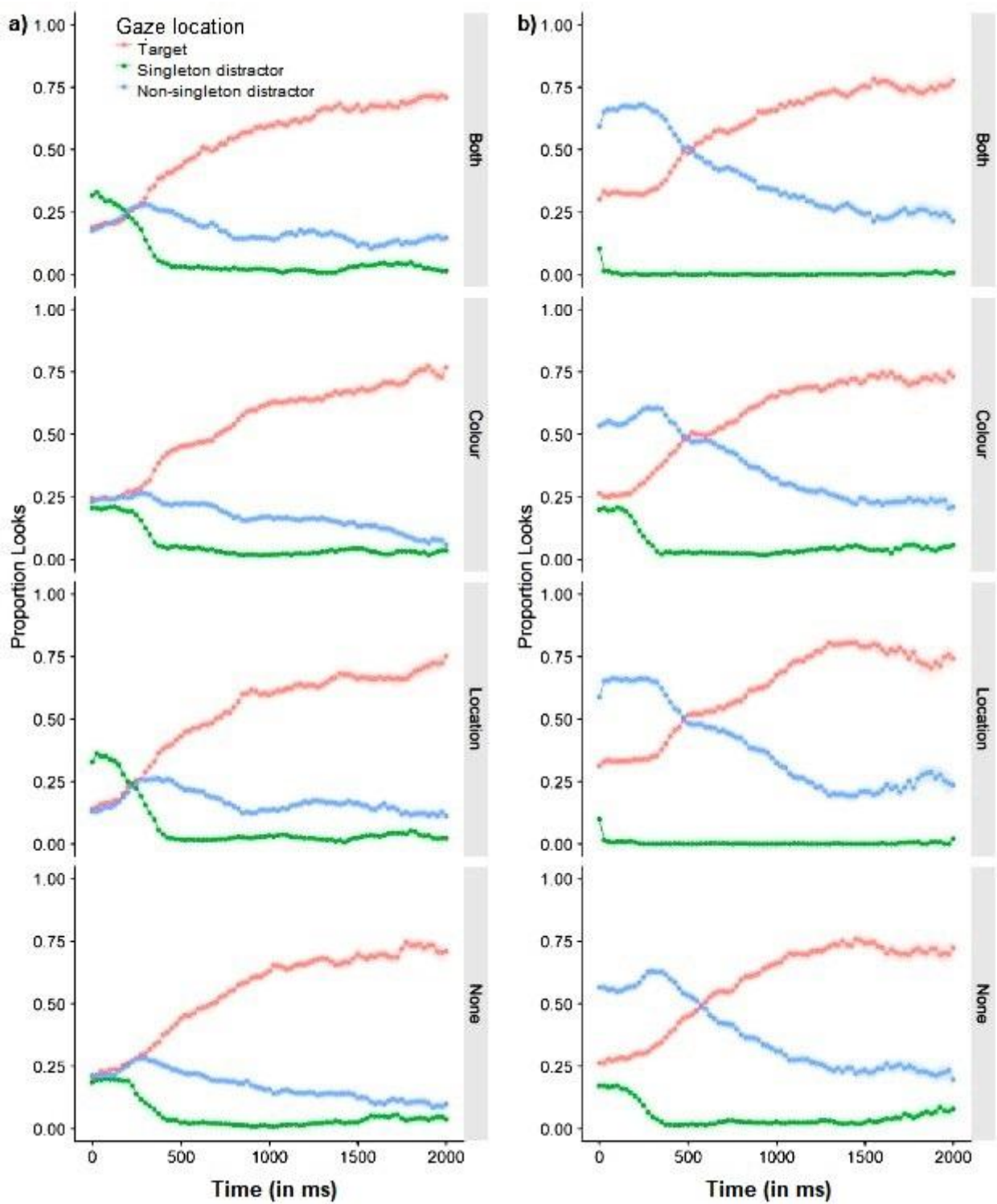


Figure 3.3. Time course of gaze shift during target search. The graph indicates the movement of eyes after the search display appeared until response. Gaze fixations on target are shown in red, on the non-singleton distractor in blue and on singleton distractor in green. As the number of eye movements towards each shape increased a shift upwards on the y-axis was observed, while x-axis

indicates time during search. Typically, a bias towards the target builds during search and stays until response was made. Critically, bias against the singleton distractor was seen consistently through task conditions and experiments. Experiment 1 shows oculomotor capture by the singleton while oculomotor suppression was seen in Experiment 2.

3.2.5 Discussion

The singleton was suppressed during no-cue trials; Singleton presence benefit; first saccades to the singleton were significantly lower than the non-singleton distractors. However, latency of first target saccades was indifference to singleton's presence. Thus, oculomotor suppression did not influence target enhancement but benefitted decision processes and speeded reaction time. This showed a disassociation between target enhancement and distractor suppression and highlighted how they contribute to the search.

The color-matching cues trials showed greater benefit on singleton present RTs compared to no-clue trials. Even though oculomotor suppression did take place with the help of color-matching cues, as indicated by fewer first singleton saccades than non-singleton saccades, first saccades to the target were slowed significantly by it. We propose that color-matching cues pushed singleton representations and attention was later disengaged from it (Theeuwes, Atchley & Kramer, 2000). Thus, orienting to the target was slowed significantly on singleton present trials but the rapid disengagement regardless enhanced RTs. The singleton however captured covert attention and no overt shift of eye movements took place, as seen in the time course of eye gaze, suggesting that color-matching cues aided in oculomotor suppression of the singleton.

The location-matching and both-matching cues showed the same degree of singleton presence benefit as the no-cue trials. Unlike the color-matching cues, these pushed the singleton's location or feature and caused oculomotor capture, early during the search. However, a rapid disengagement process yielded suppression of the singleton and prevented search RTs from increasing on singleton

present trials. The color-matching cues led to a covert attention shift towards the singleton but the location-matching and both-matching cues resulted in overt and (likely) covert attention capture by the singleton. Since the both-matching cues behaved similarly to the location-matching cue more than the color-matching cue, we suggest that knowing the location of an upcoming singleton makes overt capture by it inevitable. However, knowing its features only captures attention covertly. This suggests a dissociation between feature and location cues in their relationship with covert and overt attention orienting.

We wanted to replicate this study with subliminal cues to reconcile how conscious perception of the cues affects their influence on suppression.

3.3 Experiment 2

3.3.1 Methods

Twenty naive volunteers ($M_{age} = 24.5$ years, 9 females) participated in Experiment 2. One participant performed with an accuracy lower than 50% and was discarded from all analyses. Except few alterations, trial sequence between Experiments 1 and 2 remained similar. First, the cue was presented for 16 ms only. This was to render the perception of the cue subliminal (Garofalo et al., 2020; Prasad & Mishra, 2019). Second, participants completed a visibility test reporting their perception of the cue at the end of the main experiment. They located the placeholders that changed color from black to a different color, using mouse clicks and also indicating the changed color. For instance, when a location-matching cue was presented, they were expected to click on the placeholder that turned white and press right-click to indicate white color. But when a both-matching cue was presented, they would click left on the respective placeholder, indicating a color change to red. On no-cue trials, they were instructed to simply scroll forward. Participants completed 20 trials for each cue type and cue duration (16 ms and 500 ms cues-catch trials). Since 500 ms was sufficient time for the cues to be perceived consciously, they were used as a baseline

for conscious awareness.

3.3.2 Results

Manual RT and Suppression Index

The main effect of the trial was significant, ($F(1, 18) = 103.853, p < .001, \eta^2 = .852$). RTs were faster on singleton present trials compared to singleton absent trials (133 ms) ($t(18) = 10.191, p < .001, dz = 2.338$), indexing suppression of the singleton distractor. The main effect of the cue was not significant ($F(3, 54) = 1.155, p = .335, \eta^2 = .060$). The interaction of trial and cue was significant, ($F(3, 54) = 3.382, p = .025, \eta^2 = .158$) such that the singleton was suppressed in all cue blocks, see figure 3.2(b). When the suppression index was compared between cues, none of the cues showed a significantly higher suppression compared to the no-cue trials.

Latency of the first target saccades

The main effect of the trial was not significant ($F(1, 18) = 0.050, p = .826, \eta^2 = .003$), see figure 3.2(d). The main effect of the cue was also not significant ($F(3, 54) = 1.556, p = .211, \eta^2 = .080$). The interaction of trial and cue was significant, ($F(3, 54) = 3.489, p = .022, \eta^2 = .162$). However, the oculomotor suppression index for all cues and the no-cue trials was comparable.

Percentage of First Saccades

The main effect of the cue was not significant ($F(3, 54) = 8.080, p = 1.000, \eta^2 = 4.893$) but the main effect of the saccade end location was significant ($F(2, 36) = 166.487, p < .001, \eta^2 = .902$), see figure 3.2(f). A greater percentage of first saccades landed on the target compared to the singleton distractor ($t(19) = 15.964, p < .001, dz = 3.662$) and the non-singleton distractors ($t(19) = 15.636, p < .001, dz = 3.587$). The first saccades to the singleton distractor were not significantly lower than saccades to the non-singleton distractors ($t(19) = 0.328, p = .745, dz = 0.075$), suggesting no

oculomotor suppression of the singleton distractor. The interaction of the cue and saccade end location was also not significant ($F(6, 108) = 1.477, p = .193, \eta p^2 = .076$).

The time course of gaze shift

From the start of the search, eye gaze was biased towards the non-singleton distractor compared to the target and this competition was resolved after 500-600 ms. This pattern was consistent across cued trials and no-cue trials. On the no-cue trials, eye gaze to the singleton was suppressed from the start of the search and continued until the end of search. This pattern of eye movements was replicated on color-matching cue trials, (similar to experiment 1). However, location-matching and both-matching cues resulted in even lower eye gazes towards the singleton distractor from the start of the search, suggesting no oculomotor capture by the singleton (unlike in Experiment 1), see figure 3.3(b).

Visibility test

Repeated measures ANOVA on detection accuracy showed the main effect of cue duration, $F(1, 19) = 12.638, p = .005, \eta p^2 = 0.558$. The 500 ms cues were reported more accurately than 16 ms cues (35.60 %), ($t(19) = 3.555, p = .005, dz = 1.072$). Cue detection was comparable among the different cue trials, $F(1, 19) = 2.846, p = .082, \eta p^2 = 0.222$. The interaction of singleton and cue was also not significant, $F(2, 8) = 0.298, p = .746, \eta p^2 = 0.029$.

d' prime: The overall d prime was not significantly different than 0 for 16 ms cue , ($t(19) = 1.778, p = .947, dz = 0.536$), indicating that the cues were perceived in the absence of conscious awareness, while overall d prime was significantly greater than 0 for 500 ms cue , ($t(19) = 12.827, p < .001, dz = 3.867$).

Table 3.3. Mean RT and First target saccade latency on Experiment 2 trials.

Dependent Measure	Trial	Cue	Mean	Standard Error
RT	Singleton present	color-matching	1746.02	46.01
		Location-matching	1786.85	52.15
		Both-matching	1823.97	55.27
		No-cue	1797.10	50.82
	Singleton absent	color-matching	1908.12	50.83
		Location-matching	1907.28	53.71
		Both-matching	1928.04	49.29
		No-cue	1945.84	49.49
First target saccade latency	Singleton present	color-matching	176.13	9.46
		Location-matching	217.10	18.64
		Both-matching	198.60	14.04
		No-cue	213.95	12.28
	Singleton absent	color-matching	208.71	13.20
		Location-matching	206.68	18.18
		Both-matching	181.69	7.02
		No-cue	204.37	16.74

Table 3.4. Average percentage of first saccades on Experiment 2 trials.

Dependent Measure	Cue	Saccade end location	Mean	Standard Error
Percentage of first saccades	color-matching	Target	41.85	1.07
		Non-singleton distractor	30.50	0.66
		Singleton distractor	27.64	0.99
	Location-matching	Target	41.75	0.76
		Non-singleton distractor	30.22	0.91
		Singleton distractor	28.01	0.90
	Both-matching	Target	41.92	1.31
		Non-singleton distractor	27.70	0.85
		Singleton distractor	30.37	1.14
	No-cue	Target	43.58	1.42
		Non-singleton distractor	27.56	0.55
		Singleton distractor	28.84	1.24

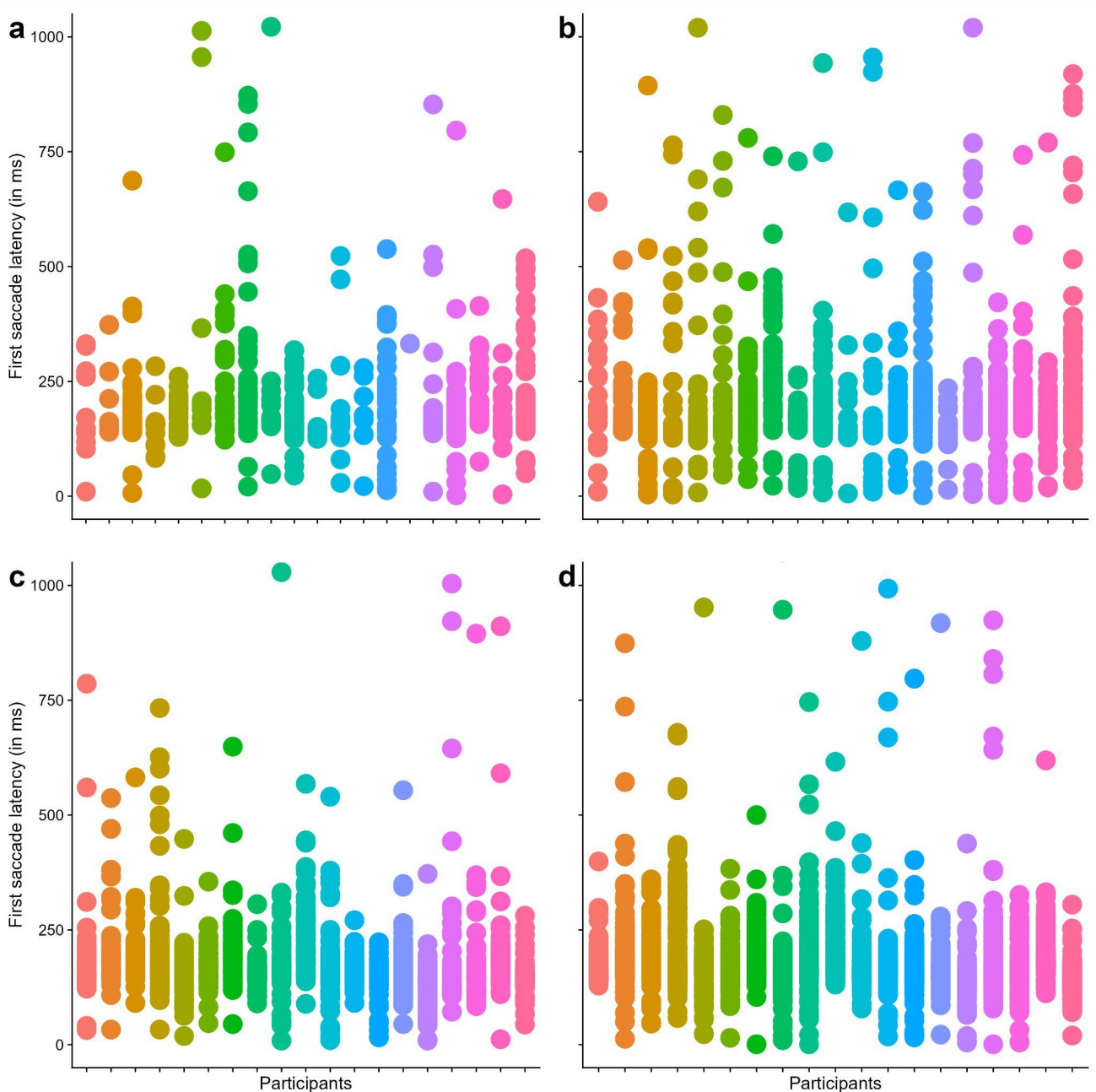


Figure 3.4. Participant wise distribution of saccades latencies of first singleton and non-singleton distractor saccades. In Experiment 1 latencies on singleton saccades (a) are shorter than latencies on non-singleton saccades (b). A majority of saccades to the singleton occur before 250 ms, suggesting reflexive stimulus driven biases towards the singleton. Whereas saccades to the non-singleton distractors occur for longer latencies and more in number. A similar pattern is seen in Experiment 2 singleton saccades (c) and non-singleton saccades (d) albeit stronger.

3.3.3 Discussion

Suppression of the singleton distractor proceeded on no-cue trials resulting in an RT benefit for search. Eye gaze trajectory indicated consistent oculomotor suppression of the singleton distractor; covert and overt attentional shifts to the singleton were prevented. On no cue trials, first target saccades were still slow on singleton present vs. absent trials—the singleton offered interference to target search. Thus the RT benefit during singleton present trials was a result of efficient target enhancement and distractor suppression.

Cues were perceived below levels of conscious awareness as cue detection accuracy and d' for the 16 ms cue were close to 0. The catch trials with 500 ms cue however were detected with greater than chance level accuracy, suggesting that cue duration reliably altered cue perception. All cue trials resulted in comparable RT benefit on singleton present trials compared to no-cue trials. This was unlike conscious cues in Experiment 1, wherein the color-matching cues contributed to a greater RT benefit. This suggested that conscious color cues push color singleton representations and allow for rapid disengagement whereas subliminal color cues did not push singleton representations and caused proactive suppression. Oculomotor suppression of the singleton occurred instantly after the search started however location-matching and both-matching cues showed greater oculomotor bias against the singleton.

3.4 General discussion

We compared the influence of consciously and unconsciously perceived cues on suppression of singleton distractors and in turn on target search. In both Experiments 1 and 2, people looked for a target feature while a color singleton interfered with search on 50% of trials. While the participants were unaware which trial could contain the singleton distractor (singleton present trials) a cue presented before the search display, alerted participants of the singleton's presence with 100% validity. In experiment 1 these cues were presented for 500 ms such that participants could perceive

the cue with conscious awareness. The cue was displayed for 16 ms in the second experiment, to prevent conscious perception and render them subliminal. These cues matched singleton distractor in color, location or both and were compared to no cue trials (baseline) to measure their influence on suppression and search. Cues influenced attentional orienting, hence presence of cue before search was expected to influence search performance.

In both experiment 1 and 2, cue was not necessary to incur singleton presence benefit. This typically suggested that the distractor was suppressed in the absence of any cues, as is seen in many feature search studies. It was confirmed by saccadic analysis, which showed significantly less first saccades to singleton than to non-targets, although only in experiment 1. This suggested that participants attended the more to the non-targets (oculomotor suppression), in experiment 1. Thus, we observed a dissociation between manual response suppression and oculomotor suppression during feature search; manual response suppression does not guarantee oculomotor suppression (see figure 3.4). Further, target enhancement remained unaffected by manual and oculomotor suppression in both experiments 1 and 2. This was checked by comparing latencies of first target saccades. If the suppressed distractor interfered with target enhancement, eye gaze towards the target would have slowed on singleton trials, while results showed no effect on singleton's presence on target latencies.

Perceptual awareness of the cues interacted with its ability to influence attentional priority. For instance, when participants were aware of the cues, in Experiment 1, the color-matching cue led to covert attention capture by the singleton, while location-matching and both-matching cues led to overt attention capture by the singleton. However, attention was quickly disengaged from the singleton preventing RT cost on singleton present trials. Naturally, faster disengagement was possible with color-matching cues (only covert capture) and hence it resulted in greater benefit for search than location-matching and both-matching cues. We suppose that given sufficient time for top-down control to set in, color-matching cues helped in proactive suppression of the singleton.

Whereas, location-matching and both-matching cues resulted in reactive suppression of the singleton. When the cues were perceived below perceptual awareness, in Experiment 2, all cue types i.e. color-matching, location-matching and both-matching cues resulted in the same degree of suppression in manual responses. But on the other hand, cues didn't lead to capture. The oculomotor bias against singleton distractor was significantly strong from the beginning and stayed until the button press, irrespective of the type of cue preceding search.

Compared to the no-cue trials, the color-matching cue offered greater benefit for suppressing oculomotor as well as manual responses corresponding to the singleton. This suggested that knowing the color feature of an upcoming color singleton, irrespective of perceptual awareness of the color feature, helped in suppressing the color singleton distractor. We called this the contingent-suppression effect, analogous to the contingent-capture effect. According to which, information about targets makes up the attentional set, such as task-relevant features and locations. Thus, items matching the set capture attention just like the target. Similarly, information about the distractors makes up the suppression set (excluding task-irrelevant information). In this task, color red (or blue) was a task-irrelevant feature and hence part of the suppression template. When a cue matching the suppression template was presented before the search, it helped in suppression, and thus color-matching cues helped in suppression of the singleton. However, no location was associated with a distractor more than another, and neither was associated with the target. Hence, the suppression template does not contain spatial representations of the distractors. And location-matching and both-matching cues did not benefit suppression.

In a similar study, Travis et al. (2019) showed visible and invisible distractor-colored cues resulting in Pd in equivalent magnitudes. They suggested that goal-directed control settings facilitates suppression independent of conscious perception. Taken together without findings, it seems that distractor suppression is independent of conscious perception. However, we extended this

finding by distinguishing conscious and unconscious features and spatial suppression both at pshysiomotoric and oculomotor stages of searching. Our findings indicated a disassociation between oculomotor suppression and manual response suppression, suggesting independent processes of conscious and unconscious top-down control. While it may seem that color-matching cues are more effective in guiding suppression, it may well be a result of the feature search paradigm we used for this study. When spatial knowledge of the singleton varies in a task, we may find more insights into spatial top-down suppression. This question was explored in chapter 5.

