

# **Within- versus cross-dimensional capture in fixed-feature visual search**

**by**

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## Abstract

Recent ERP findings indicate that colour singletons fail to capture attention when observers search for a less salient shape that remains fixed across trials. This is consistent with the dimensional weighting account, according to which signals on the relevant (shape) and irrelevant (colour) dimensions are enhanced and suppressed, respectively. The goal of the present experiments was to examine the influence of prior knowledge of a target for over-riding a more salient distractor in a compound search task, when the target and distractor exist within the same visual dimension (colour versus colour; Experiment 1) and across different visual dimensions (shape versus colour; Experiment 2). More interference was found in the within-dimensional condition than the cross-dimension condition (18 msec vs. 7 msec). Both the within- and cross-dimensional targets elicited an N2pc component (indexing selection) and the distractor elicited a  $P_D$  component (indexing suppression). In the within-dimensional experiment, the amplitude of the N2pc varied as a function of the proximity of the distractor to the target. These results indicate that when dimensional weighting is not a viable selection strategy, the visual system suppresses the location of the distractor while selectively processing the target.

**Keywords:** attention, capture, visual search, event-related potentials, N2pc, dimensional weighting

## Table of Contents

Approval.....	ii
Partial Copyright Licence .....	iii
Abstract.....	iv
Table of Contents.....	v
List of Tables.....	vi
List of Figures.....	vii
<b>Introduction .....</b>	<b>1</b>
Electrophysiological Indices of Attentional Selection .....	5
Rationale for the present study .....	7
<b>Experiment 1 .....</b>	<b>10</b>
Methods .....	10
Participants .....	10
Apparatus.....	10
Stimuli and procedure .....	11
Electrophysiological recording .....	12
Data analysis.....	12
Results .....	14
Behavioural results.....	14
Electrophysiological Results .....	16
Experiment 1 Discussion.....	21
<b>Experiment 2 .....</b>	<b>24</b>
Methods .....	24
Participants .....	24
Apparatus.....	24
Stimuli and procedure .....	24
Electrophysiological recording .....	25
Data analysis.....	25
Behavioural results.....	25
Electrophysiological Results .....	28
Experiment 2 Discussion.....	32
<b>General Discussion.....</b>	<b>34</b>
<b>References .....</b>	<b>43</b>

## List of Tables

Table 1.	Within-dimension RTs .....	15
Table 2.	Within-dimension n-1 RTs .....	16
Table 3.	Within-dimension proximity analysis RTs .....	16
Table 4.	Cross-dimension RTs .....	26
Table 5.	Cross-dimension n-1 RTs .....	27
Table 6.	Cross-dimension proximity analysis RTs.....	27

## List of Figures

Figure 1. Search arrays that elicit electrophysiological indices of selective attention. ....	6
Figure 2. Sample of distractor present trial in Experiment 1.....	11
Figure 3. Within-dimension grand-averaged ERPs.. ....	18
Figure 4. Within-dimension RTs and contralateral-ipsilateral ERPs. ....	19
Figure 5. Within-dimension proximity RTs and contralateral-ipsilateral ERPs.....	20
Figure 6. Sample of distractor present trial in Experiment 2.....	25
Figure 7. Cross-dimension grand-averaged ERPs. ....	29
Figure 8. Cross-dimension RTs and contralateral-ipsilateral ERPs.....	30
Figure 9. Cross-dimension proximity RTs and contraateral-ipsilateral ERPs. ....	31
Figure 10. Comparison of hypothetical N2pc and observed N2pc. ....	38
Figure 11. Model of visual attentional selection based on dimensional weighting of stimuli. ....	42



# Introduction

As the visual system is inundated by a perpetual stream of information, selective attention affords us the capacity to effectively and efficiently process a small subset of this information. As humans, we can seemingly rely on two generally basic principles to bias selective attention. William James (1890) was amongst the first to explicate this differentiation, making the distinction between the passive, sensorial attention to which we are automatons, and the active, voluntary attention which, by will, can be initiated and controlled. While well over a century ago James full well realized the existence and necessity of both, the extent and role of each has remained a contentious issue in modern psychology and neuroscience. Today, referred to as bottom-up and top-down control, debate persists over the role and reach of these antithetic concepts.

The *saliency-driven capture hypothesis* proposes that initial visual selection is determined by the bottom-up activations triggered by the stimuli themselves. By this account, the most salient item in the visual field is selected automatically. This saliency-driven prioritization of processing occurs regardless of the intentions or expectations of the observer and only after this initial selection can top-down volitional control be exerted. In the context of visual search, if a target is presented alongside a more salient distractor, attention would be captured automatically by the distractor. Only after this initial shift, can attention be disengaged and redeployed to the location of the target (for review, see Theeuwes, 2010).

To investigate this saliency-driven capture hypothesis, Theeuwes (1991, 1992, 1994) conducted a series of visual-search experiments using what has become known as the *additional singleton paradigm*. Here, observers covertly search an array for a target singleton defined by one feature dimension (e.g., form) while ignoring a distractor singleton defined in a different feature dimension (e.g., colour). Theeuwes found the presence of a more salient distractor to delay reaction times (RTs) by 20-25 msec when the target and distractor features remain fixed (Theeuwes, 1992) and by 100-150 msec

when the target and distractor features are swapped randomly across trials (Theeuwes, 1991). In line with the salience-driven capture hypothesis, Theeuwes took the RT interference as evidence for the stimulus-driven, automatic capture of the highly salient distractor singleton. Only after this initial shift could the distractor singleton be deemed irrelevant and then attention be reoriented to the target. Several studies have since replicated these findings (e.g., Hickey & Theeuwes, 2011; Hickey, McDonald & Theeuwes, 2006; Jonides & Yantis, 1988; Theeuwes, 1992, 1994), however, not all researchers have interpreted this interference as evidence for capture (e.g., Bacon & Egeth, 1994; Jannati, Gaspar & McDonald, in progress; Lamy & Egeth, 2003; Pashler, 1988; Wienrich & Janczyk, 2011).

In contrast to the salience-driven capture hypothesis, the *contingent-capture hypothesis* argues that the capture of attention is always dependent on the top-down control set adopted by the observer. Volition initiates and guides early visual processing and the allocation of attention in line with whatever behavioural goals are set. According to top-down, contingent-capture models of visual selection, highly salient objects that are irrelevant to the observer's attentional set fail to capture attention automatically and any RT interference caused by the presence of a salient distractor can be explained as a non-spatial filtering cost (Folk & Remington, 1998).

Using a spatial-precuing paradigm, Folk, Remington, and Johnson (1992) were amongst the first to show that a spatially non-predictive cue whose defining feature matched the defining feature of the target impaired the identification of the target. In this task, participants were asked to respond to a search display containing either an abrupt-onset target or a colour-singleton target. Folk and colleagues found RT interference only when the display was preceded by a non-predictive cue singleton in the same feature dimension as that of the target. For example, an abrupt-onset cue was found to delay search for a subsequent abrupt-onset target that appeared at a different location but had no effect on search for the colour-singleton target. By contrast, a colour-singleton cue delayed search for a subsequent colour-singleton target that appeared at a different location but had no effect on search for the abrupt-onset target. Folk and colleagues took this as evidence for top-down prioritization for selection: irrelevant cues that matched the attentional set summoned attention reflexively, but participants were seemingly able to ignore cues that did not match their preconfigured attentional set.

Various versions of this precuing paradigm have replicated these basic findings (e.g., Folk and Remington, 1998; Folk et al., 1994; Folk, Leber, & Egeth, 2002; Gibson & Amelio, 2000; Gibson & Kelsey, 1998; Leblanc, Prime, & Jolicoeur, 2008; Leblanc & Jolicoeur, 2005).

The relative contributions of bottom-up and top-down factors have been built into several models of visual search (for review, see Cave & Wolfe, 1990; Itti & Koch, 2001; Theeuwes, 2010; Triesman & Gelade, 1980; Wolfe, 1994). Typically, these models posit two general stages of early visual processing: an early pre-attentive stage and a subsequent attentive stage (c.f. Theeuwes, 2010). During the pre-attentive stage, the visual system analyzes the relative saliency of individual items in visual field. Each item is processed individually based on its low-level basic visual features (e.g., colour, form, size). The saliency of each item is computed across all such features without identifying the features themselves and is represented on a 2-dimensional topographical saliency map of the entire visual field. During the attentive stage, the location that registers the peak activation on the saliency map is selected for further analysis (location selection). Object features at that location are then processed selectively while objects features at other locations are ignored (object selection).

According to the salience-driven capture perspective, the salience computations in the pre-attentive stage are based entirely on bottom-up information about the relative contrast of the stimuli (see Theeuwes, 2010). By this account, the item with the highest local contrast will have the highest activation on the saliency map and will thus be selected first. That item will then be processed selectively in order to identify it as either a target or a nontarget. If the item is identified as a nontarget, attention will be disengaged from that location and redeployed automatically to the location of the next highest peak on the saliency map. If the initially selected item is identified as the target, its features will be processed in order to perform the task at hand.

Several other models of visual search propose that the activations on the saliency map are determined not only by bottom-up information such as local contrast but also by the current behavioural relevance of that information to the observer. This enables the observer to bias selection in favour of task-relevant objects and to mitigate the distraction caused by salient-but-irrelevant objects. For example, dimension-based

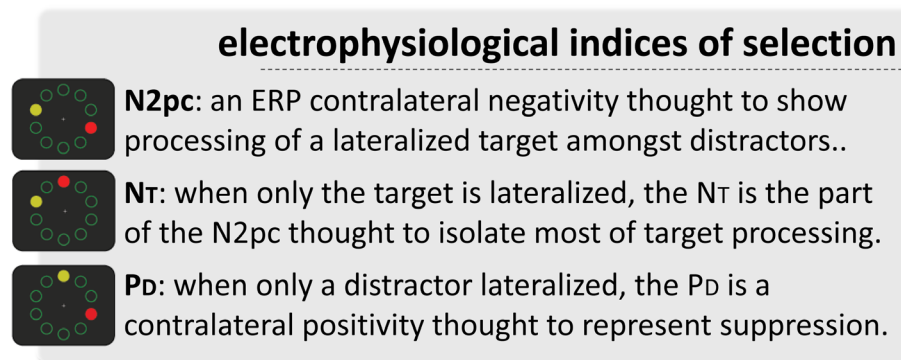
theories of visual attention propose that an object's salience is determined not only by its physical contrast but also by prior knowledge of a target-defining dimension. Here, object salience can be up-weighted and down-weighted depending on whether or not the item in question is defined on the basis of the relevant feature dimension (e.g., shape, form, colour) in order to facilitate search for task-relevant information. The amplification of this signal on these low-level feature dimensions produce strong, accumulated activations over time on the master saliency map (Found & Müller, 1996; Müller, Heller & Zeigler, 1995). Thus, in visual search, the greater the weight assigned to the to-be-attended target dimension, the more rapid the observer will orient to this target; however, changes of the target dimension across trials reset these weights, in turn, slowing search.

One such model that has received considerable empirical support is the Dimensional Weighting Account (DWA) proposed by Müller and colleagues (Found & Müller, 1996; Müller et al., 1995; Müller, Reimann, & Krummenacher, 2003). In an early study (Müller et al., 1995; experiment 2), participants were asked to report the presence or absence of target singletons amongst an array of homogenous non-targets. On some trials, a distractor singleton appeared in place of the target singleton, and observers were instructed to make a *target-absent* response. Critically, the distractor singleton could be defined in the same dimension as the target (within-dimension condition) or in a different dimension (cross-dimension condition). They found that participants took longer to respond to targets in the within-dimension condition than in the cross-dimension condition. This led them to propose that dimensional relevance influenced activity on the master saliency map. For example, when searching for a red colour singleton, the salience of any colour singleton would be up-weighted, while the salience of singletons defined on any other dimension would not be up-weighted (and might be down-weighted). In the context of the cross-dimension variant of the additional singleton task, dimensional weighting would enable participants to respond quickly even in the presence of a salient distractor because only the target is up-weighted and thus only the target singleton *pops out*. However, in the within-dimension condition, both the target and distractor singletons would be up-weighted on the saliency map and so further attentional processing was required to determine whether the item *popping out* was a target or distractor.

## Electrophysiological Indices of Attentional Selection

Concomitantly measuring electroencephalography (EEG) and behavioural RTs offers the unique opportunity to study the brain mechanisms underlying visual-spatial attention. By then averaging EEG trials of similar content, event-related potentials (ERPs) can be used to index moment-to-moment changes in post-synaptic potentials unique to varying display configurations in search tasks. ERPs can be used to examine neural activity in the absence of any response, making it perfectly suited for the evaluation of task-relevant target and task-irrelevant distractor processing in visual search paradigms.

An ERP component called the posterior contralateral N2 (N2pc) has been linked to visual selection. As its name suggests, the N2pc is an enhanced negative-going voltage in the time range of the N2 peak (~170 to 300 msec following the onset of the display) that is observed over the posterior scalp contralateral to an attended item. Researchers have proposed this component reflects attentional suppression of unattended items (Luck & Hillyard, 1994a, 1994b; Woodman & Luck, 1999, 2003), the selective processing of the attended item (Eimer, 1995, 1996; Kiss, Van Velzen, & Eimer, 2008), or a combination of both (Hickey, Di Lollo, & McDonald, 2009). As such, the N2pc has been widely used as a measure of attentional processing in visual-search experiments, including those utilizing the additional-singleton paradigm (Hickey, McDonald, & Theeuwes, 2006), spatial precuing (Lien, Ruthruff, Goodin, & Remington, 2008; Leblanc, Prime, & Jolicoeur, 2008), and dimensional-weighting paradigms (Töllner, Zehetleitner, Gramann, & Müller, 2010).



**Figure 1.** *Search arrays that elicit electrophysiological indices of selective attention.*

Figure 1 displays three visual-search displays containing two colour singletons, a relevant one (e.g. the yellow disc) and an irrelevant one (e.g., the red disc). The N2pc has been measured in numerous studies utilizing laterally balanced displays like the one illustrated in Figure 1a. In this case, the ERP recorded over the right occipital scalp would be more negative than the ERP recorded over the left occipital scalp in the 170–300 msec. This difference is usually regarded as an enhanced negativity contralateral to the attended target on the left side of fixation. Mathematically, however, it is unclear whether it is an enhanced negativity over the right side of the scalp, an enhanced positivity over the left side of the scalp (i.e., contralateral to the unattended singleton), or both. These sub-components can be isolated by presenting one of the two singletons on the vertical meridian so that it is unable to elicit any lateralized activity (Hickey, Di Lollo, & McDonald, 2009; see also Woodman & Luck, 2003). In Figure 1b, any lateralized ERP activity in the time range of the N2pc would be attributable to the target singleton; while in Figure 1c, any such lateralized activity would be attributable to the distractor singleton.

Hickey, Di Lollo, and McDonald (2009) revealed a novel component thought to index the direct suppression of a salient to-be-ignored distractor singleton. Participants were required to respond to a salient target and to ignore a less-salient distractor whose brightness was matched to that of the background. Hickey and colleagues discovered that when the target appeared along the vertical meridian and the distractor was the only item lateralized (as in Figure 1c); it elicited a positive-going voltage contralateral to the to-be-ignored item. Hickey et al. hypothesized that the presence of this component – which they labelled the distractor positivity (P<sub>D</sub>) – likely reflects distractor suppression.

Hickey et al. examined lateralized ERPs elicited by search displays containing a lateral target and midline distractor (as in Figure 1b). This display configuration was found to isolate the activity associated with target processing; the  $N_T$ . They proposed that the absolute algebraic sum of the  $N_T$  plus the  $P_D$  could reflect individual, discrete components that comprise the balanced N2pc array. As such, the N2pc as a balanced array was a culminated representation of both target processing and distractor suppression simultaneously.

The N2pc has been used recently to determine whether salient-but-irrelevant stimuli capture attention. Hickey, McDonald, and Theeuwes (2006) were the first to use the N2pc to study whether attentional capture occurred using the additional singleton paradigm. Similar to the original cross-dimension, mixed-feature search (Theeuwes, 1991), participants responded to the orientation of the line inside a target shape singleton. In order to maximize RT interference, the colour and shapes of the items were swapped randomly across trials. For example, on one trial, the target could be a green diamond amongst green circles, while the distractor was a red circle, whereas on the subsequent trial the target could be a red diamond amongst red circles, while the distractor was a green circle. In this case the shapes stay the same, but the colour of the target and distractor are swapped. On half of trials, this highly salient-but-irrelevant color singleton in the opposite dimension appeared simultaneously in the search array. They found that in mixed-feature search tasks a lateralized distractor did elicit an N2pc, which provides evidence for capture of attention by the most salient item in the display. While this is certainly consistent with salience-driven capture, subsequent studies have revealed that salient distractors do not elicit N2pc when the features of the stimuli remain fixed across trials (Jannati, Gaspar & McDonald, in preparation; McDonald & Di Lollo, 2009; Schubo, 2009). Recently, Jannati and colleagues (in preparation) have also shown that the distractor only elicits an N2pc on the slowest half of trials in mixed-feature search tasks.

## Rationale for the present study

The following experiments were conducted to investigate the influence of prior knowledge of a fixed target feature, when a more salient singleton distractor was defined

in the same or across different feature dimensions. Previous studies have shown that salient distractors fails to capture attention (elicit N2pc) in the fixed-feature variant of the additional-singleton paradigm when targets and distractors were defined on different dimensions (Jannati, Gaspar & McDonald, in preparation; McDonald & Di Lollo, 2009; Schubo, 2009). This may have enabled participants to take advantage of a dimensional-weighting strategy to boost the saliency of the shape-defined target and down-weight the saliency of the colour-defined distractor. If on the other hand the two singletons were both defined on the colour dimension, up-weighting this dimension would not enable observers to selectively bias search in favour of the relevant, but physically less salient, target. Rather, it would up-weight the distractor as well as the target, thereby leaving the distractor as the most salient item on the master saliency map. As such, DWA would posit the need for further attentional processing to bias competition in favour of the target and, therefore, dimensional weighting alone would not be a viable search strategy.

The fixed-feature variant of the additional singleton paradigm (cf. Theeuwes, 1992), was used in each of two experiments. Participants searched for either a colour singleton or a form singleton, while ignoring a more salient colour singleton that appeared 50% of the time. Both the target and distractor features remained fixed for the entirety of the experiments. Since both singletons existed within the same feature dimension (colour) in experiment 1, we predicted greater RT interference in the within- versus the cross-dimension condition (experiment 2). Dimensional weighting has also been shown to have carryover effects across trials, both facilitating and impeding search (Kumada & Humphreys, 2002; Found & Muller, 1996). In the present study, RTs for several successive search-display pairings were examined to determine whether the location of each singleton influenced the processing of those singletons on the next trial. Consistent with *priming of pop-out* (Maljkovic & Nakayama, 1996), we expect speeded responses when targets appear in the same location across trials. We further predict the slowing of RTs when a target falls in a location previously occupied by either a target or distractor.

Following the RT analyses, ERPs were examined to investigate whether the salient-but-irrelevant distractor singleton captured attention. Successful and efficient search likely requires a number of steps both involving the processing of target as well as the suppression of irrelevant stimuli. To isolate the electrophysiological contributions



of target and distractor processing, ERPs to several display configurations of interest were examined separately to segregate lone target processing ( $N_T$ ), distractor processing ( $P_D$ ), as well as balanced visual search arrays (see Figure 1 for examples).