CHAPTER 4

Testing the Limits of Unconscious Feature Suppression

The visual world is filled with stimuli which are irrelevant to our current goals. These stimuli act as distractors, while they appear dynamically and unpredictably during search. While studies show that singleton distractors can be suppressed such that they do not interfere with goals, it is unclear how an unpredictable distractor can be suppressed. Studies in chapter 2 have shown, with the help of a cue matching singleton feature, the singleton can be suppressed better. However, there is an initial capture followed by suppression of the singleton. While conscious access to these cues interacts with the degree of suppression they result in, we wanted to explore this further by degrading the perception of subliminal cues using a visual mask. In two experiments, a singleton distractor was presented unpredictably during search. A brief cue matching the singleton color, target color or neutral color was presented before the search display, either masked (Experiment 1) or unmasked (Experiment 2). The unconscious cues influenced target search in both masked and unmasked conditions, but suppression was altered with the help of unmasked cues alone. Cues matching the singleton color did not benefit singleton suppression. These results extend on the role of conscious awareness in suppression during visual search.

4.1 Introduction

Searching for goal-relevant objects is challenged by the array of distractors that surround us. These distractors, although filtered out during selection, capture attention if they are more salient compared to other search elements. Making the task more specific to finding the target feature can encourage attentional control settings to prioritize specified target features and hence ignore salient distractors or even suppress them. But having a mechanism to suppress distractors is not enough. Distractors must be predicted beforehand if they have to be completely ignored. How do we acquire information about things before they are seen—using cues? Cues occur in nature for the purpose of guiding attention to objects. Studies have consistently shown attentional orienting to cues influencing target localization. However, cueing processes differ when the cue holds task-irrelevant information. Studies show that cued distractors hamper search by capturing attention. A goal-directed attentional shift with respect to distractor cues has rarely been seen. Research suggests that awareness of cues when reduced below a threshold can change the cueing effect. Here we explored how making cues unconscious can help in strategic distractor suppression without initial capture with completely unconscious cues. While in Chapter 2, we discussed studies where the 16 ms cues produced lower signals compared to the 500 ms cues, it did not guarantee unconscious perception. In this study, we accessed cue awareness subjectively and objectively on every trial and used a color mask to further shield it from conscious awareness.

Salient stimuli can escape filtering and capture attention. In a classical study, Theeuwes (1992) demonstrated a phenomenon called *singleton capture*, wherein salient stimuli capture attention in opposition to the task goals. He introduced a unique color (red among greens) distractor during the search for a uniquely shaped target and homogeneous distractors (diamond among circles). The RTs were slower on trials when one of the distractors was salient compared to trials when all distractors were non-salient. It suggested that singletons capture attention irrespective of

task goals. Bacon and Egeth (1994) provided a counter-interpretation for these findings and suggested that the design used in Theeuwes (1992) induced a singleton-detection mode. They proposed that during singleton search, participants are encouraged to look for singletons instead of the specified target feature. Thus, the color singleton fulfilled this search template and captured attention. A modification of singleton search nullified this capture effect and supported goal-directed attention control. This paradigm called feature search encouraged participants to look for the critical target feature and rendered singletons irrelevant. This was achieved by simply making all search items a unique shape such that none of them remain singleton in shape, which was the target defining feature. According to the goal-driven model of attention capture, any stimuli matching the representations of task-relevant items receive greater priority for attention (Folk & Remington, 1998) and stimuli that do not match the representations are ignored.

Singleton distractors can not only be ignored, but also suppressed when they are irrelevant to the task goals. This was shown earlier by Gaspelin et al. (2015) when they tested the hypothesis from Bacon and Egeth (1994) by modifying Theeuwes (1992). The search display comprised all unique shapes, one of them being the target shape. Hence, the target was not a unique shape (or unique in any other feature). Either non-target was presented in a unique color 50% of times—mixed randomly with singleton absent trials. The assumption was that such a design would encourage a feature search mode, and hence a singleton would not capture attention. But instead of finding the *absence of singleton capture*, they found *singleton presence benefit*. They suggested that the singleton was not only ignored but suppressed during feature searches, while other distractors were passively filtered. Since these experiments emphasized singleton distractors, they proposed that salient items generate an attend-to-me signal which is later suppressed by the goal-directed control, *the signal suppression hypothesis* (Gaspar & McDonald, 2014; Gaspelin & Luck, 2015, 2018a, 2018b; Sawaki & Luck, 2010). This notion was recently challenged by Lien et al. (2021), when they showed that any distractor with features consistently associated with distractors can be suppressed, irrespective of its

salience.

As goals change, the definition of distractors changes. Hence, suppression of a distractor must be sensitive to dynamic adjustment in goals. Cues in the environment often warn against changes in task goals. Past studies have explored how attentional suppression is affected by such cues (Wang & Theeuwes, 2018a). Moher and Egeth (2012) cued non-target features during search and found slower RTs at short SOA but faster RTs at long SOA. In another study, Chang et al. (2019) found that the presence of an arrow cue indicating the location of a singleton distractor eliminated the cost of capture by the singleton. However, target responses compatible with the singleton (compatibility effect) still slowed RTs to the target, suggesting that the singleton was suppressed after attention was initially captured by it (rapid disengagement) (Chang et al., 2019). Heuer and Schubö (2020), in a recent study, introduced spatially predictive and non-predictive distractor cues prior to a singleton search task, and found comparable RT for both types of cues. However, a smaller P_d was found for predictive compared to non predictive cues. A few studies also suggest that suppression of a distractor can benefit by cueing its features with substantial practice (Cunningham & Egeth, 2016).

Awareness of the distractor and distractor cues can influence how they can be avoided. In recent studies, target detection was slowed when participants were aware that a singleton distractor captured their attention, than when they were unaware of the capture (Adams & Gaspelin, 2020, 2021). Memory precision for salient non-targets also reduces when they are suppressed (Won et al., 2022). Hence, it is possible that awareness of distractor cues influences whether the distractor can be suppressed with the help of the cue or not. Travis et al. (2019) have directly looked at the influence of unconscious cues on distractor suppression. They used target as well as singleton distractor color matching cues, along with two neutral color cues, in a search task. The cue display was suppressed using continuous flash suppression[1] on half of the trials, such that awareness of the cue could be

manipulated within the task. Even in the absence of cue awareness, a significant validity (valid RT < invalid RT) effect was observed for target-colored cues. Distractor-color cues resulted in negative compatibility (valid RT > invalid RT). This suggested that unconscious cues enhanced priority for feature-matching objects, irrespective of their relevance to the task (distractor cue). Hence, the unconsciously cued distractor was harder to suppress.

Current Study

This study aimed to further explore how unconscious distractor cues can guide suppression by overcoming the shortcomings of Travis et al. (2019) and studies discussed in Chapter 2. We asked new questions on how the mechanisms of unconscious distractor suppression work. Firstly, studies have shown that 100% informative cues are more effective in guiding endogenous attention to the target compared to less informative cues (Yantis & Jonides, 1990). In Travis et al. (2019) and others, feature cues guided attention endogenously but also unpredictably, and hence could have been ineffective in enhancing suppression of the distractor. In the current study, we similarly introduced singleton ‘distractor color’ and ‘target color’ matching cues before the search, but only in the center of the display—facilitating endogenous orienting. The cue color matched the singleton or target or a neutral color (cueing threshold). We expected the neutral cue as well as the target cue to facilitate search, but not the suppression. On the other hand, distractor cues would alter priority of the singleton distractor, and in turn influence suppression. To facilitate the suppression of the singleton, the search task was similar to Gaspelin et al. (2015).

Secondly, studies in Chapter 2 looked at the influence of conscious distractor cues and unconscious distractor cues alone. If we assume that awareness is a graded phenomenon, then the gradation would result in graded suppression as a consequence. To examine this in the current study we used a brief cue of 16 ms (Mulckhuyse et al., 2007; for a review see Prasad & Mishra, 2019) which was masked by a color patch in experiment 1 and was not masked in experiment 2. This

allowed us to explore if unconscious cues that stay in iconic memory for longer, impact suppression differently than unconscious cues that do not. The cue was a colored square which fit directly into the fixation square of the search display that followed, creating a metacontrast mask in both Experiments 1 and 2. The cue duration and metacontrast masking ensured that the cue was perceived unconsciously yet the presence of a forward color patch as mask in experiment 1 allowed less time for the cue to be in iconic memory—tapping into multiple levels of perceptual awareness (Fleischhauer et al., 2014).

4.2 Experiment 1

4.2.1 Methods

4.2.1.1 Participant

Power analysis (“pwr” package in R) was performed to obtain a sample size, significant enough to show the influence of the unconscious cue on search. Previous visual search studies (Travis et al., 2019; Wang & Theeuwes, 2018) suggested an effect size in the range of 0.3 - 0.4, which yielded a sample size of 11–19 participants, for a desired power of 0.5 and a confidence level of 0.05. In order to obtain greater power and effect size, we selected thirty naive volunteers (16 females, mean age = 28 years, SD = 2) from the University of Hyderabad. All participants scored above 90% accuracy in the red-green test and Ishihara color blindness test (specific to discriminating red from green).

4.2.1.2 Apparatus, Stimuli & Procedure

On a grey background ($x = 0.312$, $y = 0.329$, 0.1 cd/m^2), a fixation ($0.6^\circ \times 0.6^\circ$) was presented for 100 ms followed by a cue ($0.6^\circ \times 0.6^\circ$) display for 16 ms and a mask for 50 ms. The cue comprised a solid square colored, red ($x = 0.640$, $y = 0.330$, 12.1 cd/m^2), green ($x = 0.288$, $y = 0.556$, 12.1 cd/m^2) or black, see figure 4.1(b). The mask was created by placing smaller pink and yellow squares on a larger grey square. Search of 2000 ms and had four shapes—three distractors and a target—all

presented in green color (or all red-counterbalanced across participants), as shown in figure 4.1(a). The target could be a circle ($1.7^\circ \times 1.7^\circ$) or a diamond ($1.7^\circ \times 1.7^\circ$) shape (counterbalanced among participants), among hexagon ($1.7^\circ \times 1.7^\circ$) and pentagon ($1.7^\circ \times 1.7^\circ$) distractors. A horizontal/vertical line was superimposed on all shapes while participants reported the the line on the target. Cue visibility was assessed on every trial, first by objective color detection and later using the Perceptual Awareness Scale (PAS).^[2] Feedback of 500 ms was provided for incorrect and missing search responses during all trials and for incorrect cue visibility responses during practice trials. The next trials started after a 500 ms blank display. Catch trials with a cue duration of 500 ms were included in the practice trials to discourage false positives in the cue visibility test.

4.2.1.3 Design

The fixation was always presented in the center, and also the cue and the mask. The search display was arranged in an invisible rectangle around the fixation ($5.8^\circ \times 3.5^\circ$). All shapes appeared equally likely at all locations. Any distractor appeared in red among all greens or vice versa, on 50% trials. The cue matched target color or singleton color or a neutral color, in separate blocks, randomized between subjects. There were 300 experimental trials; 100 trials with each cue color, containing 50 singletons present and 50 singletons absent trials. The singleton present (or absent) trials did not appear consecutively for more than three trials, to ensure unpredictability of the singleton. All participants completed at least one session of 15 practice trials containing all representative trials before they started the main experiment.

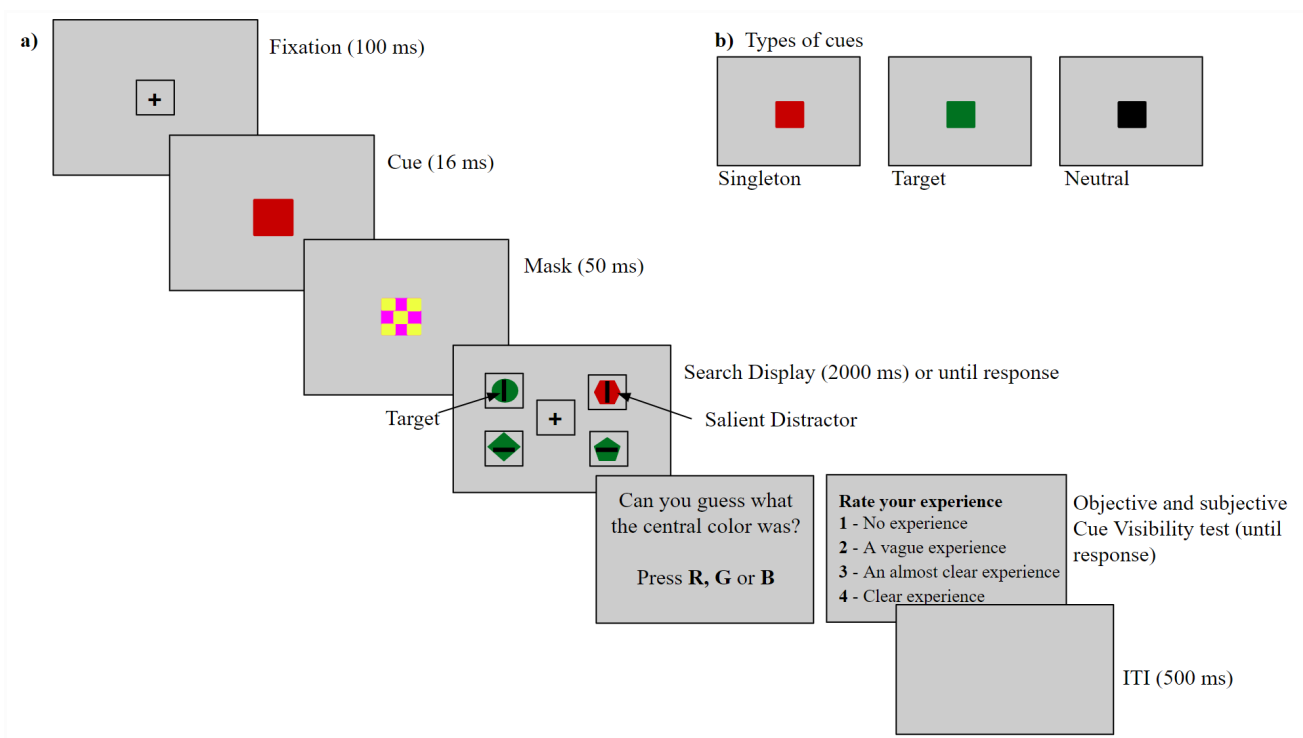


Figure 4.1. Flow of a trial in Experiment 1 and the types of cues (a) shows a typical trial sequence with a singleton cue and a singleton present trial. Participants find the target circle and press the key corresponding to the vertical bar. Then they press R, G or B to report the color of the cue (here R is correct) and rate the confidence of their response on a scale of 1 to 4. Figure 4.1(b) shows cue colors, red, green, and black which correspond to singleton matching, target matching and neutral cues respectively, in distinct blocks of trials.

Note: Objects in figure 4.1 are enlarged for the purpose of illustration.

4.2.2 Analysis

RStudio Version 1.2.5003 (2009-2019 RStudio, Inc) was used for identifying and eliminating outliers. We removed incorrect and missed response. Trials with RTs faster than 200 ms and slower than 1500 ms (Gaspelin et al., 2017), as well as RTs outside the range of ± 2.5 median standard deviations range (MAD) for each condition, were also excluded as outliers (Eng et al., 2018; Lim et al., 2019). The filtering led to a 15% loss in the raw data. Only one participant showed an accuracy

of less than 50% and was excluded from RT and accuracy analysis.

Mean RTs and accuracy were subjected to a repeated measures ANOVA run on JASP Team (2020). JASP (Version 0.14.1), with singleton (absent vs present) and cue color (singleton, neutral, target) as within-subjects factors. When the interaction of singleton and cue color was significant, the suppression index was calculated by subtracting singleton present trial RTs from singleton absent trial RTs (Gaspelin et al., 2017) and was compared across the cues, in a one-way ANOVA. To check that the feature search design indeed encouraged serial search, RTs as a function of singleton-target spatial distance were compared in a t-test. A singleton could either appear at an adjacent location or a diagonal location to the target. RTs would differ among adjacent and diagonal singleton trials for serial searches.

If the singleton was suppressed on a given trial, the remnants of that effect would prevent attention from returning to the suppressed location even if the target appears there on a later trial. Inter-trial transfer of suppression was calculated by comparing trials where the target location matched the previous singleton location to trials where it matched other locations (mismatched). Finally, RT distribution analysis was compared across the cue blocks to see the change in singleton present vs absent RTs as they increased gradually from very fast to slow RTs. Since attentional processes during faster RTs correspond to more stimulus-driven influences and those during slower RTs correspond to goal-driven influences, RT distribution analysis clarified if the cues led to an initial stimulus-driven capture followed by suppression, like previous studies.

A one-sample student t-test was performed on the average cue detection accuracy (Mulckhuyse et al., 2007) which was compared across conditions of singleton (present vs. absent) and cue colors in a repeated measures ANOVA. Further, sensitivity to the cues was calculated by measuring d prime (d') the difference between z-transformed probabilities of hits and false alarms according to the signal detection theory (Mulckhuyse & Theeuwes, 2010). A t-test compared the d prime to zero, and a

repeated measures ANOVA compared the *d* prime across task conditions. Finally, an average PAS score was obtained and compared to the mean of the PAS score (2.5) in a t-test and across task conditions, similar to the *d* prime. In comparisons where the assumption of sphericity was violated, the Greenhouse-Geisser corrected values of *p* were reported instead.

4.2.3 Results

Mean RT

Reaction times were quicker in singleton's presence (1045 ms) than its absence (1058 ms), $F(1, 28) = 6.51, p = .016, \eta^2 = 0.189$. Cues influenced search RTs significantly, $F(2, 56) = 3.41, p = .040, \eta^2 = 0.109$. The fastest RTs were seen on target cue trials (1025 ms) compared to neutral cue trials (1082 ms), $t = 2.58, p = .037$. RTs were comparable among singleton (1047 ms) and neutral cue, $t = 1.60, p = .342$, as well as the singleton and the target cue trials, $t = 0.98, p = .988$. The interaction of singleton (present vs absent) and cues was not significant, $F(2, 56) = 0.45, p = .637, \eta^2 = 0.016$, suggesting that the cues affected search performance but not the processing of the singleton, see figure 4.2(a).

Mean Accuracy

Search accuracy was unaffected by singleton presence (89.22 %) and absence (88.55 %), $F(1, 29) = 2.23, p = .146, \eta^2 = 0.071$ and by the type of cue preceding the search: target (89.83 %), singleton (89.06 %), and neutral (87.76 %), $F(2, 58) = 0.65, p = .522, \eta^2 = 0.022$. The interaction of distractor and cue was also not significant, $F(2, 58) = 0.04, p = .959, \eta^2 = 0.001$.

RTs as a function of target-singleton distance

On singleton present trials, RTs were equivalent when the target and the singleton were adjacent (1039 ms) to each other compared to when they were diagonally opposite (1050 ms) to each other, t

=0.49, $p = .622$ as shown in figure 4.2(c).

Intertrial suppression effect

RTs were comparable when the current target location matched the previous singleton location (1062 ms) or another location (1047 ms), $F(1, 25) = 1.84$, $p = .186$, $\eta^2 = 0.069$, suggesting the absence of inter-trial suppression which was consistent for all cue colors also indicated by insignificant interaction between target-singleton location match vs mismatch and cue type, $F(2, 50) = 0.43$, $p = .651$, $\eta^2 = 0.017$, see figure 4.2(b).

Distribution analysis

As shown in figure 4.2(d), suppression of the singleton was observed when RTs were slower than 1128 ms, corresponding to Bins 4 and 5, indicated by a significant interaction of singleton (present vs absent) and bins, $F(4, 112) = 2.65$, $p = .037$, $\eta^2 = 0.087$. This suggested that the singleton distractor was suppressed by goal-driven influences after attention was captured by stimulus-driven influences. All cue colors led to a similar pattern across the RT distribution.

Objective visibility test

Overall cue detection accuracy was significantly less than the chance level (44.86 %), as indicated by a one-sample t-test, $t = 2.35$, $p = .020$. Repeated measures ANOVA on accuracy showed a main effect of the cue, $F(2, 58) = 3.47$, $p = .038$, $\eta^2 = 0.017$. The neutral cues (56.10 %) were reported more accurately than singleton cues (37.40 %), $t = 2.48$, $p = .047$, while target (41.10 %) and neutral cues were reported with comparable accuracy, $t = 1.99$, $p = .152$. Cue detection was comparable among singleton absent (45.35 %) and present (44.37 %) trials, $F(1, 29) = 1.81$, $p = .189$, $\eta^2 = 0.059$. The interaction of singleton and cue was also significant, $F(2, 58) = 5.50$, $p = .006$, $\eta^2 = 0.160$, but did not generate meaningful interactions relevant to the hypothesis.

d' prime

The overall d' prime was not significantly different from 0, $t = 1.46$, $p = 1.000$, indicating that the cues were perceived in the absence of conscious awareness. The d' prime values varied across cues, $F(2, 58) = 3.47$, $p = .038$, $\eta^2 = 0.107$ and were greater for neutral cues (0.7) than the target (0.2) and singleton cues (0.5).