In Experiment #1, it is uncertain whether top-down control is possible in the face of within-dimension competition. Since dimensional weighting cannot be implemented to reduce the relative saliency of the distractor, attention might be captured by the distractor. This would result in a distractor-elicited N2pc, as was observed in the original Hickey et al. (2006) study. If the salience-driven capture hypothesis is correct, delayed RTs should be accompanied by an N2pc first to the distractor singleton prior to the disengagement and redeployment of attention to the target. Rather, if contingent capture is valid, observers would be able to successfully inhibit attentional capture by the salient-but-irrelevant distractor, and only lateralized targets would elicit an N2pc. Should the latter be the case, it is not unreasonable to expect that lateralized distractor singletons may elicit a  $P_D$  component, indicative instead of the suppression of the salient, to-be-ignored item. Experiment #2 is expected to replicate the main finding of other similar cross-dimensional, fixed-search tasks. As such, we do not expect the distractor to elicit an N2pc in the cross-dimension experiment, in line with other findings (Janatti, Gaspar & McDonald, in preparation; Schubo, 2009).

We also examined whether the proximity of the target from the distractor had any effect on RT interference. Hickey and Theeuwes (2011) have recently shown receptive-field-scaled proximity distractor costs in a cross-dimension, fixed-feature search, but only when the target was a shape and not a colour singleton. They argued that the proximity effects observed constituted an index of capture by the distractor. Alternatively, ambiguity resolution theory proposes that ambiguities in the discrimination of features can arise when multiple objects share the same neural receptive field (Luck, Girelli & McDermott, 1997). Any additional interference that is incurred from when the target and distractor singletons reside closer to one another in the search array could be the result of filtering costs associated with receptive field overlap and not capture. ERPs for the various target-distractor proximities were created to investigate the relationship between the N2pc and the behavioural costs observed.

# Experiment 1

## Methods

The Research Ethics Board at Simon Fraser University approved the experimental procedures used in this study.

### *Participants*

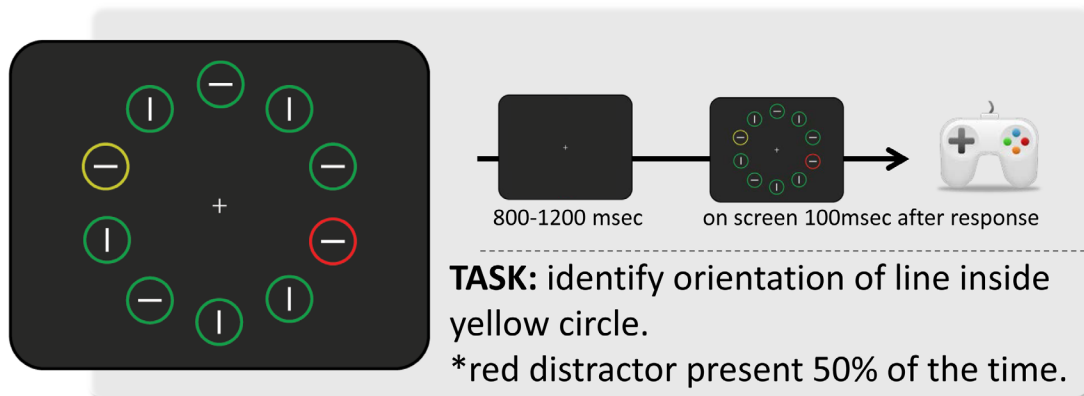
Twenty neurologically typical students from Simon Fraser University were recruited from an undergraduate research pool and gave their informed consent to participate for pay or course credit. From the data, four subjects were excluded due to excessive ocular artifacts in the electroencephalogram (EEG). Of the remaining 16 participants (8 women, age  $21.25 \pm 2.96$  years, mean  $\pm$  SD; 1 left-handed), all reported normal or normal-to-corrected visual acuity and were tested for typical colour vision using Ishihara colour test plates.

### *Apparatus*

Participants were seated on an adjustable chair inside a dimly lit, sound-attenuated and electrically shielded chamber. Experimental stimuli were presented from a Microsoft Windows-based computer system running Presentation (Neurobehavioral Systems Inc., Albany, CA, USA) onto a 19-inch CRT monitor positioned approximately 57 cm from participants. Pressing either the left or right bumper button, responses were collected using a Logitech Dual Action™ Gamepad (Logitech, Fremont, CA, USA). A second Microsoft Windows-based computer system controlled EEG acquisition using the Biosemi ActiveView software (BioSemi, Amsterdam, the Netherlands).

## Stimuli and procedure

The visual search array was comprised of ten discrete shape stimuli presented equidistant ( $9.2^\circ$ ) from a central fixation point on a uniform black background (Figure 2). On every trial, the target colour singleton – an unfilled circle ( $1.7^\circ$  radius) with a thin ( $0.3^\circ$ ) green-yellow (RGB = 200, 200, 0) outline – appeared at one of the ten possible positions in the array. In 50% of the trials, a distractor colour singleton – an unfilled circle ( $1.7^\circ$  radius) with a thin ( $0.3^\circ$ ) red (RGB = 255, 0, 0) outline – also appeared in the array. The remainder of the array consisted of unfilled circles ( $1.7^\circ$  radius) with thin ( $0.3^\circ$ ) green (RGB = 0, 160, 0) outlines. A gray line ( $0.3^\circ \times 1.5^\circ$ , RGB = 150, 150, 150) randomly oriented vertically or horizontally was contained within each of the stimuli.



**Figure 2.** Sample of distractor present trial in Experiment 1.

The target singleton was the only unique object in the array for 50% of the trials (distractor absent; DA trials) and could appear in any of the ten (eight lateralized, two midline) positions. In the remaining 50% of the trials, the distractor singleton appeared simultaneously (distractor present; DP trials). Target and distractor locations were varied to produce the following display configurations: lateral target, no distractor (33%); midline target, no distractor (17%); lateral target, midline distractor (11%); lateral target, ipsilateral distractor (11%); lateral target, contralateral distractor (11%); midline target; lateral distractor (11%); midline target, midline distractor (6%). The order of these display configurations was determined pseudo-randomly within each block of trials.

At the beginning of each experimental trial a fixation point appeared at the centre of the screen for 800–1200 msec. After this inter-trial interval, one of the search displays

described above was presented around the fixation point. Participants were instructed to maintain eye fixation on the central point and to identify the orientation of the gray line inside the target singleton by pressing one of two response buttons as quickly as possible. The search array remained on the screen for 100 msec after a response had been made, at which point the next trial began. Each experimental block was comprised of 36 trials, after which a mandatory minimum 5-second break was given to participants. Participants were encouraged to rest and to start the next block of trials when ready. The experiment contained 35 blocks for a total of 1260 trials per participant. At least 36 practice trials were given to each participant prior to commencing the experiment.

### *Electrophysiological recording*

Electrophysiological data were recorded from active sintered Ag-AgCl electrodes (BioSemi, Amsterdam, the Netherlands) from 125 standard and three nonstandard sites inferior to the standard occipital locations. Horizontal electrooculogram (EOG) was recorded using two electrodes positioned 1 cm lateral the external canthi and vertical EOG was recorded using two electrodes positioned above and below the right eye. All EEG and EOG signals were digitized at 512 Hz and referenced in real time to an active common-mode electrode. Electrode offsets were continually monitored to ensure the quality of the data.

### *Data analysis*

EEG processing and ERP averaging were performed using ERPSS (University of California, San Diego). A semi-automated procedure was used to discard epochs of EEG contaminated by blinks, eye movements, or excessive noise (for details, see Green, Conder, & McDonald, 2008). Visual inspection of the continuous EEG and EOG was used to determine an appropriate threshold value that would maximally eliminate artifacts while retaining artifact-free epochs. The same threshold value was used for artifact rejection across all subjects. Any trial with an artifact that exceeded the threshold within -200 msec to 800 msec post-stimulus was rejected. Artifact-free epochs associated with the various search display configurations of interest were then averaged separately to create ERP waveforms. The resulting ERP waveforms were digitally low-pass filtered (-3 dB point at 28 Hz) and digitally re-referenced to the average of the left

and right mastoids. All ERP amplitudes and baselines were computed using a 200 msec pre-stimulus window. The averaged event-related HEOGs did not exceed 2  $\mu$ V for any individual participant, suggesting their gaze remained within 0.3° of the fixation point for a majority of the trials (see McDonald & Ward, 1999, for HEOG calibration).

The primary analysis focused on grand-averaged ERPs elicited by the following display configurations: (i) a lateral target with a midline distractor; (ii) a lateral distractor with a midline target; (iii) a lateral target with a contralateral distractor; (iv) a lateral target with an ipsilateral distractor; (v) a lateral target and no distractor. Trials that simultaneously contain a midline and a lateral stimuli (see configuration: i and ii) are integral for investigating target and distractor processing in the additional-singleton paradigm, as they afford the opportunity to isolate the N2pc to the lateral singleton (Woodman & Luck, 2003; Hickey, Di Lollo & McDonald, 2009; Hickey, McDonald, & Theeuwes, 2006). Configurations where both singletons are laterally presented (see configuration: iii and iv) allow for the examination of the relative effect of target-distractor separation. Finally, configurations where only the target singleton appears (see: configuration v) allows for the investigation of target processing in the absence of the distractor.

For each individual participant, ERPs to the various search displays were collapsed across left and right visual hemi-fields and left and right electrodes, resulting in waveforms recorded ipsilateral and contralateral to a lateral singleton (the target, unless otherwise noted). N2pc components were then derived for each condition by subtracting the ipsilateral waveform from the corresponding contralateral waveform using lateral occipital electrode sites A10 and B7 (Biosemi nomenclature), which correspond approximately to P07 and P08 of the international 10-10 electrode placement system.

A follow-up N2pc analysis was performed to assess target-distractor proximity effects. The ERPs were re-averaged according to the distance between target and distractor, which ranged from one item (target and distractor side-by-side) to five items (five items away; i.e., four intervening items; see Figure 4). N2pc waveforms were then computed by again subtracting the ipsilateral waveforms from the corresponding contralateral waveforms using lateral occipital electrode sites A10 and B7, separately for each of the target-to-distractor distances.

# Results

## *Behavioural results*

7.5% of trials were excluded from the analyses because participants responded either too slowly (RT < 1500 msec; 0.88%) or incorrectly (6.63%). An additional 13.28% of correct trials were excluded due to eye movements, blinks, and amplifier-blocking artifacts in the EEG/EOG data. Of the remaining trials, median reaction times (RTs) and error rate data were computed for each of the display configurations of primary interest (Table 1). To assess the overall distractor interference effect, RTs for all distractor-present trials were pooled and compared to distractor-absent trials. Inter-participant means of the median RTs for distractor-present and distractor-absent trials were 626 msec and 608 msec, respectively. A repeated-measures analysis of variance (ANOVA) for distractor presence (present vs. absent) as the sole factor found the 18-msec difference to be statistically significant [ $F(1,15) = 29.12$ ,  $p < 0.001$ ]. A similar analysis of error rates revealed that participants produced fewer errors when the distractor was absent (5.45%) than when the distractor was present (6.15%); however, this small difference was not statistically significant [ $F(1,15) = 3.71$ ,  $p = 0.07$ ].

**Table 1. Within-dimension RTs**

Experimental Condition	RT	Error %
Lateral target, no distractor	614.3 (63)	6.0 (3.0)
Lateral target, contralateral distractor	624.3 (75)	6.5 (2.5)
Lateral target, vertical distractor	639.2 (73)	7.3 (4.1)
Lateral target, ipsilateral distractor	648.1 (71)	7.6 (4.7)
Vertical target, lateral distractor	613.6 (64)	5.3 (2.6)
Distractor present total	626.1 (70)	6.2 (2.6)
Distractor absent total	608.2 (61)	5.4 (3.0)

**Median correct response times (msec) with standard deviations and error rates (%) by experimental condition with standard deviations for experiment 2.**

Following the main distractor-interference analysis, we examined the effects of repeating or swapping locations of the singletons across successive trials. For this inter-trial analysis, median RTs were pooled across all distractor-present conditions for three possible occurrences: (i) the distractor appeared in a location previously occupied by a target (T-D), (ii) the target appeared in a location previously occupied by a distractor (D-T), and (iii) the target appeared in a location previously occupied by a target (T-T). Table 2 presents median correct RTs (msec) for the three conditions. To determine what additional costs or benefits were associated with the aforementioned display sequences, RTs in these three conditions were compared against the average RT for distractor-present trials (626 msec). When the distractor appeared in the location previously occupied by the target (T-D) there was an additional 7 msec cost, which was not significant [ $F(1,15) = 1.7345$ ,  $p = 0.208$ ]. When the target appeared in the location previously occupied by the distractor (D-T), there was an additional 30 msec cost, which was significant [ $F(1,15) = 28.0158$ ,  $p < 0.001$ ]. Finally, when the target appeared in the same location across consecutive trials (T-T) there was a 27 msec RT benefit, which was significant [ $F(1,15) = 25.0600$ ,  $p < 0.001$ ].

**Table 2.**        *Within-dimension n-1 RTs*

<b>Experimental Condition</b>	<b>RT</b>	<b>RT - DP</b>
Target then distractor (T-D)	632.6	6.5
Distractor then target (D-T)	656.4	30.3
Target then target (T-T)	599.5	-26.5

We further analyzed median RTs for the five possible target-distractor proximity conditions (see Figure 4). As illustrated in Table 3, RTs trended linearly, decreasing as the target moved further from the distractor in the array. A repeated measures analysis of variance (RANOVA) found a main effect of proximity to be statistically significant [ $F(4,48) = 21.45$ ,  $p < 0.0001$ ]. When the RT behavioural results of the furthest target-distractor proximity (Distance 5) were contrasted against the distractor absent (DA) condition, there was no significant difference ( $F(1,15) = 0.1503$ ,  $p = 0.7037$ ).

**Table 3.**        *Within-dimension proximity analysis RTs*

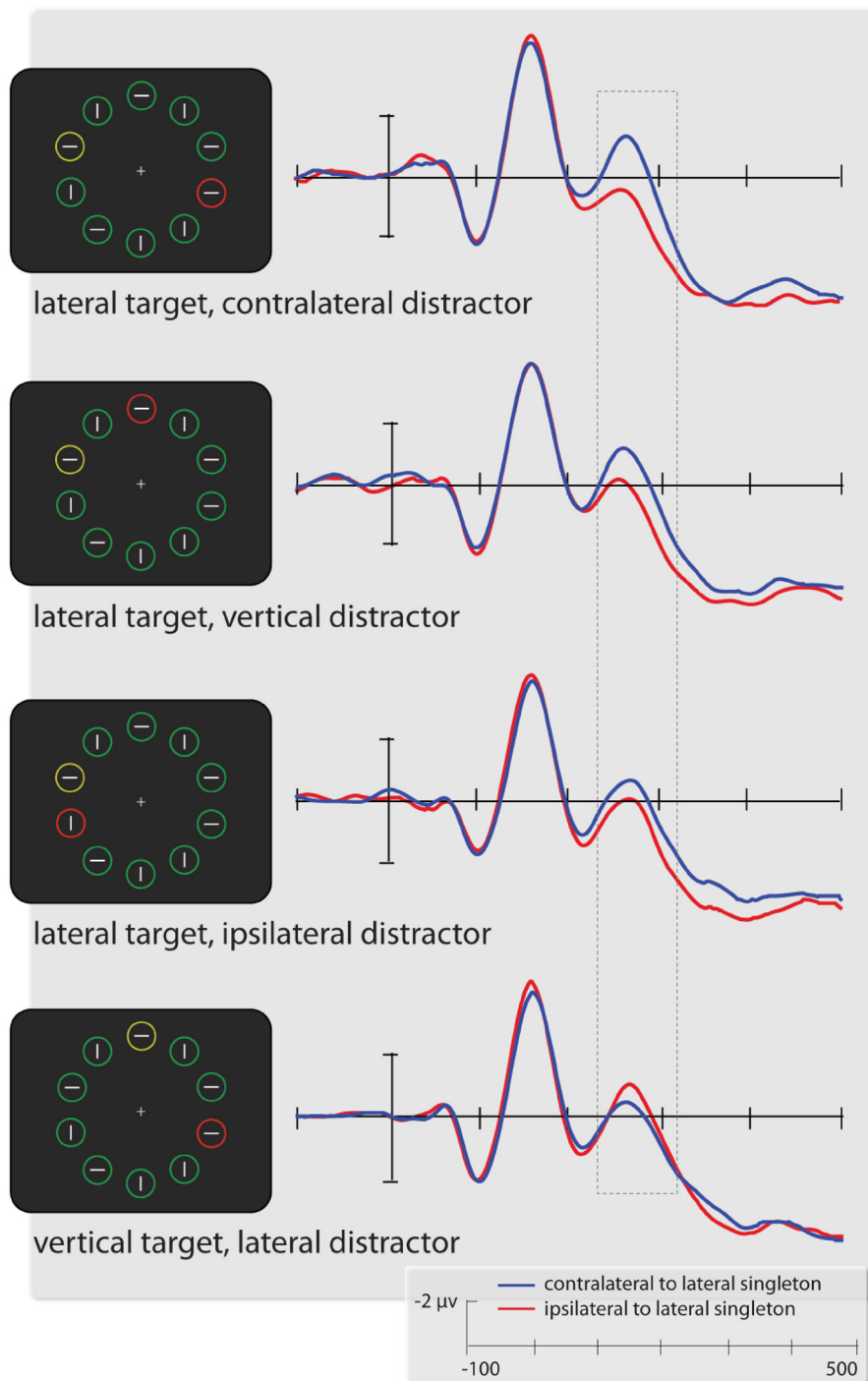
<b>Distance of target from distractor</b>	<b>RT</b>
Distance 1	661.3
Distance 2	634.5
Distance 3	620.5
Distance 4	613.5
Distance 5	605.7

### *Electrophysiological Results*

Figure 1 presents grand-averaged ERPs from lateral-occipital electrodes for the distractor-present display configurations of primary interest. These ERP waveforms consisted of a series of positive and negative-going peaks oscillating at approximately 10Hz, including prominent P1 (100 msec), N1 (160 msec), P2 (220 msec), and N2 (270 msec) components. The contralateral and ipsilateral waveforms largely overlapped one another in the time range of the P1 and N1 components but began to diverge thereafter. The ERPs associated with each lateral-target configuration (top three plots) contained an N2pc component. Namely, the ERP was more negative contralateral to the target