Subjective visibility test

The Average PAS score for all cues (1.7) was significantly less than the mean score (2.5), according to the one-sample t-test on PAS scores, $t = 11.58$, $p < .001$. The presence (1.7) or absence (1.7) of the singleton on a given trial did not affect the PAS rating significantly, $F(1, 29) = 1.86$, $p = .182$, $\eta^2 = 0.061$. Neutral cues (2.0) were, however, reported with greater confidence than singleton (1.6) cues, $t = 4.16$, $p < .001$ and target cues (1.6), $t = 3.99$, $p < .001$, $F(2, 58) = 11.11$, $p < .001$, $\eta^2 = 0.277$.

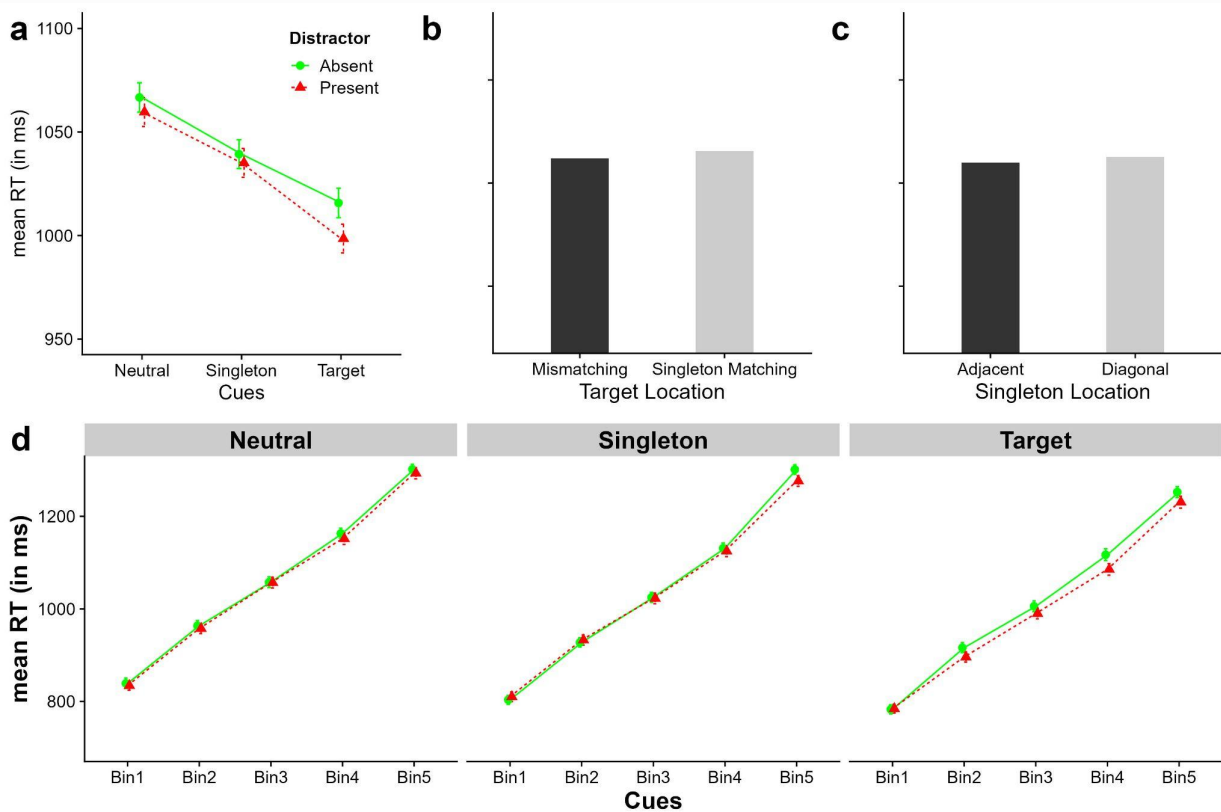


Figure 4.2. Mean RT results of Experiment 1. (a) Mean RTs on (b) when the current target

location matched the previous singleton location vs matched other locations (mismatched) and (c) singleton's position relative to the target (d) RT distribution in ascending order, across condition of cue types. The results indicate faster RTs in the presence of singleton, more so for target cues. The presence of the cue does not influence the suppression of the singleton distractor.

4.2.4 Discussion

In experiment 1 we examined if unconscious cues can influence the processing of a singleton distractor during feature search. The reaction time measurements indicated that target search was facilitated in the presence of the singleton distractor, while accuracy remained unaffected. This could point towards two possibilities, first, the singleton was filtered and hence the target search was faster and second, the singleton was suppressed. When the former singleton coordinates were assumed by target, no difference in RTs was found compared to when it was presented at another location, indicating that inhibition at the singleton location was either absent (supporting the filtering hypothesis) or was weak to carry over to the next trials. Moreover, singleton presence benefit was seen for slower RTs, suggesting that the target search was facilitated with goal-driven influences enhancing suppression of the singleton distractor post initial attention capture. Findings altogether, suggest suppression during the search. The cues were perceived below significant thresholds of conscious perception, as supported by both objective and subjective assessments of cue perception, d prime and PAS respectively. The cues matching the singleton led to slowed target search compared to target cues but did not affect the singleton presence benefits differently than target cues. This suggested that the unconscious cues influenced the search, but did not impact the processing of the singleton distractor or its suppression.

4.3 Experiment 2

Experiment 1 suggested that unconscious cues can influence feature search but failed to show that singleton processing was affected by them. In previous studies, cues that were visible and

perceived consciously by the participants have been shown to influence the suppression of singleton distractors. Taking this into consideration, we suspected that making the cue more perceivable would enhance the chances of it influencing singleton suppression. While keeping the cue unconscious, we tried to enhance its perception by removing the color mask that appeared after the cue and before the search display. Removing the mask would serve two purposes, first, increase the perception of the cue by encouraging iconic memory representations of the cue to persist for a longer duration (Hagmann & Potter, 2016). And second, by allowing the cue representations to be active until the search—thus influencing attentional priority for the search. However, the PAS rating that followed cue detection made participants more aware of the cue. To avoid making the participants completely aware of the cue, given the removal of the mask, we also removed the PAS rating step from the trial. Hence, every participant only reported the cue color at the end of each trial.

4.3.1 Methods

4.3.1.1 Participant & Procedure

Thirty naive volunteers completed Experiment 2 which had a similar design apart from the replacement of the mask by the fixation screen for 50 ms. Also, the participants only reported the color of the cue and did not rate the confidence of their experience.

4.3.2 Results

Mean RT

RTs on singleton present trials (1055 ms) were faster than RTs on singleton absent trials (1074 ms), $F(1, 29) = 10.51, p = .003, \eta^2 = 0.266$. RTs varied with cue color, $F(2, 58) = 3.67, p = .032, \eta^2 = 0.112$. They were slower for singleton cues (1089 ms) compared to neutral cues (1054 ms), $t = 2.21, p = .06$ and the target cue (1051 ms), $t = 2.45, p = .051$. Unlike experiment 1, there was a significant interaction between singleton (present vs absent) and cue color, $F(2, 58) = 3.92, p = .025, \eta^2 =$

0.119, indicating the suppression of the singleton varied with the cue presented before the search. The suppression index was highest for the target (28 ms), $t = 2.41$, $p = .054$ and neutral cue (28 ms), $t = 2.43$, $p = .054$, compared to the singleton cue (-1 ms). ⁹Here, the negative sign indicates the absence of suppression for singleton cues as shown in figure 4.3(a).

Mean Accuracy

Accuracy on singleton present trials (93.44 %) was marginally greater than accuracy on singleton absent trials (92.28 %), $F(1, 29) = 3.78$, $p = .061$, $\eta^2 = 0.116$. Cues did not influence mean accuracy, $F(2, 58) = 0.79$, $p = .457$, $\eta^2 = 0.027$, and the interaction of singleton (present vs. absent) trials and cues was insignificant $F(2, 58) = 0.51$, $p = .600$, $\eta^2 = 0.017$ as well.

RTs as a function of target-singleton distance

On singleton present trials, RTs were faster when the target and the singleton were adjacent to each other compared to when they were diagonally opposite to each other, $t = 3.12$, $p = .004$, see figure 4.3(c). This suggested that the participants engaged in serial searches.

Intertrial suppression effect

RTs were faster by 38 ms when the target location matched the previous singleton location on a given trial versus when it matched another location, $F(1, 25) = 6.77$, $p = .015$, $\eta^2 = 0.213$, see figure 4.3(b). This indicated that inhibition at the singleton location prevented selection of that location, even when the target was presented there afterward. This effect did not differ across the different cues, $F(2, 50) = 1.86$, $p = .165$, $\eta^2 = 0.070$, suggesting that inter-trial suppression was independent of the features of the cues preceding the search.

Distribution analysis

Suppression of the singleton distractor was observed when RTs were slower than 1051 ms (however

faster than experiment 1), corresponding to Bins 3,4 and 5, indicated by a significant interaction of singleton (present vs absent) and bins, $F(4, 116) = 3.98, p = .005, \eta^2 = 0.121$. Suppression across the RT bins also varied for the different types of cues, indicated by the three-way interaction between singleton, cue color and bins, $F(8, 232) = 2.82, p = .005, \eta^2 = 0.089$. We calculated the mean suppression index for each cue color, across bins and subjected them to a repeated measures ANOVA, which suggested that only target cues showed an increase in suppression in Bin 3: $t = 3.76, p = .016$, Bin 4: $t = 4.73, p < .001$ and Bin 5: $t = 3.96, p = .008$ compared to Bin 1. The suppression index did not increase significantly from Bin1 to Bin 5 for neutral and singleton cues, see figure 4.3(d).

Objective visibility test

Overall cue detection accuracy (51.35 %) was not significantly different from the chance level, as indicated by a one-sample t-test, $t = 0.50, p = .615$. Repeated measures ANOVA on accuracy showed a main effect of the cue, $F(2, 58) = 3.58, p = .034, \eta^2 = 0.110$. Target cues (62.56 %) were reported with greater accuracy than singleton cues (40.20 %), $t = 2.67, p = .029$, while the target and neutral cues (51.30 %) were reported with comparable accuracy, $t = 1.34, p = .365$. Cue detection was comparable among singleton absent (51.82 %) and present (50.88 %) trials, $F(1, 29) = 1.31, p = .262, \eta^2 = 0.043$.

d' prime

The overall d prime was not significantly different from 0, $t = 335.41, p = 1.000$, indicating that the cues were perceived in the absence of conscious awareness. The average d prime values varied across cues, $F(2, 58) = 3.58, p = .034, \eta^2 = 0.110$ and was greater for target cues (0.6) compared to the singleton cue (0.2), $t = 2.67, p = .029$ and was comparable among target cue and neutral cue (0.0), $t = 1.34, p = .548$.

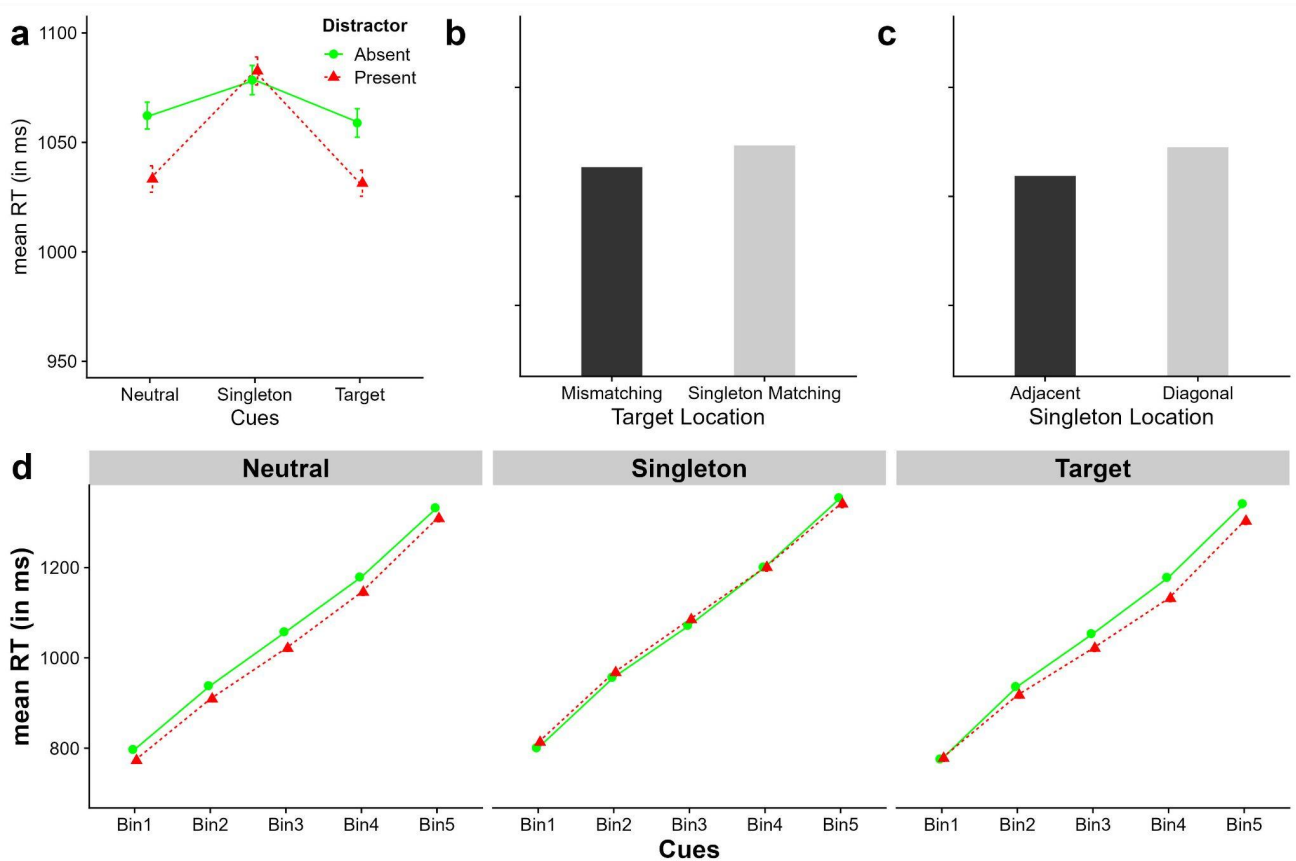


Figure 4.3. Mean RT results of Experiment 2. Mean RTs on (a) types of trials, (b) for conditions of target location match vs. mismatch and (c) singleton adjacent vs diagonally to a target (d) RT distribution across the condition of cue color. RTs were faster in the presence of target cues compared to singleton cues. The presence of the singleton cue hampers suppression of the singleton, while target and neutral cues affect suppression similarly. There was inter-trial suppression. RTs were slower when singleton and target were placed diagonally in a display versus adjacent to each other, confirming that the search for the target followed serial mode.

4.3.3 Discussion

The key results replicated the results from Experiment 1, such as the singleton presence benefit. Singletons presented diagonally opposite to the target slowed RTs compared to singletons adjacent to the target, suggesting a serial mode of search. Further, the suppressed location continued to be inhibited until the next trial even after the target occupied that location, suggesting that the

suppression was relatively higher. Suppression of the singleton started relatively early compared to experiment 1, around 1050 ms, and continued for the duration of the search. The cues were perceived unconsciously, despite the removal of the mask, and indeed influenced suppression. Distractor cues could not enhance singleton present benefit, whereas target cues and neutral cues did enhance singleton present benefit. The results suggested that unconsciously perceived cues that match features of the singleton distractor pushed its priority higher, hampering suppression. Future studies can explore if unconscious singleton cues can be in fact used to enhance suppression of the singleton distractor in differential task conditions.

4.4 General Discussion

Can unconscious cues influence attentional processing? We confirmed that brief cues were perceived below the levels of conscious perception, and they influenced attentional processes during the search. In Experiment 1, target cues enhanced overall search RTs when compared to neutral cues, suggesting that target processing was facilitated by the cues. In Experiment 2, when the singleton was cued, target search was slowed compared to when the target or a neutral color was cued. This suggested that the target and the neutral cue did not affect search performance much, but the singleton cue hampered target search. Further, we found a singleton presence benefit, supporting the possibility of distractor suppression. Suppression of the salient distractor influenced attentional processing at the target across trials (inter-trial suppression), only in the second experiment. Further, this suppression was hampered by the distractor-matched cue while it remained unaffected by target-matched and the neutral cue. The cues did not influence suppression in experiment 1, as expected, since memory traces of these cues were faint and hence not sufficient to alter attentional priority processing before the search.

One of the key differences between Travis et al. (2019) and the current study was that the cue predictability was 100% in the current study and 25% in Travis et al. (2019). We expected that a

100% predictive cue would make endogenous orienting to the cue more effective, which it did. Singleton cues influenced target search by slowing RTs overall and making suppression of the singleton distractor difficult, replicating the attentional white-bear effect (Cunningham & Egeth, 2016). The neutral cues did not interfere with suppression, suggesting that the feature match with the salient distractor (on distractor cue trials) prevented its inhibition and not the absence of inhibition itself (despite the cue). Endogenous attention was oriented towards the singleton and not away from it. This suggested that the predictability of an endogenous cue does not guarantee goal-directed processing of the cue. A fluid control mechanism allows reorienting and disengaging from potential threats (distractors) towards relevant goals (targets). Studies that did show better suppression when the singleton was cued allowed time for the cues to be processed (Moher & Egeth, 2012; Stilwell & Vecera, 2019a, 2019b) and rapid disengagement was initiated before the distractor appeared (Cunningham & Egeth, 2016).

These findings raised an important question. Is proactive suppression possible when the singleton is cued? This is to say, if foreknowledge of a potential distractor is provided by a cue, the distractor can be suppressed without initially capturing attention. Studies with conscious cues show better suppression on endogenously pre-cueing the distractor. For instance, van Zoest et al. (2021) used a central arrow cue (experiments 1 and 2) indicating the location of a singleton distractor or a word display (experiment 3) in the color of the singleton distractor, for 500 ms, prior to the search for an orientation target. These were compared to a no-cue condition. In all three experiments, a greater % of saccades ended at the salient item in the no cue condition vs. cued condition, suggesting that prior knowledge of the singleton location and feature helped in suppressing eye movements to the singleton. Assimilating observations from the past together with the results, we suggest that suppression of a singleton is possible with the help of endogenous cues when sufficient time is available for attentional disengagement from the cued location.

An alternative explanation for the lack of goal-driven control of cues is the lack of incentive to do so. For instance, Conci et al. (2019) manipulated task difficulty by altering target-distractor similarity. A cue preceding the target cueing the target, distractor or neutral color appeared on screen while people looked for the target alphabet. They performed both, an easy search (Experiment 1) and a relatively difficult search (Experiment 2). Faster RTs were recorded with target cue compared to the neutral cue in both experiments. Whereas only the difficult task, provided sufficient incentive to yield an RTs benefit for the distractor cue compared to the neutral cue. The facilitation effect of the distractor cues was observed only when discriminating the target from the distractors was difficult. Sufficient attentional control was needed to perform the difficult search task, and hence task-irrelevant information was also utilized in a goal-directed way (Conci et al., 2019). Hence, participants only used strategic suppression, when necessary, see Geng et al. (2019) for a discussion. In the current study, the set size was 4, which is less than the studies discussed such as van Zoest et al. (2021). Hence, the perceptual load was low and so was the incentive for goal-directed control (Lavie, 1995). Since, there is no consensus over strategic control of unconscious processing (Ansorge et al., 2014), future studies must explore this question by directly testing unconscious strategic suppression under high perceptual load.

Suppression, earlier considered a cursory mechanism to target enhancement, seems to be highly adaptive. Cues, awareness, and variability of distractor features, all influence suppression in a complex manner. Not all distractors are suppressed during the search, but both salient and non-singleton distractors can be suppressed if the task demands it. Any object can be a distractor in one instance and a target in another. Thus, no distractor can be permanently inhibited. Suppressing distractors must be controlled by a process more dynamic than those responsible for target enhancement. Attentional control processes need to adapt to changing task demands in order to define distractors and suppress them. Quick adaptation can be brought about by cues with information on the location and features of to-be-distractors. While processing a range of conscious

cues can create a cognitive load, unconscious cues can be processed without putting excessive cognitive demands. We propose that distractor suppression must be more sensitive to unconscious cues that contribute to the adaptive control-*adaptive suppression hypothesis*. Future studies must investigate the limits of adaptive suppression in a range of unconscious processes using a variety of tasks.

[1] Continuous Flash Suppression is a technique used to present subliminal stimuli in visual cognition experiments (Tsuchiya & Koch, 2005). Independent stimuli are presented to each eye. A salient mosaic patch flickers continuously in the dominant eye which dominates awareness and blocks awareness of the stimuli in the non-dominant eye, making it subliminal.

[2] Participants reported PAS to be a more intuitive scale of perceptual judgment in several past studies, suggesting that it can be used to assess the subjective perception of stimuli without introducing external confounds (Ramsøy & Overgaard, 2004; Sandberg & Overgaard, 2015).

CHAPTER 5

Investigating Top-down Spatial Suppression

In recent years, evidence has accumulated towards a distractor suppression mechanism that enables efficient selection of targets in a visual search task. According to these findings, the search for a target is faster in the presence of a singleton distractor in a display among homogenous distractors as opposed to its absence. Studies have also shown that distractor suppression not only operates on the feature level but can also be spatially guided. The motivation of the current study was to examine if spatially guided distractor suppression can be goal-driven. We tested this across four experiments. In Experiment 1A, the task was to search for a shape target (e.g., a circle) and discriminate the orientation of the line within it. In some trials, a salient color distractor was presented in the display while participants were told that it appeared in one of the two locations on the horizontal axis (or the vertical axis, counterbalanced across participants). We expected enhanced distractor suppression when the singleton distractor appeared within this “spatial filter” but did not find it since the target was also presented at the filtered locations. Experiment 1B replicated Experiment 1A, except that the target was always presented outside the filter; filtering enhanced search performance. In Experiment 2 even when the filter contained the singleton distractor in only 65% of the filtered trials, filtering benefited search performance. In Experiment 3, the filter changed on every trial and did not benefit suppression.

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5.1 Introduction

Everyday goals compel us to perform tasks that we often get distracted from. Distractors are everywhere, and they come in a variety of forms that we may fail to predict. Attentional mechanisms help in distinguishing targets from distractors. Attention can be directed to goal-relevant objects, rewarded objects or ones prioritized in the past (selection history and priming) (Anderson, 2016; Gottlieb, 2012). While these factors bias attention towards the target and enhance attentional processing, an interesting question is whether they also bias attention away from the distractors. Recently, a distractor suppression mechanism has been found that prevents attention from being deployed to the distractors which interferes significantly with task goals (Caputo & Guerra, 1998). In the lab-based tasks used to study this phenomenon, these “salient” distractors typically stand out in terms of features like color, orientation, onset, etc. When singleton distractors are suppressed, attentional deployment to the target is faster. Several studies show that singleton distractor locations can be suppressed by learning from past experience, habituation, and probability cueing (Anderson & Kim, 2020; De Tommaso & Turatto, 2019; Leber, Gwinn, Hong & O’Toole, 2016). What remains unclear is whether distractor suppression can be goal-driven. In this study, we inquired whether explicit knowledge of expected singleton distractor locations can modulate the extent of distractor suppression during a feature-search task.

Salient stimuli are suggested to cause a reflexive attentional shift towards it (Theeuwes, 1992). Typically, studies show that irrelevant singleton distractors slow down responses significantly when searching for a target, in an additional singleton paradigm. However, recent studies using a feature-search paradigm have found that responses become faster in the presence of the singleton distractor vs its absence (Gaspelin, Leonard & Luck, 2017). This benefit results from the suppression of the singleton distractor. While the difference in the two types of studies is a minor change in search strategy from singleton search to feature search, the latter strategy renders the singleton

distractor completely irrelevant to the task because it shares no features with the target (Bacon & Egeth, 1994). Thus, the incentive to attend to it is significantly reduced. In one of the earliest studies to demonstrate distractor suppression, Gaspelin, Leonard and Luck (2015) administered an additional singleton search task (Experiment 1) where the participants searched for a uniquely shaped target among only homogeneously shaped distractors, or among a color singleton distractor on half of the trials. Crucially, an additional probe detection task was administered on some trials where alphabets were briefly presented on each shape and the observers were asked to report as many alphabets as they could. Since the singleton distractor in this task captured attention, probe detection accuracy was higher at its location than at the other distractor locations. In a feature-search task (Experiment 2) when the target was presented among heterogeneous distractors including a singleton distractor color distractor, the accuracy of probe detection at the singleton distractor location was significantly lower than at the other distractor locations, supporting the claim that the singleton distractor was indeed suppressed during search (Gaspelin, Leonard, & Luck, 2015).

Can spatially guided suppression be goal-driven? Models of visual search do not conclusively suggest whether priority computations happen first at the featural or spatial level of processing. For instance, the SEarch via Recursive Rejection (SERR) model suggests that feature computations add up to a location map (Humphreys & Muller, 1993), whereas the Area Activation model suggests that saccadic selectivity is modulated by spatial affordance more than featural (Pomplun, Reingold & Shen, 2003). In a recent review, Luck et al. (2021) compared existing frameworks of attentional selection, viz contingent involuntary orienting hypothesis, stimulus-driven account and the signal suppression hypothesis. All three hypotheses proposed the concept of spatial and featural gain control. These control maps add up to the saliency computation of object features and locations in the visual field and combine to form the priority map (Egeth, Virzi & Garbart, 1984;

Wolfe, 2021). Hence, spatial attention prioritizes objects in the visual field based on their saliency computations. These models and past research suggest that both explicit goals and implicit learning can influence the priority map by biasing the spatial gain control but whether the resulting guidance influences target enhancement and distractor suppression *equally* remains contentious. Some findings suggest that a top-down spatial bias facilitates target enhancement but does not benefit distractor suppression, whereas implicit learning benefits both (Gao and Theeuwes, 2020). Hence, the predictions from Luck et al. (2021) should be tested further, especially for goal-directed spatial distractor suppression.

Observers can easily learn with experience if a location is more often linked to the distractor and suppress it. For instance, Wang, van Driel, Ort and Theeuwes, (2019) introduced a color singleton distractor in one location in 55% of the trials and 15% of trials in other locations (Experiment 1). Relative differences in RTs between singleton distractor present and absent trials reduced significantly at the high probability location compared to the low probability location suggesting that participants suppressed singleton distractor more efficiently in the high probability location (also see Britton & Anderson, 2020; Failing, Wang & Theeuwes, 2019; Ferrante, Santandrea & Chelazzi, 2018; Kerzel & Cong, 2021). To test if these effects can also be obtained through active, goal-driven suppression, Wang and Theeuwes (2018b, Experiment 2) conducted a study where instead of presenting the distractor more often at specific locations (as in Wang & Theeuwes, 2018a), the distractor location was predictively cued on a majority of the trials. The hypothesis was that if suppression can be achieved in a goal-driven manner, then the participants should be able to use the highly predictive cue to anticipate the distractor locations and effectively suppress them. This was not to be found. Cued distractors, in fact, led to more capture than uncued distractors. In line with this, several studies have argued that top-down control cannily is exercised on target selection, whereas distractor suppression operates based on habitual, experience-driven processes (Duncan & Theeuwes, 2020; Noon et al., 2016; see van Moorselaar & Slagter, 2020 for a

comparative review).

Given this, what was the objective of conducting this study, testing goal-driven spatial suppression? First, it is worth noting that the studies discussed here used the additional singleton paradigm, whereas our goal was to test goal-directed spatial suppression in the feature search paradigm. During a singleton search, participants form an attentional set to ‘find the singleton’ since the target is a shape singleton, hence even a color singleton captures attention. Past studies have indicated that feature search creates an opportunity for suppression (Bacon and Egeth, 1994) since the goal of finding the target with a specific feature precludes a singleton distractor (lacking that feature) from capturing attention. Second, when both featural and spatial expectations of a distractor are available, guidance can be an additive outcome of the two (Failing & Theeuwes, 2020; Gong & Theeuwes, 2021). But when Van Moorselaar, Daneshmandi & Slagter (2021), tested this by dynamically updating distractor location and features in a block of trials, they found that featural expectancies did not interact with location expectancies and hence, suggested that the two influence attention independently. Another possibility is that it was difficult to dynamically update the attentional template based on features and spatial expectancies. This could also explain why Wang & Theeuwes (2018b) did not find evidence for cued suppression because in that study the cue direction changed dynamically, thereby requiring participants to set up a new top-down goal on every trial depending upon the cue direction. Hence, we propose to have two constant locations, one of which will contain the singleton distractor required on a given trial. We believe that this could potentially be a reliable method to test goal-driven effects on spatial suppression, without requiring the participants to set up completely new control settings on every trial while also avoiding statistical learning effects.

Several studies have investigated if restricting the spatial scope of attentional guidance influences attentional selection (Burnham, 2018; Ishigami et al., 2009; Ruthruff & Gaspelin, 2017; Yantis & Jonides, 1990). For example, Ishigami et al. (2009) presented four (figure. 8) placeholders on the screen arranged in the form of a plus sign. Importantly, each participant was asked to only attend to locations either on the left/right or above/below the central fixation. Thus, the irrelevant, to-be-ignored locations remained constant throughout a session. The responses on irrelevant cue trials were slower than relevant invalid (when cue and target appear at different, relevant locations) trials suggesting reduced capture at irrelevant locations (also see Prasad, Mishra, & Klein, 2021; Ruthruff & Gaspelin, 2018). While these studies examined target selection when participants were asked to selectively attend to specific locations, our interest in the current study was to examine if selectively ignoring specific locations influences distractor suppression.

Selective ignoring was examined in a study by Burnham (2018) who used the classic contingent capture paradigm of Folk, Remington and Johnston (1992), except that the location where the target would NEVER appear was pre-cued at the start of every trial (Experiment 1, 2, and 4). The results showed that target-relevant cues (for example, red cues while searching for a red target) captured attention even when they appeared at to-be-ignored locations. This could be taken to suggest that suppressing distractors at to-be-ignored locations is not possible. But an important point to be noted is that Burnham (2018) showed a failure in ignoring *target-relevant* information at to-be-ignored locations. The *target-irrelevant cues* at the to-be-ignored locations in that study failed to capture attention as expected, analogous to distractor suppression. Further, in another experiment where the target location was pre-cued (instead of pre-cueing the location where the target doesn't appear), no capture was found even for target-relevant cues at the to-be-ignored locations. It is difficult to reconcile the findings from all the above-mentioned studies because of differences in

study design and motivation. But, it is safe to conclude that there is enough evidence for the role of spatial filtering on attention capture by spatial cues.

Current study

We combined the methodology of spatial filtering studies (e.g., Ishigami et al., 2009; Prasad et al., 2021) with a feature-search task. The display consisted of a feature target (green circle) amidst three other shape distractors. Among the distractors, two were of the same color as the target (green) and the third one was of a different color (e.g., blue or red). The four objects were arranged in the form of a plus sign. The task was to find the target and report the orientation of the line within the target (rightward tilted/leftward tilted). The participants were told that a singleton distractor would appear either on the horizontal axis or the vertical axis (“Filter present” condition) when the singleton distractor was red (or blue for another group of participants). Thus, this instruction was expected to inform the participants about the locations to reject as they were likely to contain the singleton distractor (to be referred to as the “Filter present” condition). It is to be noted that “filter” refers to the rejection template the participants are expected to have due to the instructions. Trials in which no instructions regarding the location of the singleton distractor were given, contained a blue (or red for another group of participants) singleton distractor and were administered as baseline (henceforth referred to as the “Filter absent” condition). As is typically observed in such studies, reaction times to target were expected to be faster in the presence of the singleton distractor as opposed to its absence (Blakley, Gaspelin & Gerhardstein, 2022; Hamblin-Frohman & Becker, 2022; Lawrence & Pratt, 2022; Stilwell, Egeth & Gaspelin, 2022). This RT benefit was expected to be higher in the “Filter present” condition compared to the “Filter absent” condition, thereby providing evidence for spatially-guided suppression based on task goals. In Experiment 1A, the singleton distractor was presented within the filter in all trials. This was to ensure that the filter was 100% predictive of the distractor location.

Target was equally likely to appear in any of the four locations, which meant it was presented within the filter on 50% of the trials. One could argue that expectancy related to the target appearance inside the filter could compromise distractor suppression. But, there is also a good reason why this wouldn't happen. The target appeared within the filter on 50% of the trials, whereas the singleton distractor was presented within the filter on all trials. Thus, the expectancy related to the singleton distractor was higher. But, we do agree that the possibility of suppression being lower due to the appearance of the target within the filter can't be ruled out. To test if this was happening, we analyzed if the extent of suppression varied as a function of the target inside filter vs. target outside filter. Further, we also conducted a control experiment where the target was never presented inside the filter. This allowed us to verify if the target-within-filter condition indeed reduced the extent of suppression.

In Experiment 2, the singleton distractor was presented within the filter only in 65% of the trials. A similar cueing study by Wang and Theeuwes (2018) failed to observe goal-driven suppression when the cue reliably predicted (65%) the distractor location. It is possible that goal-driven suppression is observed when participants have prior knowledge of the distractor locations with full certainty. It is known that endogenous orienting is most efficient when a central cue is 100% predictive (Yantis & Jonides, 1990). For instance, in an early study investigating the role of spatial filtering on target selection, Theeuwes, Kramer, and Atchley (2001) found that the magnitude of interference from a singleton distractor was lower when a 100% valid pre-cue indicated the target location suggesting that spatial filtering attenuated interference from the singleton distractor. If, according to our hypothesis, the absence of a 100% predictive cue in Wang and Theeuwes (2018) was responsible for the effects observed in that study, then we would similarly find that the filter had no effect on distractor suppression in Experiment 2 of the current study. The

RT benefit in the presence of a singleton distractor would be the same in the filter present vs. filter absent condition.

In Experiments 1A and 2, the filter or the axis to be ignored was counterbalanced across participants. Thus, half of the participants were told that the singleton distractor would appear on the horizontal axis and the other half on the vertical axis. This was to keep the top-down goals (that is, the locations to be ignored) constant across each session. However, it has been suggested that such blocking of task instructions can induce a form of learning and cannot be termed as goal-driven (Belopolsky et.al, 2015). Similarly, it can be argued that repeated presentation of the target within a particular axis in Experiment 1A induces statistical learning regarding the location of the singleton distractor. More recently, Gao and Theeuwes (2022) showed that explicit knowledge of where the distractors would appear does not boost the extent of distractor suppression in a singleton search task. The authors argued that this finding is consistent with the notion that statistical-learning based suppression is automatic and is not enhanced by conscious effort. The main objective of our study, on the other hand, was to examine if goal-driven control driven by explicit knowledge of distractor locations can boost distractor suppression. Thus, we needed to rule out statistical-learning based explanations of our findings. To address this, Experiment 3 had a mixed presentation of task goals. A horizontal or a vertical bar was presented at the beginning of every trial to indicate the corresponding axis in which the distractor appeared. The mixed presentation of the horizontal and the vertical bars ensured that participants did not learn the probability of distractor locations since there were no statistical regularities in the distractor locations. If such spatially-guided modulation of suppression is indeed goal-driven, we expected similar effects (albeit smaller) as we did for Experiment 1A.

5.2 Experiment 1A

5.2.1 Methods

5.2.1.1 Participants

GPower analysis suggested a sample size of 12 to obtain a medium effect size of 0.5 for the desired power of 0.8 and a confidence level of 0.05 (Faul, Erdfelder, Lang & Buchner, 2007). Based on previous spatial filtering studies in the literature conducted both offline (Ishigami et al., 2009; Ruthruff & Gaspelin, 2017) and online (Prasad et al., 2021), the experiment was administered to 40 participants ($M_{age} = 25.2$ years, 15 females). Prasad et al., (2021) also used a spatial cueing paradigm with a search task and found expected effects with the given sample size. Participants were healthy, young adults with normal or corrected-to-normal vision. The experimental procedure was approved by the Institutional Ethics Committee of the University of Hyderabad.

5.2.1.2 Stimuli & Procedure

The experiment was designed in SR Research Experiment Builder Software and administered on a 15-inch Dell laptop, with a resolution of 1920*1080 and a refresh rate of 60 Hz. Participants were given detailed instructions to minimize distractions during the experiment (e.g., “please keep your phone on silent mode”). They were seated at a distance of 60 cm from the display screen. The experiment consisted of 1000 main trials and 20 practice trials. Every participant completed a practice session at least once before starting the main experiment. Each trial started with a blank display rgb (153, 153, 153) for 500 ms, followed by a fixation display rgb (0, 0, 0), ($0.52^\circ \times 0.52^\circ$) for 100 ms. Participants were asked to keep fixating until a search display appeared in green (0, 114, 32). As shown in figure 5.1, the search display was presented for 2000 ms and participants were instructed to find the target circle (1.1° diameter) or diamond ($0.9^\circ \times 0.9^\circ$) (counterbalanced across participants), among hexagon (1.1° in width and height) and square ($1.0 \times 1.0^\circ$) shaped distractors, and report the orientation of the line (0.5° in width and height) on the target (right tilted/left tilted) by pressing a button on the keyboard. If the responses were incorrect or slower than 2000 ms, a feedback message appeared on the screen (“Incorrect” or “Too slow”). In 70% of trials (700 trials), one of the distractors (all distractor shapes were equally likely) was a color singleton distractor, red

(199,0,0) or blue (99, 50, 255) while 30% of trials had no singleton distractor. Each participant randomly encountered a ‘Filter present’ block (350 trials) and a ‘Filter absent’ block (350 trials) as shown in Fig.1(b). Since the filter predicted the distractor location with 100% validity in this experiment, the distractor was present within the filter on all 350 trials of the filter present block. The color of a singleton distractor was constant for a block and counterbalanced across blocks, between participants. For instance, if the distractor in the filter present block was red colored singleton distractor, the distractor in the filter absent block was blue colored singleton distractor. Participants were informed before starting the experiment which color was associated with the filter.

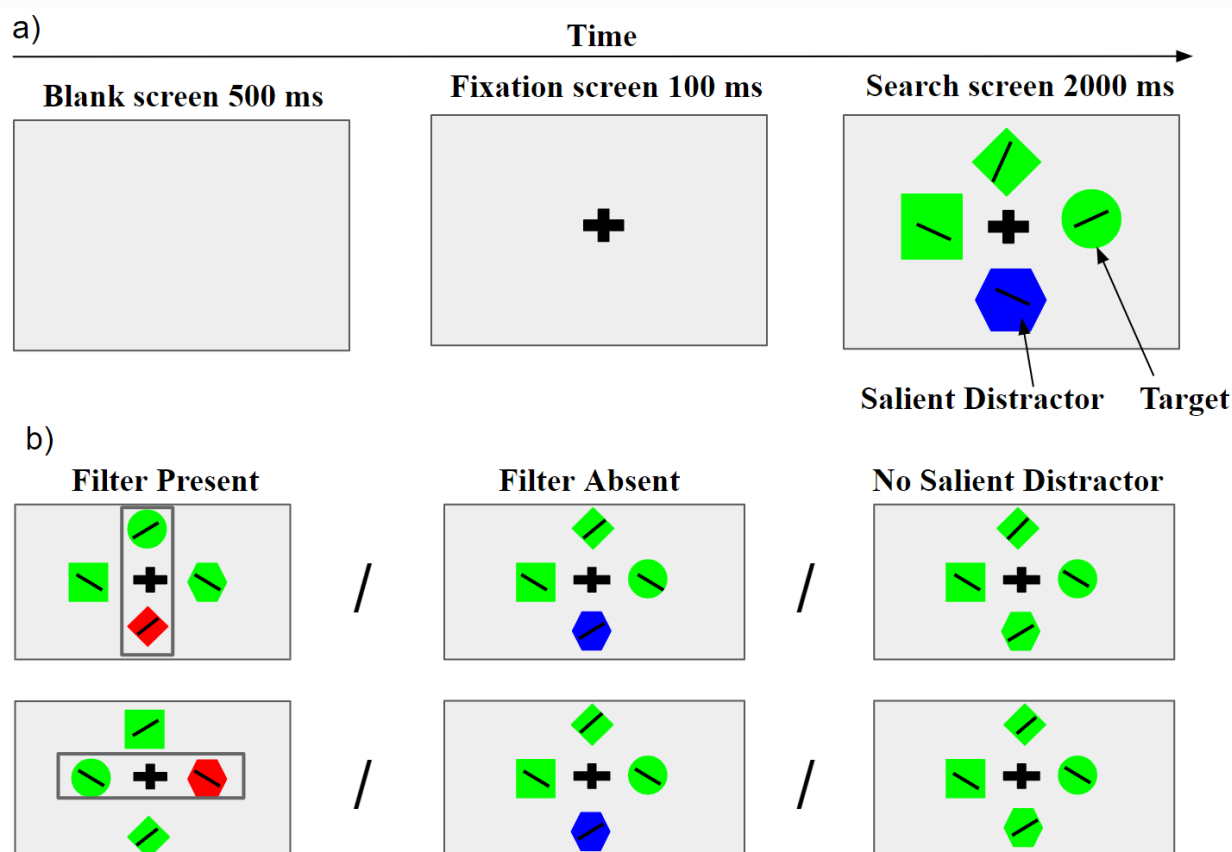


Figure 5.1. The sequence of trials and search conditions in the current study. a) Sequence of events on a sample trial. In this example, the green circle is the target and the blue hexagon is a singleton distractor. The task was to respond to whether the line on the target was tilted towards the

right or left. b) illustration of all trial conditions i.e., filter present, filter absent and no singleton distractor conditions.

Note: the rectangular box denoting the filter is shown only for the purpose of illustration. It was not presented on the screen to the participants.

Analyses

The analysis was performed using RStudio (Version 2023.09.1+494) and JASP (Version 0.16). Trials with Response times (RTs) less than 200 ms and greater than 1500 ms (1.93%) were discarded as outliers. Incorrect responses were also discarded from RT analyses (3.46%). All participants had greater than 60% accuracy and were included in all further analyses. One-way repeated measures ANOVA was conducted on the remaining RTs with distractor condition (distractor absent, Filter present, Filter absent) as a factor. If the main effect of the condition was observed, the following t-tests were conducted to test our hypotheses: a) distractor absent vs. filter absent conditions were compared to examine if basic distractor suppression was seen in the absence of spatial filtering. b) distractor absent vs. filter present conditions were compared to examine if distractor suppression was seen in the presence of spatial filtering. c) filter present vs. filter absent conditions were compared to check if spatial filtering benefited suppression. d) To verify that the filter affected performance, trials in the filter present condition were analyzed by comparing trials in which the target appeared within the filter to the trials in which the target appeared outside the filter. Responses on trials with the target in the filter were expected to be slower than responses on trials with the target outside the filter since the filter was expected to influence target processing at filtered locations, even though it was equally likely to appear at all locations. Finally, it is possible that intertrial priming effects were responsible for the effects expected in the filter present condition. This was because the probability of a distractor appearing at the same location was 50% on filter present trials (because there were only two possible distractor locations), whereas the probability was 25% in the filter absent trials

(because there were four possible distractor locations). To address this, e) a subset of trials where the distractor location was not repeated from the previous trial was analysed separately using the procedure mentioned in c). If the results observed were truly due to voluntary goal-driven mechanisms, then we should observe the same effects in this subset of trials.