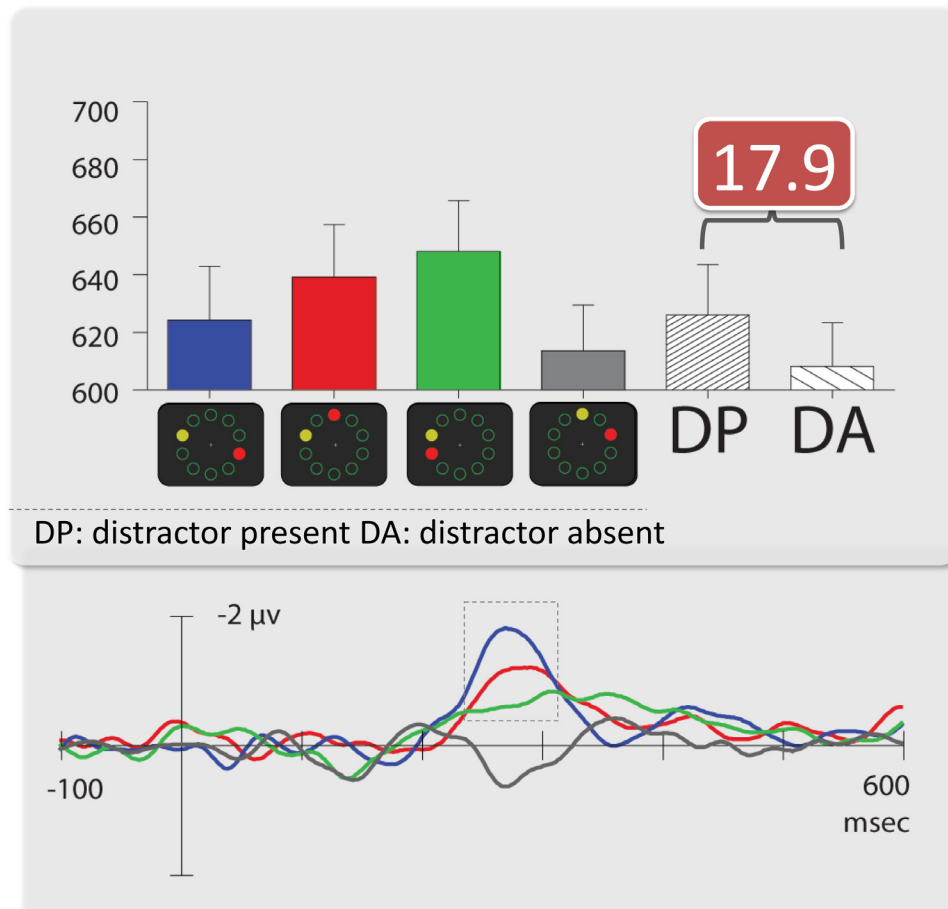


than ipsilateral to the target, starting at approximately 200 msec and peaking at approximately 270 msec. The ERPs associated with the vertical target, lateral distractor configuration (bottom plot) contained not an N2pc but rather a  $P_D$  component: The ERP was more positive contralateral to the distractor than ipsilateral to the distractor approximately 250–290 msec after display onset. A repeated-measures ANOVA with a single factor for electrode location (contralateral vs. ipsilateral, relative to the target location) was performed for each display configuration. The mean N2pc amplitudes for lateral target, contralateral distractor [ $F(1,15) = 33.5936, p < 0.001$ ], lateral target, vertical distractor [ $F(1,15) = 23.1361, p < 0.001$ ], lateral target, ipsilateral distractor [ $F(1,15) = 8.3232, p = 0.011$ ], and lateral target, no distractor [ $F(1,15) = 71.7240, p < 0.001$ ] were all found to be statistically significant within a window of 250 to 290 msec. The mean  $P_D$  amplitude for the vertical target, lateral distractor display configuration was also statistically significant in this time range [ $F(1,15) = 8.5790, p = 0.010$ ].



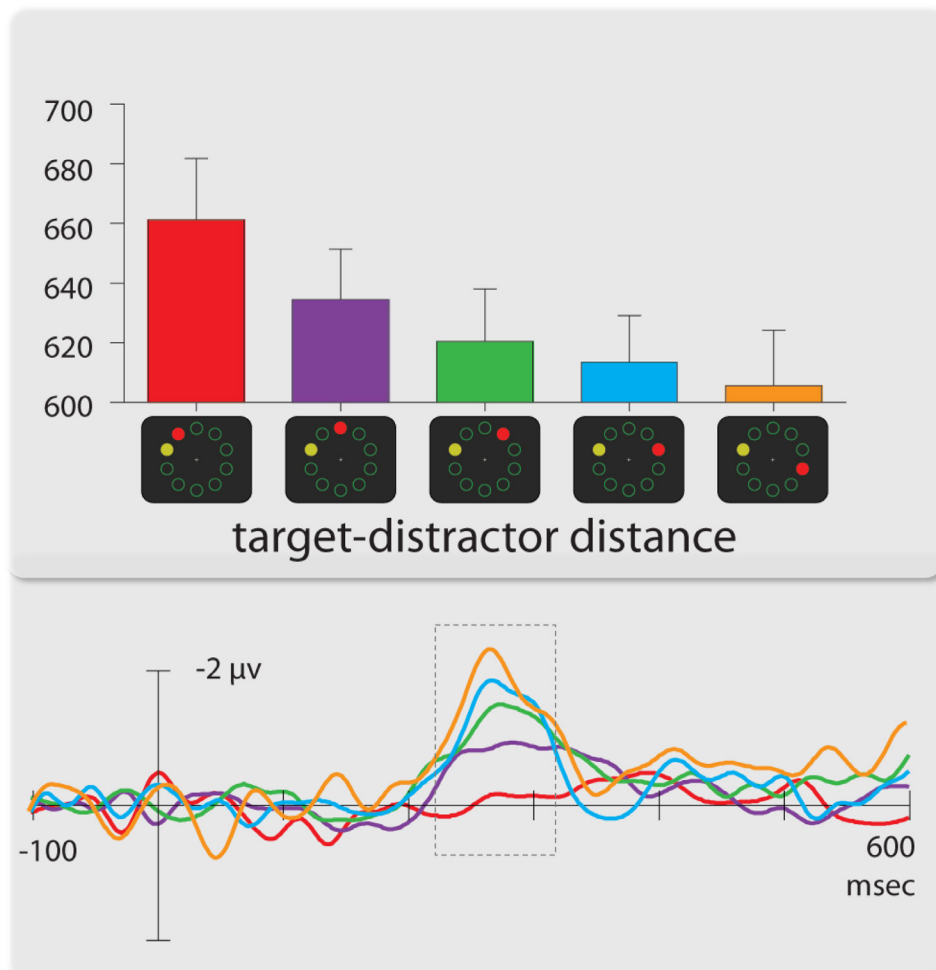
**Figure 3.** *Grand-averaged ERPs elicited in Experiment 1 for the display configurations of interest. ERPs were recorded at lateral occipital electrode sites A10 and B7 (Biosemi nomenclature), which roughly correspond to P07 and P08. Note that negative is plotted upward, and that stimulus onset occurred at 0 msec.*

Figure 2 presents difference waveforms created by subtracting the ipsilateral ERPs from the corresponding contralateral ERPs, along with the mean RTs for the primary display configurations. Here, the N2pc can be seen as an upward (negative) peak, whereas the P<sub>D</sub> can be seen as a downward (positive) peak. A repeated-measures ANOVA revealed amplitudes of the N2pc peaks differed across the three lateral-target configurations in the 250–290 msec time range [ $F(2, 15) = 16.01, p < 0.001$ ].



**Figure 4.** (a) Mean correct response times (msec) with standard error of the mean (SEM) in Experiment 1 for the display configurations of interest. The mean of the medians of all distractor present (DP) and all distractor absent (DA) display configurations are also presented. (b) Contralateral-minus-ipsilateral difference waves for the N2pc based on the display configurations of interest. Colours of the ERP waveforms correspond to the colours presented in the bar graph.

To examine whether the target-distractor proximity influenced the N2pc, contralateral-ipsilateral difference waveforms were computed for each of the five possible distances. Figure 3 shows the resulting waveforms along with the corresponding RTs. The results of a repeated-measures ANOVA with a single factor for Proximity (five levels) showed that the N2pc amplitude varied significantly as a function of target-distractor proximity [ $F(4, 12) = 7.766, p = < 0.001$ ].



**Figure 5.** *Proximity analysis for target-distractor distance. (a) Mean correct response times (msec) with SEM in Experiment 1 for the proximity analysis. (b) Contralateral-minus-ipsilateral difference waves for the display configurations of interest. Colours of the ERP waveforms correspond to the colours presented in the bar graph.*

## Experiment 1 Discussion

Recent research has demonstrated that salient-but-irrelevant distractors do not capture attention when the target and distractor are defined along different feature dimensions (cross-dimensional search; Jannati et al, in preparation; Schubo, 2009). Experiment 1 was designed to determine whether a salient-but-irrelevant colour singleton would capture attention automatically when observers were required to search for another, less salient colour singleton. As shown in Table 1, RT interference was on average greater when the distractor was present versus when the distractor was absent (18 msec). Dissected further, participants were fastest responding to distractor-present trials when the distractor was contralateral to the target (624 msec), followed by when the distractor appeared along the midline (639 msec), and slowest when the target and distractor appeared in the same hemifield (648 msec).

The inter-trial analysis sought to examine whether the previous location of the target or distractor had any carry-over effect for locating the target on the subsequent distractor-present trial. Previous research has shown that RTs can be affected by the stimulus properties of the previous display (Kumada & Humphreys, 2002; Found & Muller, 1996; Maljkovic & Nakayama, 1996; Treisman, 1988). RTs were significantly faster (27 msec) when the target appeared in the same location across consecutive trials, relative to the average distractor-present RTs. This inter-trial repeat benefit is similar to the positive priming originally described by Maljkovic and Nakayama (1996) and has also been reported by Kumada and Humphreys (2002) using a fixed target, cross-dimensional, compound search.

While there was a small 7 msec RT cost associated with the distractor appearing in the location that was previously occupied by the target (T-D), this difference was not statistically significant. However, when the target appeared in the location previously occupied by the distractor (D-T), there was a significant 30-msec increase in RT inference. Negative priming at the location formerly occupied by a singleton distractor has been shown in a number of previous studies (Kumada & Humphreys, 2002; Watson & Humphreys, 2000; Kim & Cave, 1999; Klein, 1988). Negative priming supports the notion of the carryover of suppression or inhibition at a distractor location across trials, and

compliments the presence of the  $P_D$  seen in the electrophysiological findings (see below for further explanation).

ERPs showed significant N2pc components to all lateral target conditions, and no evidence of N2pc components to any of the distractor singletons (see Figure 1). This is consistent with the hypothesis that salience-driven capture did not occur and provides converging evidence that no distractor N2pc is elicited when features of the target and distractor remain fixed throughout an entire experimental block (Janatti, Gaspar, & McDonald, in preparation; McDonald et al., in preparation; Schubo, 2009).