5.2.2 Results

The main effect of condition was significant, ($F(2, 78) = 5.391, p = .006, \eta^2 = .121$). RTs were slower on distractor absent trials (16 ms) compared to filter absent trials ($t(39) = 2.407, p = .021, dz = 0.381$) and also (28 ms) compared to filter present trials ($t(39) = 4.258, p < .001, dz = 0.673$). RTs did not differ between filter absent and filter present trials (12 ms) ($t(39) = 1.055, p = .298, dz = 0.167$). In the filter present condition, when the target was inside the filter, RTs were slower by 12 ms ($t(39) = 2.404, p = .021, dz = 0.380$) compared to trials when the target was outside the filter indicating that the filter was partly successful in creating a rejection template. In a subset of trials when the distractor location was not repeated from the previous trial, RTs between filter absent trials and filter present trials did not differ significantly (11 ms) ($t(39) = 0.977, p = .335, dz = 0.154$), see figure 5.2 (a).

5.2.3 Discussion

We observed the expected suppression of singleton distractors in the RT data. However, suppression was not influenced by spatial filtering. The singleton distractor was equally suppressed both in the absence and presence of spatial filtering, as indicated by equivalent RTs on filter present and filter absent trials. This effect was likely due to intertrial priming, as substantiated by the non-significant effect of the filter when the distractor location did not repeat across trials. It is also possible that the participants did not filter the locations where the singleton distractor appeared, and hence it did not affect suppression. The target was found faster at unfiltered locations than at filtered locations, which seems like it was due to the inhibition at filtered locations. However, it is possible

that the slower target search in the filter present condition was a result of inhibition of the previous salient (and its repetition at that location), and not due to filtering of the location altogether. We believe that the filtering of the singleton distractor did not take place due to the presence of the target at filtered locations on 50% of trials of the filter present block. Hence, the target was presented only at the unfiltered locations in Experiment 1B.

5.3 Experiment 1B

The incentive to suppress locations indicated by the spatial filter can be reduced if the target appears at the filtered locations, as it did in Experiment 1A. This could be the reason why we didn't see the influence of spatial filtering on distractor suppression in Experiment 1A. To test this hypothesis, we administered Experiment 1B where the target was always presented at the locations outside the filter. Hence, the incentive to completely discard filtered locations was higher than it was in Experiment 1A. Further, if the filter was effective in suppressing distractors, RTs on trials in filter present vs. filter absent blocks would show a significant difference. If we observed this result in Experiment 1B, all further experiments would be conducted following the design of Experiment 1B.

5.3.1 Methods

5.3.1.1 Participants

Experiment 1B was administered to 40 naive volunteers ($M_{age} = 24.5$ years, 13 females) who did not participate in Experiment 1A.

5.3.1.2 Stimuli & Procedure

The procedure of Experiment 1B remained the same as in Experiment 1A except that the target was presented ONLY at the locations outside the filter in the filter present block while it was presented at all four locations equally likely in the filter absent block.

5.3.2 Results

Similar to Experiment 1A, Incorrect response trials (4.6%) and trials on which RTs were faster than 200 ms and slower than 1500 ms (1.4%) were discarded from all analyses. The main effect of condition was significant, ($F(2, 78) = 28.843, p < .001, \eta p^2 = .425$). RTs were faster (14 ms) on distractor absent trials compared to filter absent trials ($t(39) = -2.632, p = .012, dz = 0.416$) but slower (43 ms) compared to filter present trials ($t(39) = 6.888, p < .001, dz = 1.089$). Unlike in Experiment 1A, RTs on filter absent trials were indeed slower than RTs on filter present trials by 58 ms ($t(39) = 5.280, p < .001, dz = 0.835$). The effect of filter was assessed on trials when the distractor location was not repeated from the previous trial and RTs were faster in the presence of filter than in its absence by 60 ms ($t(39) = 5.305, p < .001, dz = 0.839$), see figure 5.2 (b).

5.3.3 Discussion

The singleton distractor captured attention in the absence of the spatial filter but was suppressed in the presence of the spatial filter, unlike in Experiment 1A. The filter benefited suppression of the singleton distractor. This effect was irrespective of intertrial priming since the benefit of distractor filtering was observed even in trials where the distractor location *did not* repeat from the previous trial. As we predicted, precluding the target from the filtered locations in the filter present block, enhanced the incentive for filtering the salients at the filtered locations and benefited search. Hence, in Experiments 2 and 3 the target was presented only in the unfiltered locations.

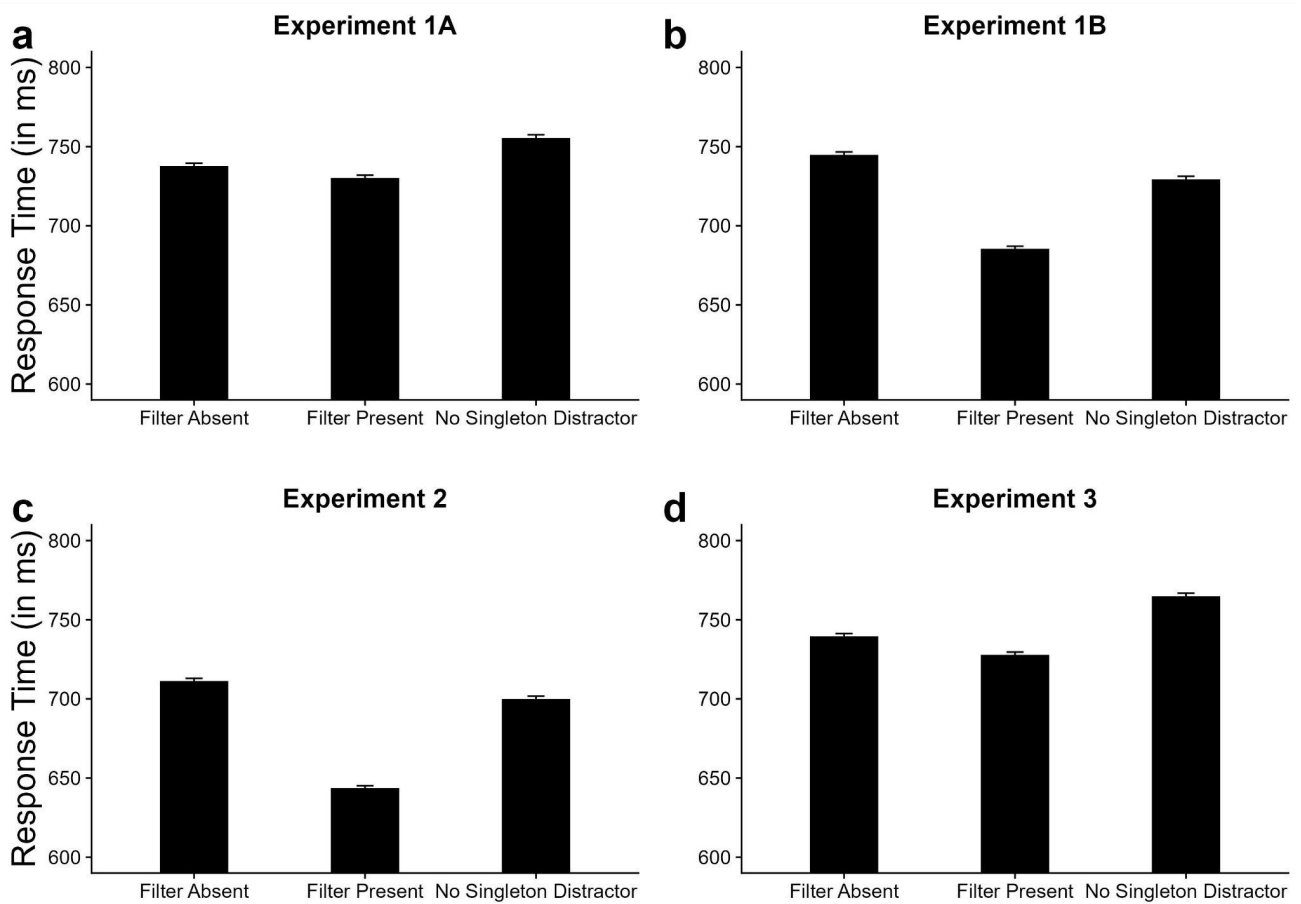


Figure 5.2. Results across filter conditions in Experiments 1A, 1B, 2 and 3. (a) In Experiment 1A, search performance did not improve because of spatial filtering since the target was also presented at the filtered locations. The no singleton distractor condition did not induce suppression and acted as an overall baseline for suppression. **(b)** In Experiment 1B, the absence of the target from the spatial filter enhanced suppression as indicated by faster RT on Filter present trials than Filter absent trials. **(c)** Similar to the Experiment 1B, in Experiment 2, RTs in the presence of the filter (65% predictable) were faster than RTs in the absence of the filter, suggesting that 100% reliability for the spatial filter is not a necessary condition for suppression of the distractor. **(d)** In Experiment 3, dynamic filtering of the distractor was not possible, and the benefit for suppression for the Filter present condition was not observed.

Table 5.1. Mean RT and standard error of the mean for trial conditions of Experiment 1A, 1B, 2 and 3.

Experiment	Condition	Mean RT	Standard Error
1A	No Singleton Distractor	755.44	2.01
	Filter Absent	737.71	1.79
	Filter Present	730.23	1.71
1B	No Singleton Distractor	729.26	2.00
	Filter Absent	744.80	1.84
	Filter Present	685.44	1.66
2	No Singleton Distractor	699.92	1.84
	Filter Absent	711.31	1.66
	Filter Present	643.70	1.46
3	No Singleton Distractor	764.82	1.97
	Filter Absent	739.56	1.69
	Filter Present	727.85	1.73

5.4 Experiment 2

5.4.1 Methods

5.4.1.1 Participants

Experiment 2 was administered to 40 participants ($M_{age} = 25.5$ years, 15 females) who did not take part in Experiments 1A and 1B.

5.4.1.2 Stimuli & Procedure

The stimuli and procedure were the same as in Experiment 1B, except for one change. The spatial filter predicted the location of the distractor on 65% of the filter present trials, i.e. the distractor was at filtered locations on 228 trials and at unfiltered locations on 122 trials. The rest of the trial sequence and conditions were the same as in Experiment 1B.

5.4.2 Results

Incorrect responses (3.37%) as well as RTs outside the range of 200-1500 ms (1.04%) were discarded from all analyses. Two participants had an overall accuracy of less than 60% and were discarded from all further analyses. In Experiment 1A and 1B, the distractor was within the filter on all trials, but here the distractor was within the filter only on 65% of the trials. To take this into account, an additional t-test was conducted only on filter-present trials to compare RT on distractor-within-filter trials vs. RT on distractor-outside-filter trials. If the 65% probability influenced distractor suppression, we would see faster RTs on distractor-within-filter trials. If not, the RTs would be equivalent in both conditions. The remaining statistical comparisons were the same as in Experiment 1A and 1B.

Similar to Experiment 1B, the main effect of condition was significant, ($F(2, 76) = 53.768, p < .001, \eta^2 = .586$), see figure 5.2 (c). RTs were faster (12 ms) on distractor absent trials compared to filter absent trials ($t(37) = -2.336, p = .025, dz = 0.369$) but were slower (55 ms) compared to filter present trials ($t(37) = 9.098, p < .001, dz = 1.457$). RTs on filter present trials were also faster than RTs on filter absent trials by 58 ms ($t(37) = 7.446, p < .001, dz = 1.192$). The effect of filter was assessed on the subset of trials when the distractor location was not repeated from the previous trial. RTs were still faster in the presence of the filter than in its absence by 69 ms ($t(37) = 6.922, p < .001, dz = 1.123$). Further, when the distractor was inside the filter, RTs were slower by 32 ms compared to when the distractor was outside the filter ($t(37) = 8.210, p < .001, dz = 1.332$). This was unusual, since we expected distractors to be suppressed better at the filtered locations than at unfiltered locations. This could have happened if instead of suppressing the filtered locations, participants used statistical knowledge of the singleton's appearance and responded accordingly. To test this, we conducted a t-test comparing RTs across the filter absent and present block when the singleton appeared only at 'not filtered locations' in the filter present block. If participants indeed suppressed the filtered locations alone, RTs across other types of trials among filter absent and present blocks must be comparable. But, if statistical regularities guided suppression, we expected RTs even at the

‘not filtered location’ in the filter present block to be faster (87 ms) than RTs in the filter absent block, and that is what we found ($t(37) = -8.743, p < .001, dz = 1.418$). RTs were also faster when the singleton distractor was inside filter trials (56 ms) ($t(37) = -6.046, p < .001, dz = 0.981$), compared to filter absent trials.

5.4.3 Discussion

Similar to Experiment 1B, the singleton distractor captured attention in the absence of the spatial filter but was suppressed in the presence of the spatial filter. Moreover, the filter also benefited suppression of the singleton distractor (equally, 58 ms benefit), even after controlling for possible intertrial priming effects, despite the filter being 65% predictive of the singleton distractor location. This suggested that 100% predictability of the singleton distractor is not a necessary condition of suppression. However, we observed that distractors were suppressed better at unfiltered locations than the filtered locations of the filter present block. Further, RTs were faster in the filter present block at both filtered and unfiltered locations compared to RTs in the filter absent block. This suggests that the distractor locations were not “filtered” but the probabilistic difference in the appearance of the singleton distractor created high-probability locations (65%) at the filtered locations and low-probability locations (35%) at the unfiltered locations. Since having a probabilistic expectation of the singleton distractor would still be more beneficial than having no expectation, like in the filter absent block, we observed the advantage of filtering.

It was harder to suppress singleton distractors at the high-probability locations compared to the low-probability locations. This was in contradiction to results observed in Failing et al. (2019) and Wang and Theeuwes (2018a), wherein distractor appearing at high probability location was suppressed better compared to distractor appearing at low probability location, both in singleton distractor search and feature search, respectively. The key difference in the current study from both previous studies was that participants were informed about the filtered location (high probability

singleton distractor location), preemptively. However, the singleton distractor also appeared outside the filter, disrupting the attentional set for singleton distractor locations. It seems that having the awareness of a high probability location preemptively enhances attention at that location; unlike previous studies where either the participants were completely unaware of the high probability location (implicit learning) or became aware through observation. As we suspected, goal-directed control over suppression is effective only when the knowledge about the singleton distractor is 100% predictive in the task. When knowledge of the singleton distractor is violated by task observations, goal-directed control is overridden by probabilistic expectations.

5.5 Experiment 3

5.5.1 Methods

5.5.1.1 Participants

Experiment 3 was administered to 40 new participants ($M_{age} = 26$ years, 15 females).

5.5.1.2 Stimuli & Procedure

The stimuli and procedure were the same as that used in Experiment 1B, except for one change. In the filter present block, at the beginning of each trial, a black horizontal or vertical bar (width 0.52°) was presented for 500 ms as a cue. The participants were told that the directionality of the bar indicates the axis in which the singleton distractor would appear. The horizontal and the vertical bars were presented randomly and equally often. The rest of the trial sequence and conditions were the same as in the Control Experiment.

5.5.2 Results

We discarded incorrect RTs (2.39%) and those faster than 200 ms and slower than 1500 ms (1.34%) from all analyses. The analysis procedure was the same as earlier experiments. Additionally, trials

where the type of filter (horizontal/vertical) repeated from the previous trial, were designated as “repeat” trials. Trials where the filter switched were designated as “switch” trials. An additional factor trial type (repeat vs. switch) was added in all relevant analyses. The main effect of condition was significant, ($F(2, 78) = 21.383, p < .001, \eta^2 = .354$). RTs were slower (25 ms) on distractor absent trials compared to filter absent trials ($t(39) = 5.043, p < .001, dz = 0.797$) and also (38 ms) compared to filter present trials ($t(39) = 8.188, p < .001, dz = 1.295$). But RTs on filter present trials were not significantly different from RTs on filter absent trials (12 ms) ($t(39) = 1.654, p = .106, dz = 0.262$). The effect of the filter was assessed on trials when the distractor location was not repeated from the previous trial, and still, no significant difference was found between filter absent and filter present trials (13 ms) ($t(39) = 1.768, p = .085, dz = 0.280$). RTs did not differ significantly when the filter locations were repeated and when they switched across consecutive trials ($t(39) = 0.399, p = .692, dz = 0.063$), see figure 5.2 (d).

5.5.3 Discussion

The singleton distractor was suppressed with and without the presence of the spatial filter and the filter did not benefit suppression of the singleton distractor, unlike in Experiment 1B and Experiment 2. This suggested that varying the filter unpredictably does not benefit suppression even if the filter is 100% predictive of the singleton distractor to be suppressed. Studies have previously found that varying singleton distractor color across blocks of trials within a task leads to a repeated pattern of initial capture by the new color singleton distractor and subsequent suppression as trials progress (Vatterott & Vecera, 2012). Even when feature cues preceding the search predicted distractor across blocks or trials (Bogaerts et al., 2022) or the singleton distractor color varied trial-by-trial (Won et al., 2019) search performance did not improve significantly. These results further confirm that goal-directed control of suppression cannot be adjusted in response to dynamic changes in the attention (suppression) template.

5.6 General Discussion

The current study explored goal-directed control of spatial distractor suppression. In all experiments, we observed distractor suppression despite spatial filtering. Filtering benefitted suppression only when the target did not appear at filtered locations and the filtered locations were predictable throughout the experiment (Experiment 1B). This effect was seen even when the singleton distractor location was predictable only on 65% of the trials (Experiment 2). When the target appeared at filtered locations (Experiment 1A) or when the spatial filter varied randomly on every trial (Experiment 3), filtering did not benefit suppression (see Table.1). In experiments that showed the benefit of spatial filtering (Experiment 1B and Experiment 2), suppression was seen even when potential intertrial priming effects of previous distractor locations were taken into account. Overall, results indicate that voluntary goal-driven control of singleton distractor suppression occurs when the knowledge of the singleton distractors is consistent throughout the task. Such goal-directed control however lacks flexibility such that knowledge of the singleton distractors needs to be consistent for a period of time. Consistent updating of knowledge cannot be utilized to guide suppression. Another important finding from the study is that the presence of a target at suppressed locations, undermines the incentive to suppress that location, even if the singleton distractor is presented there all the time (Experiment 1B), or at least more often (Experiment 2).

In Experiment 1A of the current study, the target was equally likely at all locations, but the singleton distractor was likely at two of those locations. To perform the search better, having the singleton distractor locations in the attentional template would not be an efficient strategy, as suppressing filtered locations could slow responses to the target appearing at the filtered location on the current or upcoming trial. This likely prevented the distractor filter from becoming part of the attentional template, and we did not see the benefit of spatial filtering on suppression. In Experiment 1B, however, the target locations and singleton distractor locations/filter did not overlap. Allocation

of working memory resources (WMR) to the attentional template can explain how such goal-directed suppression proceeds during search. In a recent review, Huynh et al. (2021) suggested that the representation that makes up the attentional template consumes WMR with respect to their relevance for search (Huynh et al., 2021). This means that if the multiple representations compete to become a part of the attentional template, the representations most relevant for search would be allotted WMR. Further, they also suggest that WMR are dynamically adjusted among two attentional templates depending on which is more relevant to the task goals (Huynh et al., 2020). In our study, WMR allocated to both representations could together benefit search in Experiment 1B and became part of the attentional template simultaneously.

We explored the relevance of goal-directed control by manipulating the predictability of the spatial filter in Experiment 2. Participants were told that the singleton distractor would appear *more often* (in 65% of trials) at the locations of the filter, and were expected to set up a suppression template at filtered locations. Although we found suppression during filter present trials compared to filter absent trials, the singleton distractor was suppressed better at unfiltered locations than at filtered locations. This was an unexpected finding. The probabilistic distribution of the singleton should have made suppression easier at the high probability locations (within the filter) than at the low probability locations (outside the filter) similar to previous studies (Wang & Theeuwes, 2018a, 2018b, 2019). However, a crucial difference between our study and that of Theeuwes and colleagues is the level of awareness of the statistical regularities. In Experiment 2 of our study, participants were explicitly informed that the distractors were 65% likely to appear in one of the two filter locations. In Wang and Theeuwes (2018b), the same probability distribution (65%) was learned implicitly. This was further proven in a recent study by Vicente-Conesa et al. (2023) who used a similar implicit learning paradigm as that of Wang and Theeuwes (2018b). They found that even though participants showed high accuracy in reporting the locations of high-probability distractors, they did so with very little confidence. This suggests that the benefit of statistical learning of HPDL, relies on the explicit

awareness of the statistical regularities rather than the implicit learning and experience of statistical regularity, highlighting an important distinction between goal-directed suppression control and statistical learning.