Displays containing a vertical target and lateral distractor have been used to better isolate lateralized ERP components associated with the distractor (cf. Hickey et al., 2006, 2010; Hillmire et al., 2011; Woodman & Luck, 2003). Here, the lateral distractor did not elicit an N2pc, but rather a significant  $P_D$  component with a similar temporal profile to that of the N2pc (peaking at ~270 msec). The  $P_D$  is a positive-going voltage over occipito-temporal electrode sites observed contralateral to the to-be-ignored item. Hickey, Di Lollo, and McDonald (2009) first showed a  $P_D$  to an inconspicuous distractor when participants were asked to discriminate the identity of a target singleton on the vertical meridian. They hypothesized the presence of the  $P_D$  likely served as an index of distractor suppression. Recent studies have reported similar findings (e.g. Jannati, Gaspar, & McDonald, in preparation; Sawaki & Luck, 2010; 2011, Kiss & Eimer, 2010; Hillmire, Mounts, Parks & Corballis, 2009; Eimer & Kiss, 2008).

The amplitude of the N2pc components varied across the lateral-target display configurations (see Figure 2b), with the lateral target, contralateral distractor condition eliciting the largest N2pc ( $-1.72 \mu\text{v}$ ), followed by the lateral target, vertical distractor condition ( $-1.12 \mu\text{v}$ ). The N2pc was smallest ( $-0.61 \mu\text{v}$ ) when the target and distractor appeared in the same hemifield (lateral target, ipsilateral distractor). This, coupled with the pattern of RTs for these display configurations, suggested that participants performed the task fastest and had the largest N2pc when the distractor singleton appeared furthest from the target.

To further test this hypothesis, a proximity analysis was created to assess RTs and the amplitude of the N2pc relative to the distance between the target and distractor.

With ten locations in the array, there was a maximal distance of five locations away that the distractor could fall with respect to the target. RTs for the proximity analysis showed a linear decrease. Specifically, RTs were longest when the distractor was immediately adjacent to the target, decreasing as the distractor moved further away (Figure 4). Trials where the distractor appeared furthest from the target (606 msec) showed no interference relative to trials where the distractor was altogether absent (608 msec). This pattern of results is inconsistent with the notion of attentional capture – if attention was deployed automatically to the more salient distractor before it could be reoriented to the target, one would expect RT interference to be greatest when the target and distractor were farthest away.

RT inference in Experiment 1 was overall larger than has been reported in recent fixed-feature variants of the additional singleton paradigm where the target and distractor were defined along different feature dimensions (8 msec: Janatti, Gaspar & McDonald, in preparation; 9 msec: Schubo, 2009). Moreover, whereas the distractor elicited a  $P_D$  component in the present within dimension search experiment, no such  $P_D$  was found in either of the aforementioned studies. This difference is consistent with the hypothesis that dimensional weighting alone can prevent salient distractors from interfering with search in the cross-dimension case but not in the within-dimension case; however, subtle differences in the experimental protocol between the studies require a proper control be run. Experiment 2 is identical to Experiment 1, with the sole exception that the target singleton is a green diamond instead of a yellow-green circle.

## Experiment 2

### Methods

All research and experimental protocol was reviewed and approved by the Research Ethics Board at Simon Fraser University.

#### *Participants*

Nineteen neurologically typical students from Simon Fraser University were recruited from an undergraduate research pool and gave their informed consent to participate for pay or course credit. From the data, four subjects were excluded due to excessive ocular artifacts in the electroencephalogram (EEG). Of the remaining 16 participants (10 women, age  $22.37 \pm 3.82$  years, mean  $\pm$  SD; 0 left-handed), all reported normal or normal-to-corrected visual acuity and were tested for typical colour vision using Ishihara colour test plates.

#### *Apparatus*

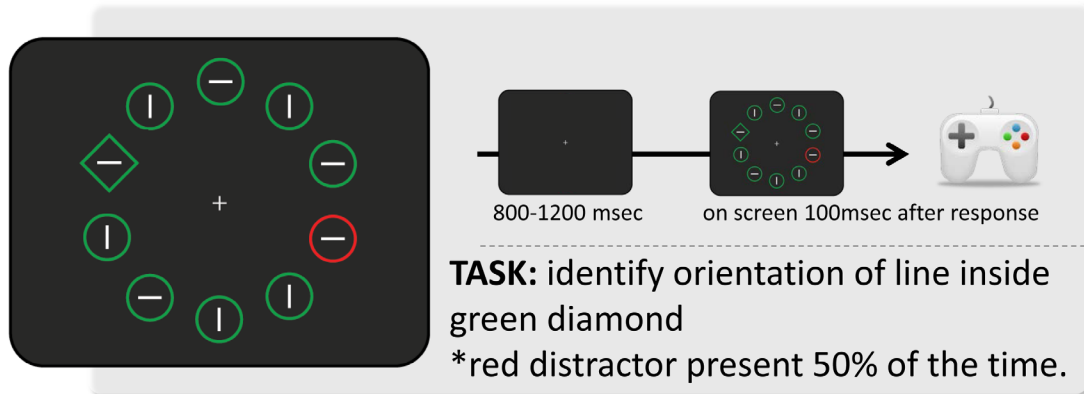
Apparatuses used were identical to those described in Experiment 1.

#### *Stimuli and procedure*

The visual search array was comprised of ten discrete shape stimuli presented equidistant ( $9.2^\circ$ ) from a central fixation point on a uniform black background (Figure 2). On every trial, the target colour singleton – an unfilled diamond ( $4.2^\circ \times 4.2^\circ$ ) with a thin ( $0.3^\circ$ ) green (RGB = 150, 150, 150) outline – appeared at one of the ten possible positions in the array. In 50% of the trials, a distractor colour singleton – an unfilled circle ( $1.7^\circ$  radius) with a thin ( $0.3^\circ$ ) red (RGB = 255, 0, 0) outline – also appeared in the array. The remainder of the array consisted of unfilled circles ( $1.7^\circ$  radius) with thin ( $0.3^\circ$ ) green



(RGB = 0, 160, 0) outlines. A gray line ( $0.3^\circ \times 1.5^\circ$ , RGB = 150, 150, 150) randomly oriented vertically or horizontally was contained within each of the stimuli.



**Figure 6.** Sample of distractor present trial in Experiment 2.

All other experimental procedures were identical to those in Experiment 1, the only difference being the target singleton. In Experiment 2, participants were instructed to identify the orientation of the gray line inside the green diamond as quickly as possible, without moving their eyes from the fixation point.

### *Electrophysiological recording*

All EEG recording methodologies were identical to those used in Experiment 1.

### *Data analysis*

All data analysis procedures used in Experiment 1 were also applied to Experiment 2.

## **Results**

### *Behavioural results*

8.35% of trials were excluded from the analysis because participants responded too slowly ( $RT < 1500$  msec; 2.01%), or incorrectly (6.34%). An additional 10.14% of correct trials were excluded due to eye movements, blinking, and amplifier-blocking artifacts in the EEG data. Of the remaining trials, median reaction times (RTs) and error

rate data were computed for each of the display configurations of interest in Experiment 1 (Table 1). Inter-participant means of median RTs were then derived for all distractor-present (645 msec) and distractor-absent (638 msec) display configurations. A repeated measures analysis of variance (ANOVA) for distractor presence (present vs. absent) as the sole factor found the 7-msec difference to be statistically significant [ $F(1,15) = 8.105$ ,  $p = 0.01$ ]. An analysis of error rates found participants produced fewer errors when the distractor was absent (6.32%) versus when the distractor was present (7.39%). The small 1.07% difference was also found to be statistically significant [ $F(1,15) = 6.594$ ,  $p = 0.02$ ]. These behavioural results closely replicate recent findings by Jannati, Gaspar, and McDonald (in preparation) using both the identical and target-distractor reversed paradigms.

**Table 4. Cross-dimension RTs**

Experimental Condition	RT	Error %
Lateral target, no distractor	645.7 (73)	7.0 (3.8)
Lateral target, contralateral distractor	646.3 (68)	7.7 (4.6)
Lateral target, vertical distractor	649.6 (69)	8.0 (3.6)
Lateral target, ipsilateral distractor	665.1 (71)	7.8 (4.5)
Vertical target, lateral distractor	633.8 (63)	6.4 (3.4)
Distractor present total	645.2 (66)	7.3 (3.7)
Distractor absent total	638.3 (70)	6.3 (3.2)

**Median correct response times (msec) with standard deviations and error rates (%) by experimental condition with standard deviations for experiment 2.**

Inter-trial RT carry-over effects were analyzed for the identical  $n-1$  events described in experiment 1. Table 5 presents median correct RTs (msec) for the three event conditions. These conditions were again compared against the distractor-present average (645 msec; see behavioural results). When the distractor appeared in the location previously occupied by the target (T-D) there was an additional cost of 15 msec which was significant [ $F(1,15) = 6.136$ ,  $p = 0.026$ ], whereas, when the target appeared in the location previously occupied by the distractor (D-T), there was an additional 9 msec

cost [ $F(1,15) = 1.0384$ ,  $p = 0.324$ ] which was not significant. There was a 34 msec facilitatory effect when the target repeated its location (T-T) [ $F(1,15) = 49.576$ ,  $p < 0.001$ ]. Table 5 visualizes median correct response times (msec) for the three conditions and displays RT cost for these conditions versus distractor present and distractor absent median RTs.

**Table 5.** *Cross-dimension n-1 RTs*

Experimental Condition	RT	RT – DP
Target then distractor (T-D)	660.2	15.0
Distractor then target (D-T)	654.6	9.4
Target then target (T-T)	610.4	-34.8

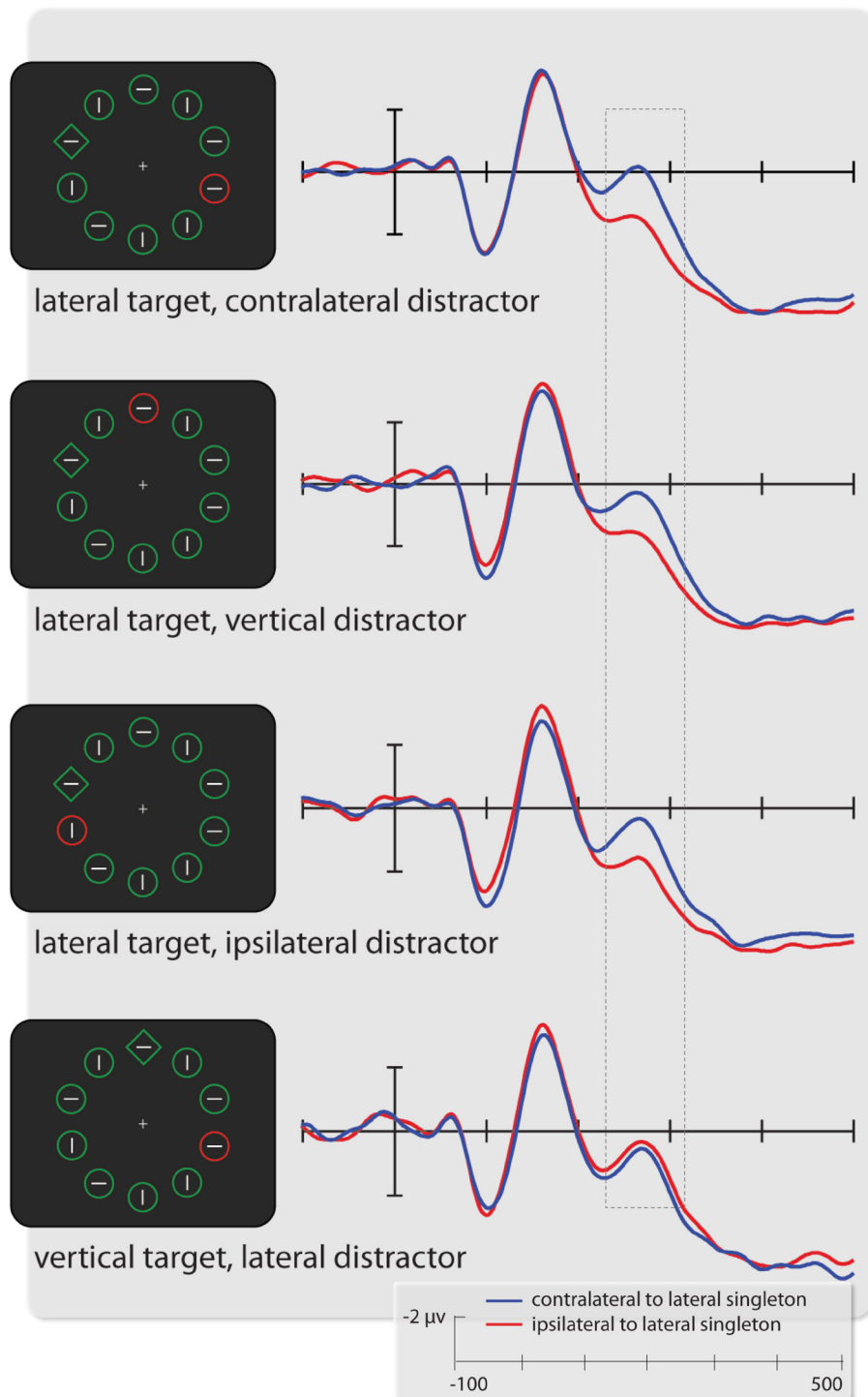
We again analyzed median RTs for the five possible target-distractor proximity conditions (see Table 6). As was the case in experiment 1, RTs here for the most part also decreased as the target moved further from the distractor in the array (see Table 6). A repeated measures analysis of variance (RANOVA) found a main effect of proximity to be statistically significant [ $F(4,48) = 9.149$ ,  $p < 0.0001$ ]. When the RT behavioural results of the furthest target-distractor proximity (Distance 5) were contrasted against the distractor absent (DA) condition, there was no significant difference ( $F(1,15) = 1.13179$ ,  $p = 0.2690$ ).

**Table 6.** *Cross-dimension proximity analysis RTs*

Distance of target from distractor	RT
Distance 1	665.5
Distance 2	649.7
Distance 3	641.8
Distance 4	643.6
Distance 5	633.1

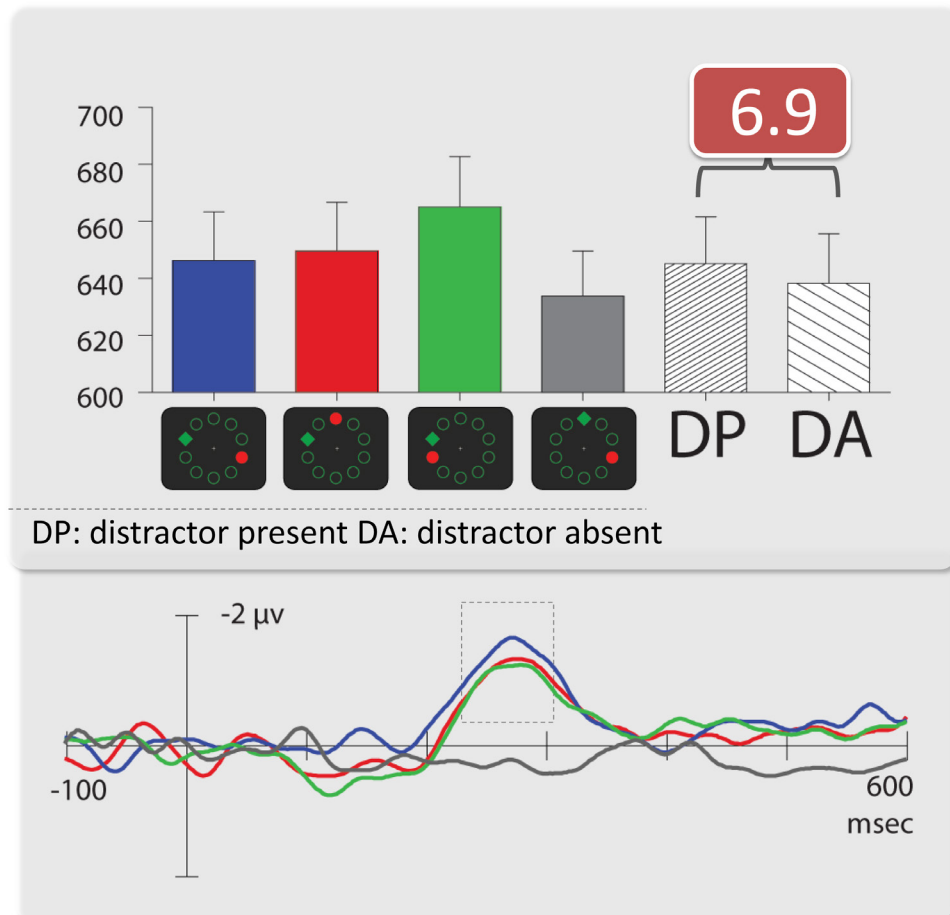
## *Electrophysiological Results*

Figure 6 presents grand-averaged ERPs from lateral-occipital electrodes for the distractor-present display configurations of primary interest. These ERP waveforms consisted of a series of positive and negative-going peaks oscillating at approximately 10Hz, including prominent P1 (100 msec), N1 (160 msec), P2 (220 msec), and N2 (270 msec) components. The contralateral and ipsilateral waveforms largely overlapped one another in the time range of the P1 and N1 components but began to diverge thereafter. As was seen in experiment 1, ERPs associated with each lateral-target configuration (top three plots) contained an N2pc component. The ERPs associated with the vertical target, lateral distractor configuration (bottom plot) contained a  $P_D$  component. Here the  $P_D$  component appears smaller than that observed in experiment 1 but was sustained for a longer period of time, approximately 200–340 msec after display onset. A repeated measures ANOVA with a single factor for electrode location (contralateral vs. ipsilateral, relative to the target location) was calculated for each display configuration: mean amplitudes for lateral target, contralateral distractor [ $F(1,15) = 29.691$ ,  $p < 0.001$ ], lateral target, vertical distractor [ $F(1,15) = 22.544$ ,  $p < 0.001$ ], lateral target, ipsilateral distractor [ $F(1,15) = 17.322$ ,  $p < 0.001$ ], and lateral target, no distractor [ $F(1,15) = 26.523$ ,  $p < 0.001$ ] were all found to be statistically significant within a window of 250 to 290 msec. The mean amplitude of  $P_D$  component was also found to be statistically significant within the same window [ $F(1,15) = 5.770$ ,  $p = 0.030$ ].