Given this, what must have resulted in faster RTs at the LPDL in the current study? A possibility worth discussing is that participants must have monitored the filter for the presence of the singleton distractor, consistently throughout the task. According to Miyake and Friedman's model of executive control, the monitoring adds or deletes stimulus from the working memory, and thus influences the attentional set of a given task (Miyake & Friedman, 2012). When the singleton distractor appeared more often at the filtered locations, WMR attributed to its representations must have influenced attentional orienting at that location (See Chun & Turk-Browne, 2007 for a detailed review). However, since knowledge of the filter did not reliably enhance search, suppressing filtered locations was a less useful search strategy. Taken together, attentional prioritization of the filtered locations as a result of active monitoring could have resulted in capture by the singleton distractors when they appeared there. The task however requires responding to the target, and hence rapid disengagement from the filtered locations must have taken place. The time spent in attending and disengaging from filtered locations in turn slowed RTs to target. In contrast, at the unfiltered locations, attention was not biased and suppression was relatively easy. We must also note that the magnitude of filtering benefit for both Experiment 1B and Experiment 2 was the same (58 ms). If Experiment 2 did not involve active monitoring at the filtered locations, we could have observed less benefit of filtering for search compared to Experiment 1B. This is to say that monitoring in Experiment 2 compensated for the lack of filter predictability (65%).

The final aim of the current study was to understand if goal-directed control of suppression can be dynamically adjusted as per task demands. To test this, we introduced an additional cue display before each trial to indicate which locations were 100% likely to contain the singleton

distractor. If knowledge of the singleton distractor locations could be used in a goal-directed manner even when it changed from trial to trial, that would indicate that suppression was truly dynamic. Past studies have criticized that evidence for goal-directed control can also be explained by statistical learning of singleton distractor location or feature (Britton & Anderson, 2020; Duncan & Theeuwes, 2020). And statistical learning is an automatic process, devoid of conscious effort (Gao & Theeuwes, 2020). It is worth noting that these criticisms do not strictly apply to Experiments 1 and 2 in our study because there were two possible distractor locations on each trial. Thus, the singleton distractor location did not always repeat from trial to trial. We also additionally analyzed the data excluding trials where the singleton distractor appeared in the same location as the last trial and found the same pattern of results indicating that potential inter-trial priming effects can't explain the spatial filtering effects observed in this study.

Nonetheless, Experiment 3 was conducted to examine if goal-driven suppression can be dynamically adjusted. The results showed no benefit of filtering for suppression, revealing the boundary conditions of goal-directed control. These findings suggest mainly the possibility that goal-directed control of spatial suppression is not dynamic, similar to goal-directed feature suppression of singleton distractors. For instance, Stilwell and Vecera, (2022, 2023) cued the distractor features, color or shape across displays that had either consistent or variable distractors. For both color and shape cues, suppressing the consistent distractor was faster compared to suppressing the variable distractor. Similar to Experiment 3 of the current study, they observed that consistently updating knowledge of an upcoming singleton feature (shape or color) makes suppression of these features difficult, even when the knowledge was available preemptively (as cues) to allow proactive suppression. When spatial locations of the singleton are known preemptively, but are updated across trials, suppression of potential locations is still difficult.

Limitations in updating working memory template guiding suppression could be the reason why dynamic control over suppression is not seen during goal-directed search.

We can conclude from the current study that goal-directed control of spatial suppression of singleton distractors is indeed possible. However, such control operates under a degree of constraints. First, knowledge of locations where the singleton distractor is most likely to be reliably true. Goal-directed control requires 100% predictability of knowledge from either instruction or cues indicating spatial contingencies of singleton distractors. When the predictability is lower than 100%, different strategies guide suppression. In the current study, we observed statistical learning-based suppression when the singleton distractor filter was 65% predictive of its location. Second, goal-directed control can consume WMR sufficient to become part of the attentional template guiding search. Hence, if the incentive to use goal-directed control is low, WMR is not allocated sufficiently to facilitate entry into the attentional template. Third, the attentional template used to suppress singleton distractors during the search cannot be updated dynamically and hence is susceptible to trial-wise variations in task sets. As task demands gradually change, goal-directed control can adapt the attentional template accordingly and guide search, as is seen in many previous studies (Arita et al., 2012; Carlisle & Nitka, 2019; Vatterott & Vecera, 2012). The current study provides evidence for goal-directed control of suppression, irrespective of inter-trial priming or statistically learned suppression.

CHAPTER 6

Individual Differences in Distractor Suppression

The loss of audition in hearing-impaired (HI) individuals often results in plastic changes in brain areas responsible for vision. So far, studies have suggested that attentional processes, especially selective attention, are enhanced in congenitally HI individuals compared to normal hearing (NH) individuals. But recent theories in selective attention posit selection to be cumulative of target activation and distractor inhibition. In this study, we explored which of the two processes change in the HI individuals because of neuroplasticity. Here we showed that HI people are better at ignoring distractors—when they are irrelevant to the task—compared to NH people. A target shape was presented among distractor shapes, near a central fixation or at the periphery. Participants responded by discriminating the orientation of a bar, vertical or horizontal, superimposed on the target, while a salient distractor appeared occasionally. The HI group displayed singleton presence benefit unlike the NH group but only during the peripheral search. Results from intertrial priming, response compatibility and RT distribution analysis demonstrate an enhanced goal-directed distractor suppression mechanism in the HI group than the NH group. We suggest that hearing impairment selectively influences inhibitory attentional processes.

6.1 Introduction

Congenital hearing impairment induces changes in the auditory cortex and enhances visual attention (Andin and Holmer, 2022, Bavelier et al., 2006). Accordingly, studies have shown that hearing-impaired (HI) people performed better than normal hearing (NH) people on attention-demanding tasks such as target detection (Whitton et al., 2021), motion processing (Quandt et al., 2021), visuospatial attention (Sehyr et al., 2020) and selective attention (Chen et al., 2010). But the advantage disappeared—when the discrimination was based on brightness, contrast, or luminance factors (Brancaleone et al., 2023; Bross, 1979; Finney and Dobkins, 2001), raising questions on the extent of the advantage. Since attentional selection is a combination of independent spatial and feature selection processes, changes induced by hearing impairment can affect them differently. Many studies have found better *spatial* selection in the HI compared to NH (Bonmassar et al., 2021; Chen et al., 2006; Quandt et al., 2021; Secora & Emmorey, 2019, 2020) but the evidence for better *feature* selection is *rare* (Heimler et al., 2015). This study explored distractor suppression in HI in comparison to NH. Unlike previous studies that measured oculomotor orienting to the target (Bonmassar et al., 2021; Prasad et al., 2015), we examined if covert orienting (without moving the eyes) differs among HI and NH people.

Selection is necessary to filter out—objects at irrelevant locations and objects with irrelevant features—from the field of attention; it happens in the dorsal and the ventral neural pathway (Moran & Desimone, 1985). The dorsal pathway is responsible for spatial recognition, and the ventral pathway gives rise to visual identification. Neurons along these pathways become increasingly specialized in function and decrease in number. Consequently, only one (or few) stimuli cross the pathway—biased competition theory (Desimone & Duncan, 1995). HI show advantage primarily in the dorsal pathway—the *dorsal route hypothesis* (Bavelier & Neville, 2002); starting from the primary visual cortex in the occipital lobe, to the parietal lobe (Rauschecker, 2018). For example,

MT/MST—which lies at the intersection of the temporal and occipital lobe, is activated in HI—in tandem with the posterior parietal cortex, during peripheral attention tasks (Bavelier et al., 2000). Such activations lead to lowering the detection threshold at the periphery (Seymour et al., 2017) which enhances the selection of peripheral targets, but can also increase interference from peripheral distractors; suppression of distractors during/after target detection hence becomes critical, for selection. Many past studies have used the Posner's cueing paradigm which limited explorations until the target detection phase; visual search paradigms on the contrary can explain engagement, disengagement and reorienting processes needed during target selection. The purpose of this study was to find differences between HI and NH people in the various processes leading to selection using visual search.

In a Posner cueing task, the target is presented at a previously cued location (valid trial), or at another location (invalid trial) (Posner, 1980). When the target is validly cued, RTs are faster. On the invalid trials, attention shifts from the cued location to the target, and detection is slowed. Prasad, Patil and Mishra (2014) found that the HI group oriented their eyes to the target faster compared to the NH group, during both valid and invalid trials, but manual RTs were equivalent among the groups. By contrast, Parasnis and Samar (1985) found faster RTs on invalid trials among the HI group, while they were comparable to NH on valid trials (Parasnis & Samar, 1985); they suggested an attentional disengagement benefit for the HI instead. Similarly, Dye and Bavelier (2013) supported the disengagement benefit and found no benefit in orienting for the HI. Despite these, later findings were unsupportive regarding the disengagement benefit, as well (Jayaraman et al., 2016; Xingjuan et al., 2011). Because attentional processes can vary with the intensity of the goal the participant perceived, tasks that did not induce a strong goal would engage attention less effectively, and may produce confusing findings. Visual search paradigms overcome this limitation by introducing distractors to the display and increasing the incentive to find the target among competing

stimuli. Therefore, studying selection using visual search allowed for holistically exploring the nature of advantages in the HI.

A number of visual search studies suggested that the HI were overall more sensitive to target appearance than NH people (Bottari et al., 2010, 2011), when presented alone (in the absence of any distractors). But when distractors were introduced, alertness to the target proved insufficient to guide the search—instead, suppressing the distractors was essential. An illustration of this was Proksch and Bavelier (2002) when participants searched for a target shape while the number of distractors surrounding it increased across trials and an additional central or peripheral matched/mismatched target shape. When fewer distractors (≤ 4) were present, distractor-matching targets were found faster than mismatching targets, suggesting that attending to the distractor in fact helped with the target search (compatibility effect). But when the number of distractors surrounding the target increased (6), RTs were similar in distractor-matching as well as mismatching-target trials. When numerous stimuli compete for attention, attention being captured by distractors can substantially slow goal-directed processes, and hence distractors need to be suppressed. Suppression thus seems like an alternative process, which takes control when the task demands it. Another study by Hauthal et al., (2012) also showed no compatibility effect in the presence of distractors—even though their stimuli were meaningful objects like male and female symbols, thus generalizing the findings to more complex feature searches.

Are HI good at suppressing distractors or just ignoring them? Search studies on NH suggest that target-like objects are prioritized for attentional processing, and ‘salient but target-unlike’ objects are suppressed below the threshold of attentional processing (Noonan et al., 2016; Pashler, 1987; Suzuki & Gottlieb, 2012). People differ in their ability to enhance targets and suppress distractors (Ashinoff et al., 2019; Gazzaley et al., 2005; Poole et al., 2016)—this is to say that being good at search can be a result of better target enhancement or better distractor suppression, or both.

The inconsistencies from previous findings preclude our understanding of how HI search differently than NH. In Proksch and Bavelier (2002), for instance, the distractor appeared at a location where the target never appeared. Finding the target was, hence, independent of ignoring the distractor. Thus, when the task favored target enhancement more than distractor avoidance, target enhancement was the search strategy; when the reverse was true, distractor avoidance was the search strategy. These findings cannot establish which of the two processes is enhanced in HI unless both processes compete during the search. Similar criticism applies to Hauthal et al., (2012), moreover, they additionally manipulated the identity of the distractor (face or object) instead of keeping it consistent with the target (male or female figure). The lack of compatibility effect in the HI in the presence of distractors could in part be attributed to it.

A later study by Heimler et al., (2015) used a search task which overcame the limitations of Proksch and Bavelier (2002) and Hauthal et al. (2012). They showed a uniquely oriented line as the target (tilted right or left) among many straight lines and a tilted distractor (tilted left or right, respectively). Here, the distractor could appear at a potential target location. Moreover, they separated the effect of distractor ignoring from target enhancement by introducing three types of trials: only target-salient, only distractor-salient trials and nothing-salient. This was to show that salient targets were found faster even in the presence of distractors (non-salient) since no other stimuli were strong enough to compete with the target (target enhancement was enough). But when the distractor was salient, target detection was delayed since the singleton distractor competed for attention, relative to nothing-salient trials (distractor suppression was needed). Thus, salience aided in capture, irrespective of the task goals, in both HI and NH people. Could it have been possible to suppress the singleton distractor given sufficient incentive and time? While this study clarified some ideas on distractor suppression in the HI, the findings could not be generalized across previous

studies. The absence of manual RT results in Heimler et al., (2015) makes it difficult to predict how HI people select target post-attentional capture.

Current Study

We used the singleton search paradigm developed by Theeuwes et al., (1992) wherein a unique target is searched among six homogeneous distractors. This was to mimic the search processes in Heimler et al., (2015), but prevent overcrowding from distractors outside the field of attention, during the search. We also wanted to measure the target-distractor compatibility effect and incorporated orientation discrimination in addition to localizing the target. Finally, we explored the nature of covert selection in HI and NH groups by restricting eye movements to a central fixation. Thus, attention shifted, engaged and disengaged covertly during the search. We used a typical singleton search task while manipulating eccentricity of search display to create a central search array vs. a peripheral search array. The target could appear at any location in the array in green along with the non-targets, except on some trials when a color singleton distractor accompanied search. Many studies mixed singleton absent and present trials to create unpredictability in distraction; singleton absent trials relied on only the target enhancement mechanism primarily, while singleton present trials relied on both target enhancement and distractor suppression. Comparing RTs across these trials indicated the degree of attention capture (Gaspelin et al., 2017; Gaspelin & Luck, 2018).

6.2 Methods

6.2.1 Participants

The sample size was estimated based on previous visual search studies measuring differences between HI and NH people in target discrimination (Bottari et al., 2010, 2011). We selected a sample size of 15 congenitally HI people (6 females, mean age = 28 years, SD = 2) and 15 NH people (5 males, mean age = 25, SD = 3). Subject sampling was done at Ali Yavar Jung National Institute for

Hearing Handicapped, Hyderabad, India. All HI participants were diagnosed with congenital hearing impairment and experienced profound auditory impairment. They were conceived by NH parents. All HI subjects could sign proficiently in ISL; they acquired ISL at an average age of 5 years. Self rating of ISL proficiency, on a scale from 3-1, showed an average score of 3 for all HI participants. All the above-mentioned information was obtained through a questionnaire previously used by Prasad et al., (2015, 2017, 2022). The NH participants did not use sign language and reported NH ability starting at birth. A speech pathologist proficient in ISL–explained the instructions to HI participants and took written consent from all participants. We received ethical certification from the University of Hyderabad.

6.2.2 Procedure

People viewed a blank display and a fixation, for 500 ms and a search screen for 3000 ms. The search display had seven shapes–six distractors and a target–all presented in green color (0,114,32) (or red (199,0,0) counterbalanced across participants), and a horizontal/vertical black line superimposed on the shapes. They were arranged around an invisible circle of 2.5° for the central display and 7.5° for the peripheral display. As shown in Figure 6.1, all distractors had the same shape except the target; all shapes appeared equally likely at all locations. Participants viewed singleton present and absent trials randomly and reported the target line while fixating at the center of the screen. There were 300 main trials and 20 practice trials. The central and peripheral displays were blocked and presented randomly–each containing 150 trials. Every block contained 75 singleton distractor present and absent trials–mixed randomly–while preventing the simultaneous occurrence of more than two present/absent trials. All participants completed at least one practice session before starting the experimental session. They were instructed to be accurate and fast in responding. Visual feedback for errors and slow responses were shown for 500 ms.

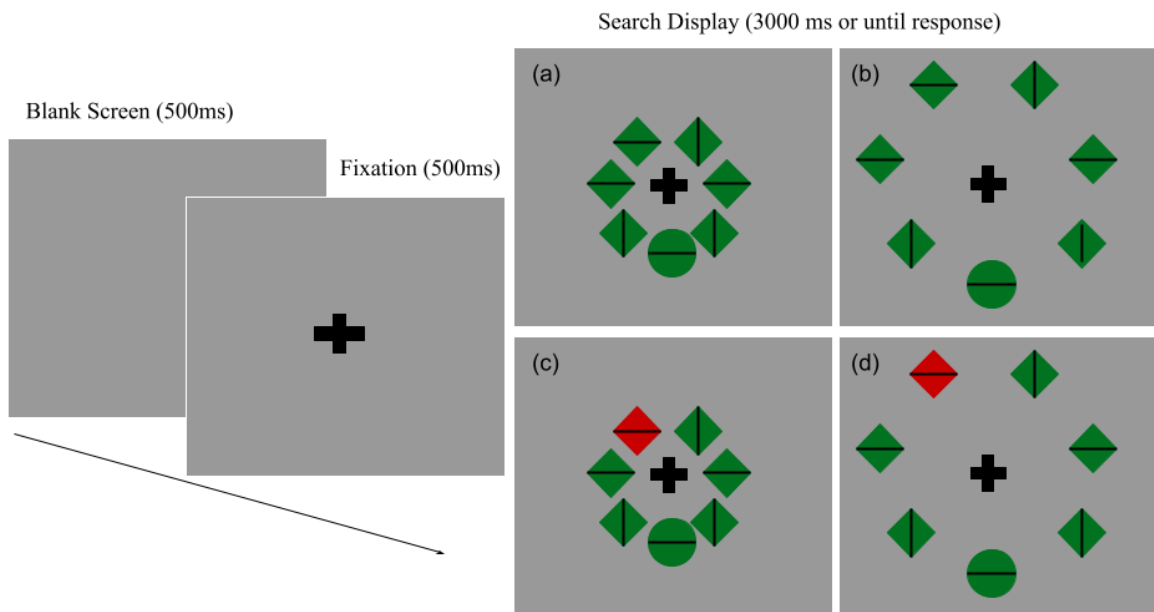


Figure 6.1. Experimental design and conditions. A typical singleton search display (a) and (b) exemplifies singleton absent trials, central and peripheral, and singleton present trials (c) and (d).

6.3 Analysis

Outliers were excluded by removing incorrect and missing response trials, very fast RT (<200 ms) or very irregular RTs (such as 3.5 MAD and above). This led to 15.5% data loss in HI and 7.4% data loss in NH. In a small sample size, outliers significantly affect the mean and standard deviation, hence, we used the MAD criterion for discarding outliers (Leys et al., 2013; Prasad et al., 2022).

A repeated measures ANOVA on mean RT and mean accuracy was performed using JASP Team (2023). JASP (Version 0.17.1)[Computer software], to check if the singleton distractor influenced target search. Singleton distractor (present vs. absent) and search array eccentricity (central vs. peripheral) were within-subjects factors, and group (HI vs. NH) was a between-subjects factor.

To test if singleton capture affected target search, we compared trials on which the current target location matched the previous target location vs. mismatched trials—across singleton absent and

present trials. We conducted a singleton distractor (present vs. absent) x target location (match vs. mismatch) x eccentricity (central vs. peripheral) x group (HI vs. NH) ANOVA.

Further, if the singleton distractor captured attention, a target appearing on a previous singleton distractor location would enhance search RT. But if the singleton was suppressed, attending to the target at a suppressed location would be difficult and RTs would be slower. To test this, we analyzed singleton distractor present trials separately and compared RTs on target-singleton match vs. mismatch trials between groups.

In studies involving discrimination, attention is not only oriented to the target, but also engaged at its location. To check if the singleton distractor only captured attention or also engaged attention, we conducted a target-singleton response compatibility analysis. Trials were called compatible when the target response (say horizontal line) matched the response induced by the singleton distractor (horizontal line). RTs on compatible trials would differ from incompatible trials if the singleton engaged attention. This was tested in an ANOVA with response compatibility (compatible vs. incompatible) x eccentricity (central vs. peripheral) x group (HI vs. NH), as factors.

Several studies have conducted an RT distribution analysis—separating faster RTs which are often a result of stimulus-driven influences from slower RTs which result from goal-driven influences (van Zoest and Donk, 2005, Donk and Van Zoest, 2008). To test how attentional control evolved among the two groups, an RT distribution was created with continuous bins.

6.4 Results

6.4.1 Mean RT

RTs between singleton present (830 ms) and absent (833 ms) trials did not differ significantly $F(1, 29) = 0.35, p = .557, \eta^2 = 0.012$. Responses were faster on central search displays (786 ms) than peripheral search displays (877 ms) $F(1, 29) = 14.41, p < .001, \eta^2 = 0.324$. RTs among the HI (851

ms) and NH (812 ms) groups were equivalent, $F(1, 29) = 0.61, p = .440, \eta^2 = 0.020$. HI were faster in the presence of the singleton (894 ms) than in its absence (936 ms); RTs of the NH group did not differ among singleton absent (831 ms) and present (844 ms), as revealed by an interaction between group and distractor $F(2, 58) = 7.22, p = .012, \eta^2 = 0.194$, see figure 6.2(a). The interactions of location and group $F(2, 58) = 2.47, p = .126, \eta^2 = 0.076$, and location and distractor $F(2, 58) = 2.71, p = .110, \eta^2 = 0.083$ were not significant.

6.4.2 Mean accuracy

Participants were more accurate on singleton absent trials (92.91 %) than singleton present trials (92.12 %) $F(1, 29) = 4.33, p = .046, \eta^2 = 0.126$. Accuracy between central and peripheral search displays was equivalent $F(1, 29) = 0.20, p = .652, \eta^2 = 0.007$. The NH group (97.06%) was overall more accurate than the HI group (87.97%) $F(1, 29) = 8.00, p = .008, \eta^2 = 0.211$. The HI group were more accurate on singleton absent trials (88.75 %) than on singleton present trials (87.20 %) but NH had equivalent accuracy on singleton present (97.04 %) and absent (97.08 %) trials, $F(2, 58) = 3.89, p = .058, \eta^2 = 0.115$, see figure 6.2(b). The interaction and location and group $F(2, 58) = 0.01, p = .915, \eta^2 = 3.830e-4$ and location and distractor $F(2, 58) = 0.17, p = .676, \eta^2 = 0.006$, was not significant.

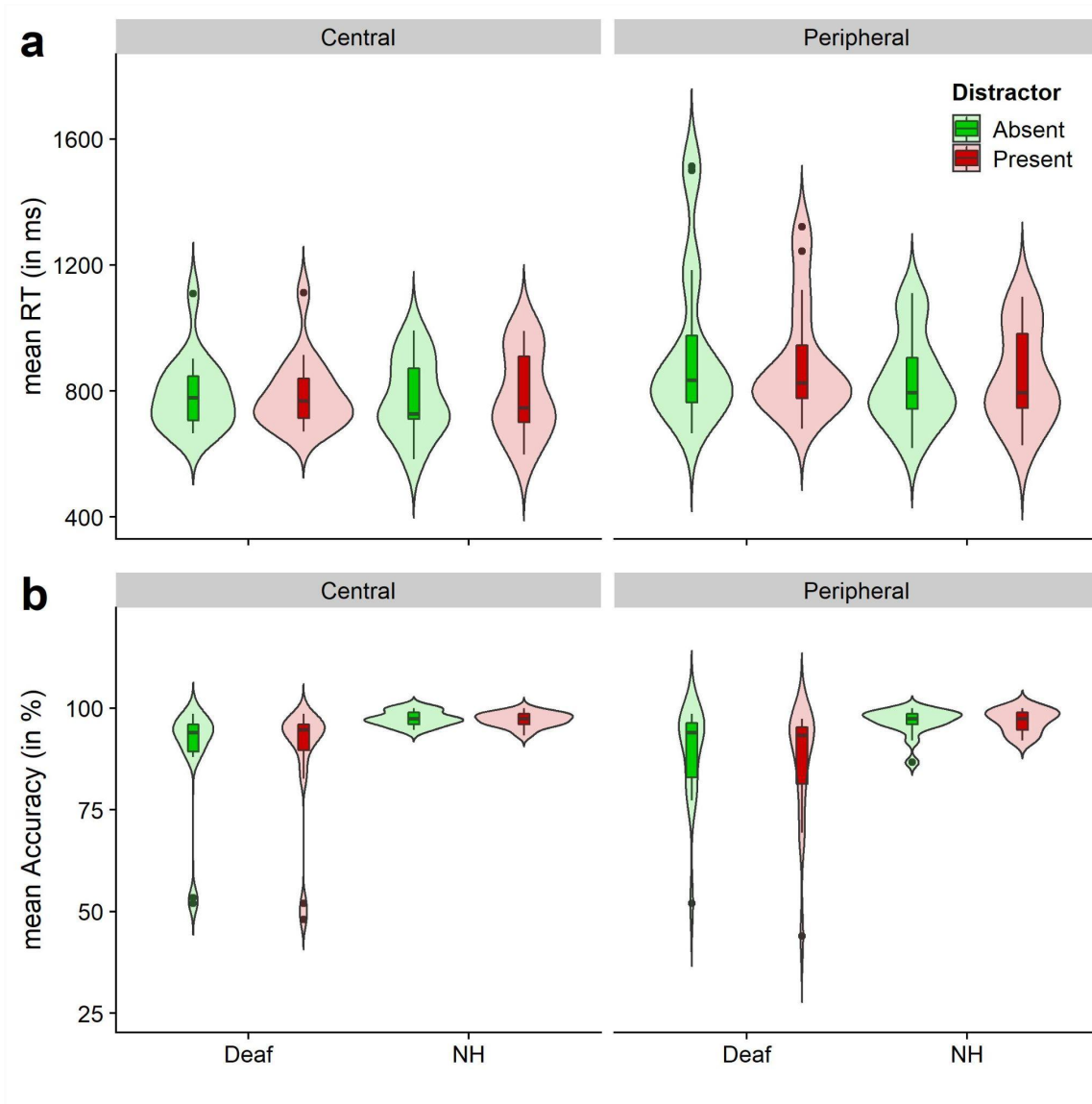


Figure 6.2. (a)Mean RT and (b)mean accuracy for both groups. A speed-accuracy trade-off was seen for the HI group, but not for the NH group. HI displayed singleton presence benefit for peripheral search.

6.4.3 Intertrial priming

RTs were faster when the target location on a current trial matched with the previous trial (808 ms) compared to when it did not (879 ms) $F(1, 29) = 38.12, p < .001, \eta^2 = 0.560$. However, this did not vary in the presence and absence of singleton distractor, indicated by the interaction between distractor and target location $F(2, 58) = 2.21, p = .147, \eta^2 = 0.069$. During the peripheral search,

the difference between target-match (849 ms) and mismatch trials (926 ms), in the presence of the singleton was lesser than the difference between target-match (835 ms) and mismatch trials (933 ms) in the absence of the singleton. During the central search, the difference between match (759 ms) and mismatch trials was seen only on singleton present trials (834 ms). This was indicated by a marginal three-way interaction between eccentricity, target location and distractor $F(3, 87) = 3.14, p = .087, \eta^2 = 0.095$. The HI group were faster on match trials (884 ms) than mismatch (966 ms) trials during the peripheral search but not during the central search (match: 797 ms, mismatch: 828 ms), while the NH group were always faster on match trials for both central (match: 740 ms, mismatch: 833 ms) and peripheral search (match: 796 ms, mismatch: 893 ms), suggested by the three-way interaction between group, target location and eccentricity, $F(3, 87) = 4.29, p = .047, \eta^2 = 0.125$ as shown in figure 6.3(a).

When only singleton distractor present trials were analyzed, RTs were faster when the current target location matched the previous target location (829 ms) instead of the previous singleton distractor location (901 ms) as shown in figure 6.3(b). But no difference was seen when it matched other distractor locations (874 ms), $F(1, 29) = 4.29, p = .018, \eta^2 = 0.125$. This pattern was consistent across groups and eccentricity.

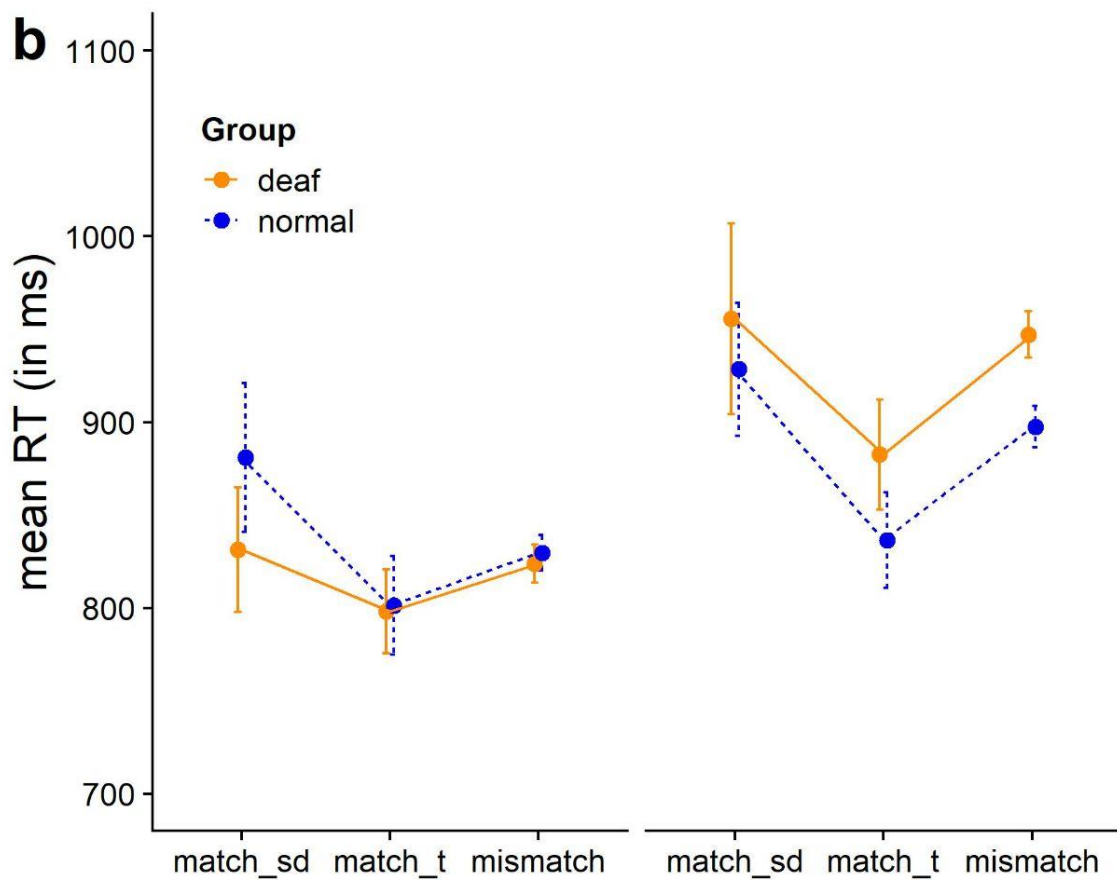
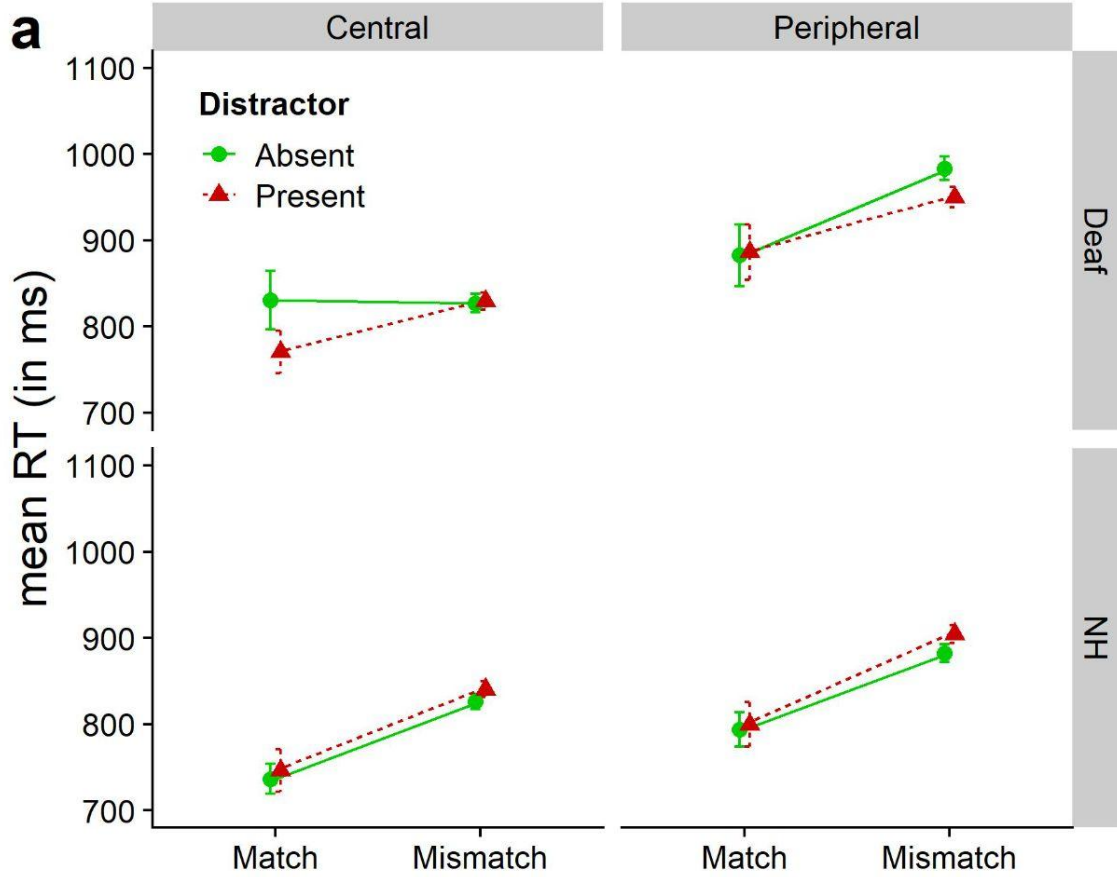


Figure 6.3. Mean RT on (a) when target location, matched or mismatched the previous target location and (b) or singleton distractor or other distractor locations, across eccentricity for both groups. Target location match resulted in fast RTs and singleton matched led to slow RTs.

6.4.4.1 Compatibility effect (meanRT)

RTs on compatible trials (834 ms) were equivalent to incompatible trials (833 ms), $F(1, 29) = 0.01$, $p = .923$, $\eta^2 = 3.19$, see figure 6.4(a). The interaction of compatibility and group $F(2, 58) = 1.21$, $p = .279$, $\eta^2 = 0.039$, and compatibility and eccentricity $F(2, 58) = 0.00$, $p = .961$, $\eta^2 = 8.06$, was not significant.

6.4.4.2 Compatibility effect (mean accuracy)

As indicated in figure 6.4(b), Accuracy on compatible trials (96 %) was greater than incompatible trials (89 %) $F(1, 29) = 13.90$, $p < .001$, $\eta^2 = 0.317$. This was seen only on central search displays (compatible-incompatible = 11.04 %) but not on peripheral search displays (compatible-incompatible = 2.87 %), suggested by the significant interaction of compatibility and eccentricity $F(2, 58) = 8.30$, $p = .007$, $\eta^2 = 0.217$. The interaction of compatibility and group was not significant $F(2, 58) = 1.37$, $p = .251$, $\eta^2 = 0.044$.

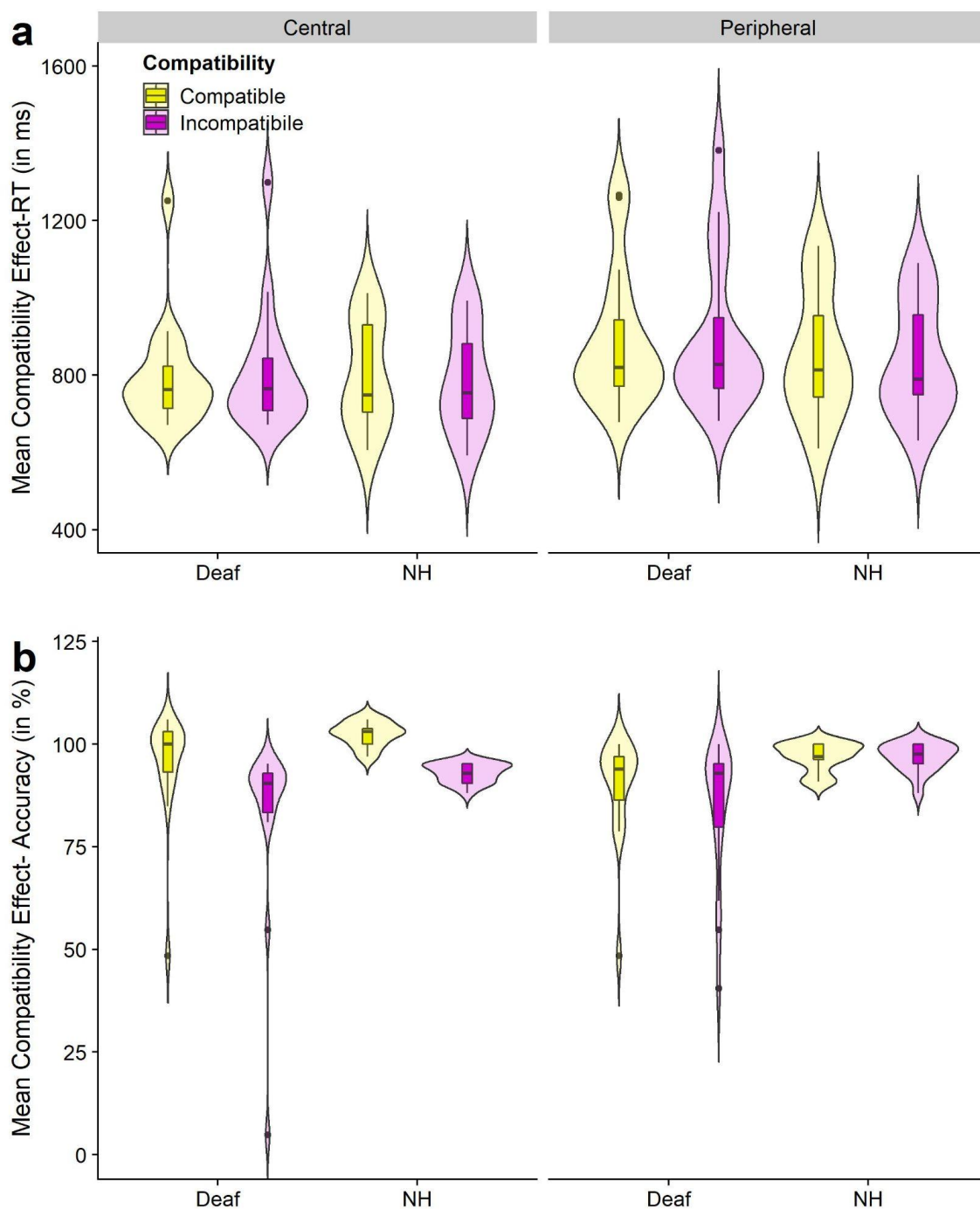


Figure 6.4. Compatibility effect (compatible trials-incompatible trials) in mean RT and mean accuracy, across eccentricities for both groups. Mean accuracy on compatible trials was greater than incompatible trials, but only on central search displays—for both groups.

6.4.5 Distribution Analysis

The HI group showed faster RTs on singleton present trials compared to singleton absent trials in the slowest RTs (bin 5), $t = 4.09$, $p = .011$. The NH group showed equivalent RTs for singleton present and absent trials across all bins. This was indicated by the three-way interaction between distractor, group, and bins $F(4, 120) = 4.69$, $p = .001$, $\eta^2 = 0.135$. This confirmed that the singleton distractor captured attention until goal-directed control could prevent it, but only in the HI group, see figure 6.5.

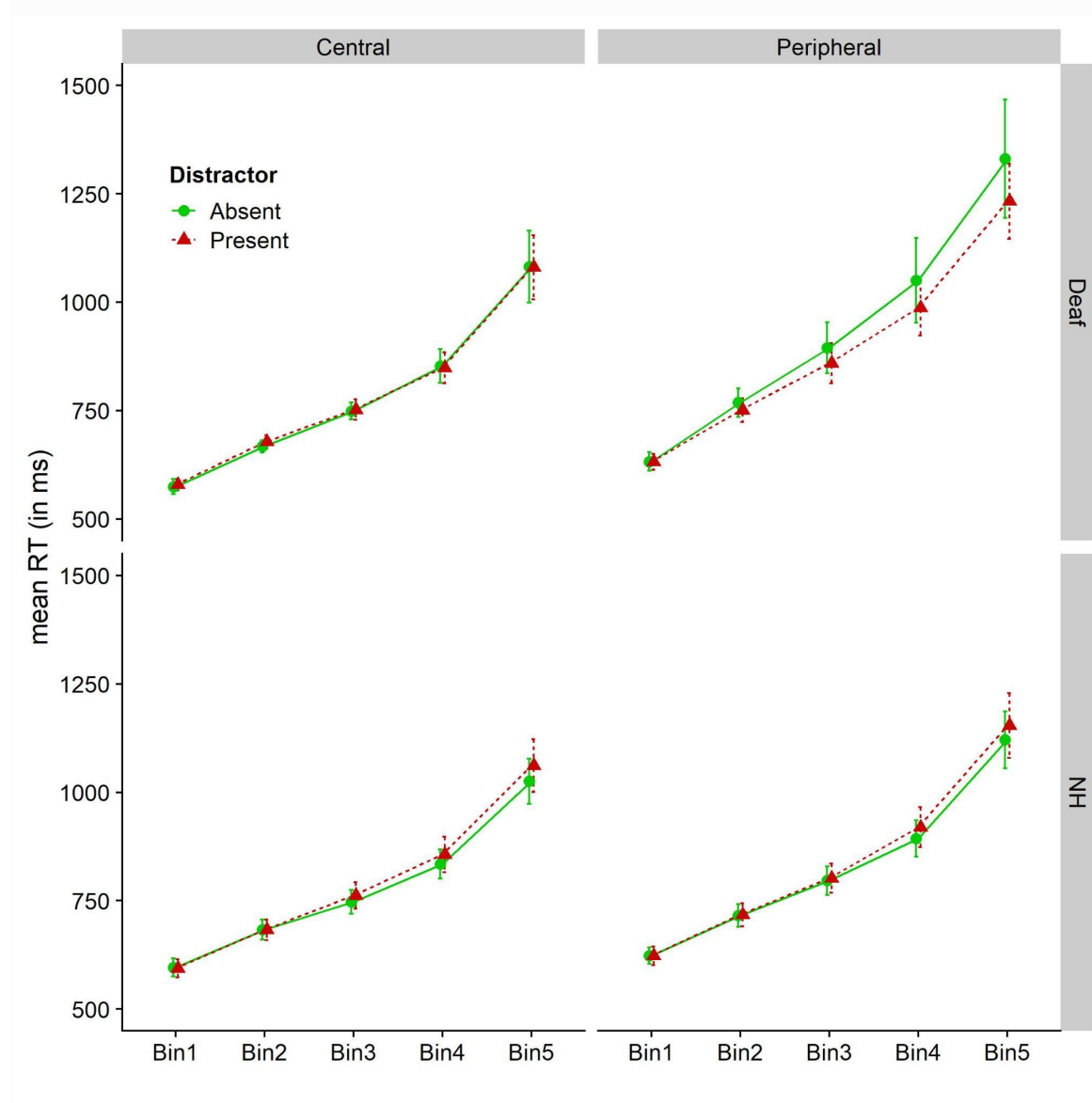


Figure 6.5. Difference in RT bins for HI and NH groups. HI showed singleton presence benefit in bin 5 alone. NH consistently show no benefit of singleton's presence.

6.5. Discussion

In the present study, we examined if HI and NH groups differ in their ability to select a target among multiple distractors and another singleton distractor, using a singleton search paradigm. The time taken to find the target was equivalent among the two groups, but the NH group did so with greater accuracy. The key finding was singleton presence benefit in HI group and its absence in the NH group. Intertrial target-target matched improved RTs and target-singleton matched hampered RTs. But when the target location matched other distractors (mismatch), RTs did not differ from target-match trials, cumulatively supporting singleton suppression. Other distractor locations were merely filtered during search. Both groups displayed attentional biases against the singleton distractor, but the only HI group inhibited it.

Another key question of the study was the nature of processes leading to selection among the two groups. Response compatibility analysis suggested that attention was not engaged at the singleton distractor, as RTs on compatible and incompatible trials were similar. Although accuracy on compatible trials was greater than incompatible trials, during central search displays, it only indicates that any attentional engagement with the singleton distractor (albeit weak) influenced later decision-making stages and not attentional stages of selection. Both groups displayed weak engagement with the singleton distractor; attention was also not strongly captured by the singleton; *the HI group yet experienced sufficient incentive to suppress the singleton while the NH group did not*. This implies that, when both target activation and distractor inhibition aided search, the HI relied on both processes while NH people relied on target enhancement alone. But the HI took time to display such suppression, as indicated in the RT distribution analysis. Singleton presence benefit, in HI, was negligible until approximately 1000-1500 ms. This could imply that the HI had superior goal-directed control over distractors compared to the NH group.

Previous studies have shown a clear advantage for the HI in spatial selection (Prasad et al., 2015). However, findings from feature selection have been mixed. Unlike spatial selection, featural selection is influenced by the nature of the feature—orientation, shape, color, etc. Studies so far looked at orientation and form (for example; c vs o) discrimination in HI and NH groups and found little or no differences among them (Bottari et al., 2010, 2011). It is still plausible that features like shape and color might show differences in selection, which we explored in the current study. The target was defined by shape (circle among diamonds or vice versa) while the singleton was unique in color feature. This design allowed us to test two things, 1) how HI and NH differ during shape search and 2) how they differ during color suppression. We found that the HI were poorer than NH during the shape search; this was because they indulged with the singleton distractor more than the NH group. Hence, to perform the search well, only the HI group needed to suppress the singleton distractor. It must be noted that even when participants fixated eyes at the center during the entire task, the HI group was influenced by the singleton distractor more strongly than the NH group. It implies that covert attentional shifts in the HI are sensitive to goal-irrelevant external stimuli, which is in line with the previous findings in the literature (Bosworth & Dobkins, 2002, but see Codina et al., 2011).

In breaking down selection into orienting, engagement and disengagement, many studies in the past have shown mixed findings. For instance, Rueda et al., (2014) studied the development of selection in younger and adolescent HI people, using an ANT task. They found that orienting and engaging attention was better in adolescents than younger HI people, but the ability to disengagement was similar. Another study by Prasad et al. also found that both HI and NH displayed equivalent disengagement from the target at slower SOA (800 ms) which lead to IOR (2015). Still, the HI did not show a benefit over NH in the ability to attend to a number of objects simultaneously, in an enumeration task (experiment 1) and multiple object tracking task (experiment 2) (Hauser et al., 2007), suggesting the orienting and engagement benefit are not enough in explaining the

differences between HI and NH people. The current study explored if orienting, engaging and disengaging differ among the groups but w.r.t target enhancement or distractor suppression. Since selection is a combination of the two mechanisms, the ability to orient may differ when it is towards the target or away from a distractor. Similarly, engagement and disengagement may also differ between the two mechanisms, among the groups. Our findings supported this by showing that the target captured and engaged it similarly in both HI and NH, however, capture by the singleton was prevented only in the HI. Engagement with the target as well as the singleton was comparable among the HI, but the HI was better at disengaging attention compared to the NH group.

Previous studies on HI have also exploited the response compatibility effect to measure attentional engagement. Chen et al., (2010) found a compatibility effect when the shape inside the target placeholder matched the shape inside a distractor placeholder. They asked participants to find the (diamond or square) target shape among different distractor shapes within placeholders. Either a diamond or a square appeared randomly on a given trial. Hence, the shape dimension was ‘relevant’ to the task and engagement with the shape was necessary. Here we asked participants to search target shape “find the unique circle/diamond” but the target shape was constant throughout the experiments. Participants pressed buttons reporting the target-line. Since all shapes had a vertical/horizontal line on them, participants had to quickly orient at the shape and engage with the line. This is to say that engagement with the target shape was mandatory in Chen et al., (2010) but not in the current study; instead, engagement with the orientation bar was necessary. This explains lack of response compatibility. More importantly, the singleton distractor in the current study was posed not significance to the task, since salience was not a target defining feature. Previously, Proksch and Bavelier, (2002) also showed that increasing the number of distractors during search, decreased the effect of response compatibility, especially in HI people.

Preventing a distractor from interfering with the search, can be achieved in mainly two ways—proactive suppression or rapid disengagement (Geng, 2014; van Moorselaar et al., 2020; Wöstmann et al., 2021). Many studies have shown that NH people can both proactively suppress and rapidly disengage from a singleton distractor; current study suggested that the HI relied on rapid disengagement alone. Since target-singleton response compatibility influenced RTs in both HI and NH groups, we can say that attention was engaged at the Singleton distractor. However, the HI group responded faster in the presence of the singleton by disengaging attention rapidly from the singleton and reorienting attention to the target—slowing down responses overall. Overall, we can say that HI are more sensitive to distractors than NH and make up for it by being better in distractor avoidance strategies. This ability however might develop at later stages of life in HI adults. A previous study on HI children in the age range of 6–13 years found that HI children were more distracted than NH children on a selective attention task (Dye & Hauser, 2014). However, this was observed among children 6–8 years of age and not among children 9–13 years of age. Taken together, these findings, we believe that the HI becomes better at ignoring distractors in adulthood compared to their NH counterparts who learn it much earlier.

Current behavioral findings help in reconciling existing neurobiological findings on hearing-impairment-induced neuroplasticity. For instance, studies have shown higher functional connectivity between left dorsal attentional IPS and right dorsal attentional IPS post-prolonged hearing impairment (Ducas et al., 2021). The dorsal network influences working memory and attention. The *frontoparietal dorsal attention network* (DAN) is critical for selection and plays a key role in the feature-based suppression of task-irrelevant information (Rajan et al., 2019). Higher DAN activity is observed when a target is selected among potential distractors instead of it being selected among alternative targets (Lanssens et al., 2020). Previous studies have found that individual differences in DAN activity predict age-related distractibility in NH adults (Amer et al., 2016). So far, stronger connectivity in the dorsal visual stream has been attributed only to better motion

processing and overall stimulus sensitivity in the HI (Andin & Holmer, 2022); the current study linked it to enhanced distractor suppression during search.

6.6 Conclusion

Congenital hearing impairment induces changes in the brain and enhances mechanisms responsible for visual selection. Many studies showed greater spatial selection in the HI over NH, especially in the peripheral visual field. The current study showed better feature selection in the HI over NH, but by employing distractor suppression instead of target enhancement alone. When a singleton color distractor appeared during the search, it affected the HI group more than the NH group, hence the HI used goal-directed control to suppress the singleton. The HI showed greater sensitivity to distractors, but they also were good at handling them. Unlike previous studies, we explain the reasons for consistently slower RTs in HI—the dynamic adjustment in orienting, engaging and disengaging attention—from the distractor and target. The cumulative findings suggest that the HI disengaged from distractors better than NH, whereas attentional orienting to target was comparable across the two groups.

7. Summary and Conclusions

The thesis aimed to compare conscious and unconscious processes of distractor suppression. A reliable paradigm to test this is yet to be created. It was important to calibrate the parameters that allow/enhance (conscious) suppression processes during feature search. The evidence of suppression has been mixed in the past literature, with some studies suggesting the influence of set size, target-distractor similarity and frequency of singleton present trials during search on the degree of singleton suppression. Moreover, the evidence for suppression has been challenged in various studies, either suggesting target enhancement (and not distractor suppression) or a mere filtering cost instead of distractor inhibition (Forschack et al., 2022; Kerzel & Huynh Cong, 2023; Oxner et al., 2023). We wanted to identify reliable indexes of suppression irrespective of target enhancement during feature search.

Studies discussed in Chapter 2 aimed at calibrating ideal conditions for suppression and finding indexes of suppression in manual RTs and eye movements corresponding to target-distractor similarity and frequency of singleton present trials. Studies have shown a consistent increase in target enhancement as task demands increase or goals become stronger. For instance, the target's appearance frequency in a detection-search task (target present vs. absent) influenced the speed of target selection. The decision criterion towards selecting a yes response vs. a no response shifts as evidence for target presence increases. Similarly, the frequency of appearance of a distractor influences the degree of capture by it, in singleton suppression paradigms. Thus, we used the frequency of appearance as a manipulation to test singleton suppression, which was also sensitive to it. We observed that irrelevant singleton distractors can be suppressed during feature search, and this suppression is enhanced as the task difficulty increases.

Additionally, a high certainty of encountering a singleton distractor makes suppression easier by encouraging proactive inhibitory mechanisms. However, the frequency of singleton distractors

was noncontributing to singleton suppression. Further experiments used the feature search display similar to Experiment 2, encouraging suppression. While eye movements to the inhibited distractor were affected by its frequency, we could not conclusively find its benefit for suppression and search. Manual response suppression remained completely unaffected by the frequency manipulation. Since the frequency manipulation did not influence manual response selection, we used the 50% distractor present condition for all further studies, allowing a baseline comparison between singleton absent and present trials during the search.

Chapter 3 investigated processes of feature and spatial suppression, available and precluded from conscious access. We found that consciousness was not necessary for distractor suppression, such that unconscious cues helped in the suppression of matching singleton similar to conscious cues. However, suppression of overt eye movements was only possible for unconsciously perceived cues, while consciously perceived cues captured attention. Spatial cues pushed spatial representations and feature cues pushed feature representations, but more so when the cues were consciously perceived. In both experiments, singleton captured attention covertly and rapid disengagement from it benefited the search. The color-matching cue benefited suppression during feature search more than the location-matching and both-matching cue (irrespective of cue awareness), pointing towards a contingent-suppression effect.

We explored unconscious feature suppression in Chapter 4 by further manipulating access to cue representations, to conscious awareness. In Chapter 3 we observed better suppression with the help of a distractor feature-matching cue presented for 16 ms. While we confirmed using *d* prime that the cue presented a weak signal compared to the 500 ms control (visible) cue, we could not be certain that participants perceived it unconsciously, by simply signal detection thresholds. To ensure that in Chapter 4, participants reported subjective awareness of cue on every trial on the perceptual awareness scale, while it matched the singleton distractor color, along with the target color

(suppression baseline) and a neutral color (cueing baseline). Additionally, perception of the 16 ms cue was further degraded by using a meta-contrast forward mask. Thus, the singleton feature-matching cues in Chapter 4 differed from Chapter 3 in access to conscious awareness, essentially being further unconscious to perception. Unlike experiments in Chapter 3, these cues did not benefit suppression compared to neutral cues but instead pushed singleton representations causing attention capture.

Taken together, the following conclusions can be drawn for distractor feature cueing: (a) both consciously and unconsciously perceived cues push distractor representations on the feature map, encouraging covert attention capture. (b) suppression is better when distractor cues are perceived below conscious levels, but now when they are completely conscious. (c) Cues perceived unconsciously also do not aid in distractor suppression, essentially a state lower than conscious perception and greater than unconscious perception is ideal for guiding suppression effectively. (d) The relationship between conscious access to cues and the degree of suppression they facilitate is shaped like a bell curve, with maximal suppression at mid-level conscious perception of the cues. (e) Unconscious cues can guide suppression better when they do not emit a signal strong enough to engage attention but sufficient to orient attention to the cued object. This facilitates rapid disengagement at the attending object. (f) Endogenous central cues can engage attention strongly such that disengagement from the cue is needed before attention orientations to the cue object. If the cued object is a distractor, further disengagement from it can be hampered as a result.

Spatial suppression of singleton distractors differs from feature suppression. On comparing experiments from Chapter 3 and Chapter 5, we can conclude that: (a) conscious spatial cues push distractor location on the spatial map, whereas unconscious spatial cues allow oculomotor suppression. (b) Consciously perceived spatial cues benefit suppression more than no cue when knowing the location contingencies of the distractor are beneficial for search. (c) Intention-driven,

top-down control over location suppression is possible with prior knowledge of distractor location, provided reliability (acquired consciously or unconsciously), and consistency throughout the task. Dynamically updating knowledge of distractor location is outside top-down control. (d) spatial suppression can be guided by both conscious and unconscious processes equally well until they are not confounded with target enhancement processes.

The final section of the thesis explored individual differences in the ability to suppress distractors as a function of differential visual processing capabilities among groups. We selected hearing-impaired individuals to be compared to normal-hearing individuals to explore the result of deafness-induced neuroplasticity on distractor suppression mechanisms. Studies in the past have found faster attentional orienting and overall sensitivity to targets in the HI people compared to NH people, the study discussed in Chapter 6 showed that HI also differs from NI in goal-directed distractor suppression. The HI group showed suppression in a task that offered less incentive to engage in top-down distractor suppression. They disengaged from the singleton distractor faster than the NH group and improved performance during the search. The findings suggest that changes in selective attention in deafness can be attributed to enhanced inhibitory attentional processes. Thus, changes in brain networks as a result of neuroplasticity can influence the process of distractor suppression, making it a more useful mechanism than it is in typical people.

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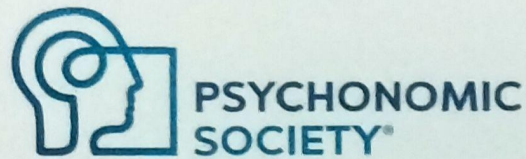
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Vaishnavi Mohite

University of Hyderabad, India

for the abstract entitled

**“Brief Cues Influence Suppression of Singleton Distractors during
Visual Search”**



Investigating the role of spatial filtering on distractor suppression

Vaishnavi Mohite¹ · Seema Prasad² · Ramesh Kumar Mishra¹Accepted: 7 December 2023
© The Psychonomic Society, Inc. 2023**Abstract**

In recent years, evidence has accumulated towards a distractor suppression mechanism that enables efficient selection of targets in a visual search task. According to these findings, the search for a target is faster in the presence of a salient distractor in a display among homogenous distractors as opposed to its absence. Studies have also shown that distractor suppression not only operates on the feature level but can also be spatially guided. The motivation of the current study was to examine if spatially guided distractor suppression can be goal-driven. We tested this across four experiments. In Experiment 1A, the task was to search for a shape target (e.g., a circle) and discriminate the orientation of the line within it. In some trials, a salient color distractor was presented in the display while participants were told that it appeared in one of the two locations on the horizontal axis (or the vertical axis, counterbalanced across participants). We expected enhanced distractor suppression when the salient distractor appeared within this “spatial filter” but did not find it since the target was also presented at the filtered locations. Experiment 1B replicated Experiment 1A, except that the target was always presented outside the filter; filtering enhanced search performance. In Experiment 2 even when the filter contained the salient distractor in only 65% of the filtered trials, filtering benefited search performance. In Experiment 3, the filter changed on every trial and did not benefit suppression.

Keywords Feature search · Distractor suppression · Spatial filtering · Goal-driven · Top-down**Introduction**

Everyday goals compel us to perform tasks that we often get distracted from. Distractors are everywhere, and they come in a variety of forms that we may fail to predict. Attentional mechanisms help in distinguishing targets from distractors. Attention can be directed to goal-relevant objects, rewarded objects, or ones prioritized in the past (selection history and priming) (Anderson, 2016; Gottlieb, 2012). While these factors bias attention towards the target and enhance attentional processing, an interesting question is whether they also bias attention away from the distractors. Recently, a distractor suppression mechanism has been found that prevents attention from being deployed to the distractors that interferes

significantly with task goals (Caputo & Guerra, 1998). In the lab-based tasks used to study this phenomenon, these “salient” distractors typically stand out in terms of features like color, orientation, onset, etc. When salient distractors are suppressed, attentional deployment to the target is faster. Several studies show that salient distractor locations can be suppressed by learning from past experience, habituation, and probability cueing (Anderson & Kim, 2020; De Tommaso & Turatto, 2019; Leber et al., 2016). What remains unclear is whether distractor suppression can be goal-driven. In this study, we inquired whether explicit knowledge of expected salient distractor locations can modulate the extent of distractor suppression during a feature-search task.

Salient stimuli are suggested to cause a reflexive attentional shift towards it (Theeuwes, 1992). Typically, studies show that irrelevant singleton distractors slow down responses significantly when searching for a target, in an additional singleton paradigm. However, recent studies using a feature-search paradigm have found that responses become faster in the presence of the salient distractor versus its absence (Gaspelin et al., 2017). This benefit results from the suppression of the salient distractor. While the

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vaishnavi32996@gmail.com¹ Centre for Neural and Cognitive Sciences, University of Hyderabad, Prof. C R Rao Road, Gachibowli, Hyderabad, Telangana 500 046, India² Cognitive Neurophysiology, Faculty of Medicine, TU Dresden, Dresden, Germany

Appendix C: Ethics Approval Certificates



Institutional Ethics Committee University of Hyderabad

Justice TNC Rangarajan
Chairperson

Prof. Geeta K. Vemuganti
Member Secretary

Decision Letter of Institute Ethics Committee

IEC No.		Date of review	31-01-2019
Application No:	UH/IEC/2019/109		
Project Title:	Understanding the nature of selective attention during attention capture by a peripheral cue using manual response time		
Principal Investigator/ Co-PI:	PI: VaishnaviHarshwardhanMohite CI: Prof. Ramesh Kumar Mishra		
Participating Institutes if any	----	Approval from Participating Institute	---
Documents received and reviewed	Protocol, ICF		
In case of renewal submission of update	----		
Decision of the IEC:	Approved after the conditions suggested at the IEC meeting were fulfilled on 12.02.2019 Duration: One year from date of approval		
Any other Comments Requirements for conditional Approval	----		
Members Present	Sri Justice Rangarajan, Prof. Geeta K. Vemuganti, Dr. C.T. Anitha, Dr. Naga Lakshmi, Dr. Sunita Mishra, Dr. Suvashesa Rana, Dr. Savitri Sharma, Smt. Vimala Sthanikam		

Please note:

- Any amendments in the protocol must be informed to the Ethics committee and fresh approval taken.
- Any serious adverse event must be reported to the Ethics Committee within 48 hours in writing (mentioning the protocol No. or the study ID)
- Any advertisement placed in the newspapers, magazines must be submitted for approval.
- The results of the study should be presented in any of the academic forums of the hospital annually.
- If the conduct of the study is to be continued beyond the approved period, an application for the same must be forwarded to the Ethics Committee.
- It is hereby confirmed that neither you nor any of the members of the study team participated in the decision making/voting procedures.

Chairperson

(Justice Rangarajan)
Chairperson

Institutional Ethics Committee (IEC)
School of Medical Sciences
University of Hyderabad

Hyderabad-500 046, Telangana.

Member Secretary

(Prof. Geeta K Vemuganti)
Member Secretary
Institutional Ethics Committee (IEC)
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University of Hyderabad

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UNIVERSITY OF HYDERABAD

INSTITUTIONAL ETHICS COMMITTEE DECISION LETTER



IEC No.	UH/IEC/2021/149	Date of review	26-08-2021
Application No:			
Project Title:	Investigating the influence of deafness induced neuroplasticity on visual selective attention in hearing impaired adults		
Principal Investigator/ Co-PI:	PI: Vaishnavi Mohite CI: Prof. Ramesh Kumar Mishra and Dr. Gaurishankar Patil		
Participating Institutes if any	----	Approval from Participating Institute	----
Documents received and reviewed	Protocol & ICF		
In case of renewal submission of update	----		
Decision of the IEC:	Approved Duration: One year from date of approval		
Any other Comments Requirements for conditional Approval	----		
Members Present	Dr. A.S. Sreedhar, Dr. P. Uday Kumar, Prof. B. R. Shamanna, Dr. M. Varalakshmi, Sri. A. Madhava Rao, Dr. Stalin Choudary, Prof. Pingali Sailaja, Dr. M. K. Aruansree, Dr. Deepa Srinivas and Ms. A. D. Shobhavathi		

Please note:

- Any amendments in the protocol must be informed to the Ethics committee and fresh approval taken.
- Any serious adverse event must be reported to the Ethics Committee within 48 hours in writing (mentioning the protocol No. or the study ID)
- Any advertisement placed in the newspapers, magazines must be submitted for approval.
- If the conduct of the study is to be continued beyond the approved period, an application for the same must be forwarded to the Ethics Committee.
- It is hereby confirmed that neither you nor any of the members of the study team participated in the decision making/voting procedures and declared conflict of interest.

A S Sreedhar
26/08/2021

Chairman

(Dr. A S Sreedhar)

B R Shamanna
26/8/2021

Member Secretary

(Prof. B.R. Shamanna)

M Varalakshmi
26/8/2021

Convenor

(Dr. M. Varalakshmi)

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Appendix D: Plagiarism report



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Ramesh Kumar Mishra, PhD
Professor & Head

Date: 05-04-2024

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Investigating Conscious and Unconscious Processes of Top-down Distractor Suppression

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