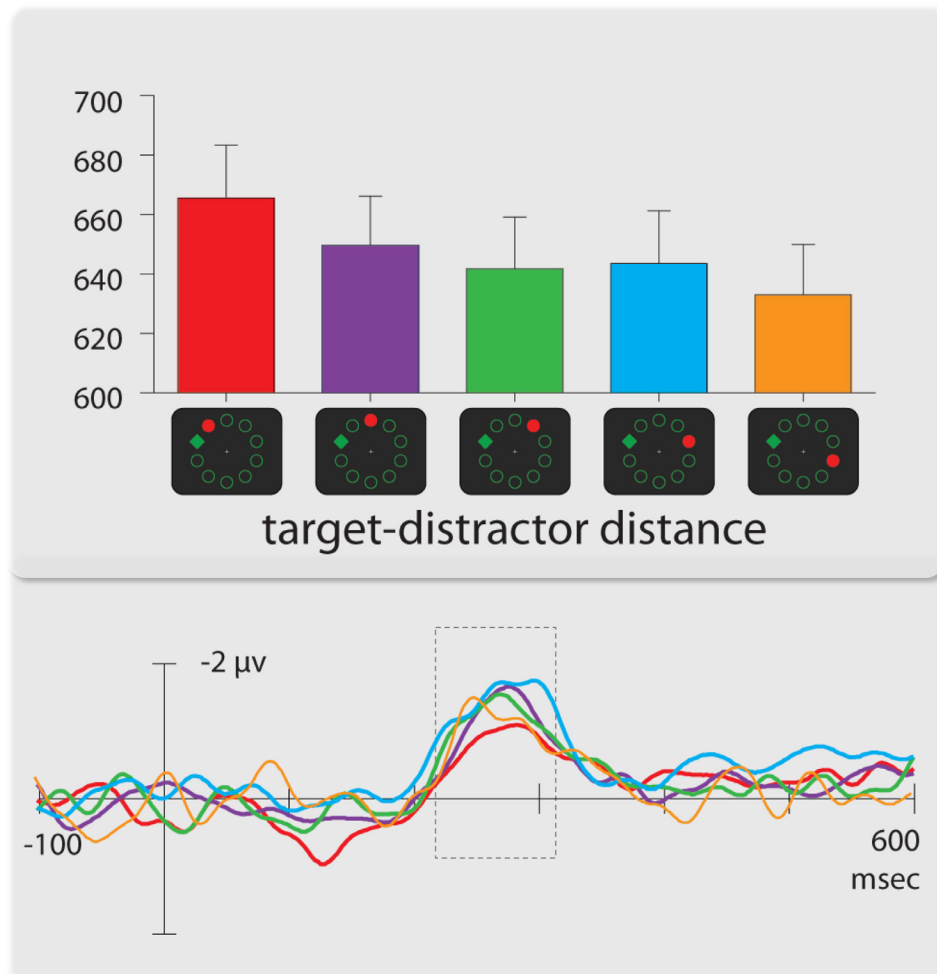
**Figure 7.** *Grand-averaged ERPs elicited in Experiment 2 for the display configurations of interest. ERPs are shown using the same display parameters used in Experiment 1.*

Figure 7 presents difference waveforms created by subtracting the ipsilateral ERPs from the corresponding contralateral ERPs, along with the mean RTs for the primary display configurations. Here, the N2pc can be seen as an upward (negative) peak, whereas the P<sub>D</sub> can be seen as a downward (positive) peak. The results of a repeated-measures ANOVA showed that the amplitudes of the N2pc peaks did not differ across the three lateral-target configurations in the 250–290 msec time range [ $F(2, 15) = 2.494, p = 0.10$ ].



**Figure 8.** (a) Mean correct response times (msec) with SEM in Experiment 2 for the display configurations of interest. The mean of the medians of all distractor present (DP) and all distractor absent (DA) display configurations are also presented. (b) Contralateral-minus-ipsilateral difference waves for the display configurations of interest. Colours of the ERP waveforms correspond to the colours presented in the bar graph (Figure 5a).

To examine whether the target-distractor proximity influenced the N2pc, contralateral-ipsilateral difference waveforms were computed for each of the five possible distances. Figure 8 shows the resulting waveforms along with the corresponding RTs. The results of a repeated-measures ANOVA with a single factor for Proximity (five levels) showed that the N2pc amplitude did not vary as a function of target-distractor proximity [ $F(4, 12) = 1.076, p = 0.376$ ].



**Figure 9.** *Proximity analysis for target-distractor distance. (a) Median correct response times (msec) with SEM in Experiment 2 for the proximity analysis. (b) Contralateral-minus-ipsilateral difference waves for the N2pc based on the all display proximity conditions. Colours of the ERP waveforms correspond to the colours presented in the bar graph (Figure 6a).*

## Experiment 2 Discussion

Experiment 2 was designed to determine whether a salient-but-irrelevant colour singleton would capture attention automatically when observers were required to search for another, less salient shape singleton. As shown in Table 4, RT interference was on average greater when the target was presented concurrently with a more salient distractor singleton versus when the distractor singleton was absent (7 msec). When parsed into their respective conditions, RTs adhered to the same basic pattern as they observed in Experiment 1: participants were fastest to respond to distractor-present trials when the distractor was contralateral to the target (646 msec), followed by when the distractor appeared along the midline (650 msec), and slowest when the target and distractor appeared in the same hemifield (665 msec).

RTs were significantly faster when the target appeared in the same location across consecutive trials. The value here (34 msec) is similar to those obtained by Kumada and Humphreys (2002), who reported between 26 and 31 msec of positive priming on distractor present, T-T trials using a similar cross-dimensional, fixed target paradigm. Of particular interest, the pattern of negative priming in the cross-dimensional experiment was the opposite of that observed in Experiment 1. Participants experienced greater interference if the distractor was presented at the location previously occupied by the target (T-D), but did not experience any significant RT interference when the target appeared in the location previously occupied by the distractor (D-T). In essence, it would appear that the previous location of the target was carried over from trial  $n-1$ , producing greater interference when the distractor then occupied that location. This is arguably indicative of a different search strategy utilized in the cross- versus the within-dimensional fixed search (see general discussion).

As in Experiment 1, a highly significant N2pc component was observed in the grand-averaged ERPs to all lateral target conditions, whereas there was no evidence of an N2pc to any of the distractor singletons (see: Figure 7). This is consistent with the



hypothesis that salience-driven capture did not occur. Once again, the vertical target, lateral distractor condition elicited a significant  $P_D$  component. Although the amplitude of the  $P_D$  was nearly half the amplitude in the within-dimension condition ( $0.49 \mu\text{v}$  versus  $0.26 \mu\text{v}$ ), the difference across experiments was not significant [ $t(30) = 1.131$ ,  $p = 0.2671$ ]. Recently, Janatti, Gaspar, and McDonald (in preparation) reversed the target and distractor dimensions, keeping the distractor as the most salient item in the array. While RT interference was near identical ( $8.5 \text{ msec}$ ), no  $P_D$  to the distractor was observed. Further research is required to ascertain the reason for the presence of the  $P_D$  component here and not in the other study.

Unlike the pattern of results observed in Experiment 1, the amplitude of the N2pc components did not significantly vary across the lateral-target display configurations (see Figure 7). The basic behavioural pattern of RT speed across the various display conditions did persist in Experiment 2; however, with smaller differences across the display configurations. Slow responses still elicited smaller N2pc components and fast responses still elicited larger N2pc components.

The proximity analysis (see: Experiment 1) was again applied to see if there was any pattern in RTs and N2pc amplitudes in the cross-dimension condition. RTs for the proximity analysis showed a linear trend, decreasing the further the distractor appeared from the target; however, the differences across the distances were not as robust as they appeared in the within-dimension experiment. These results are complementary to those reported by Hickey and Theeuwes (2011), who conducted a similar proximity analysis using the same fixed paradigm. Their experiment, however, presents only trials where the distractor is always present. As was seen in Experiment 1, comparing distractor absent trial RTs ( $638 \text{ msec}$ ) to distractor at distance 5 RTs ( $633 \text{ msec}$ ) yields no difference in RT interference, and in turn, no evidence of attentional capture when the target and distractor appear furthest from one another.

## General Discussion

The goal of the present study was to examine brain electrical responses as participants performed a compound visual search task in which they had to discriminate a target when a more salient distractor resided within the same feature dimension (colour versus colour; Experiment 2) and across different feature dimensions (shape versus colour; Experiment 2). Using the additional singleton paradigm (Theeuwes, 1992), participants were presented with visual search arrays and were asked to identify the orientation of a line located within a particular target singleton, ignoring a distractor singleton that appeared 50% of the time. Electroencephalography was recorded while participants performed the task, and ERPs were subsequently derived for the various display configurations.

As predicted, there was overall greater RT interference in the within-dimension (18 msec) than in the cross-dimension experiment (7 msec). With respect to the former, our findings closely replicate Kumada's within-dimension additional singleton experiment (1999; Experiment 5), which showed an average of 21 msec interference across various set sizes for the more salient distractor. Experiment 2 sought to replicate the original additional singleton study conducted by Theeuwes (1992). The RT interference observed in the present experiment (7 msec) is lower than the 25 msec originally published by Theeuwes; however, serves to replicate the low behavioural interference costs that have recently been reported (8 msec: Janatti, Gaspar, & McDonald, in preparation; 9 msec: Schubo, 2009).

The N2pc – an enhanced negative-going voltage contralateral to the target stimulus at approximately 170 to 300 msec post onset of the display – was elicited to all lateral target singletons. The N2pc has been interpreted to reflect attentional suppression of unattended items (Luck & Hillyard, 1994a, 1994b; Woodman & Luck, 1999, 2003), the selective processing of an attended item (Eimer, 1995, 1996; Kiss, Van Velzen, & Eimer, 2008), or aggregate attentional mechanisms reflecting both of these

operations (Hickey, Di Lollo, & McDonald, 2009). Of interest, the amplitude of the N2pc significantly varied across trials in Experiment 1, appearing largest when the distractor appeared in the contralateral hemifield, relative to the target singleton, and smallest when both the target and distractor fell within the same hemifield. In Experiment 2, although minor changes in N2pc amplitude were observed (see: Figure 7), these differences were not significant. Schubö (2009), however, has reported amplitude differences in a similar fixed target-distractor singleton experiment, showing the N2pc to be largest when the target and distractor were ipsilateral and smallest when contralateral. While we do not observe this effect in our data (in fact, the only noticeable difference is a non-significant larger N2pc to a contralateral distractor, opposite to the pattern Schubö observed), there are differences between the studies. While array size differed across the studies (eight items in Schubö, 2009), perhaps the most notable difference is the presentation of the stimuli. While distractor-present and distractor-absent trials were interspersed across blocks in our study, Schubö had exclusive target-only and target-distractor blocks. As the expectancy of the distractor-present proportion of trials varies, research has shown (Kumada & Humphreys, 2002; Geyer, Müller, & Krummenacher, 2008) that distractor interference and search strategy can drastically change in a cross-dimensional additional singleton search. Further study is needed to address these discrepant results.

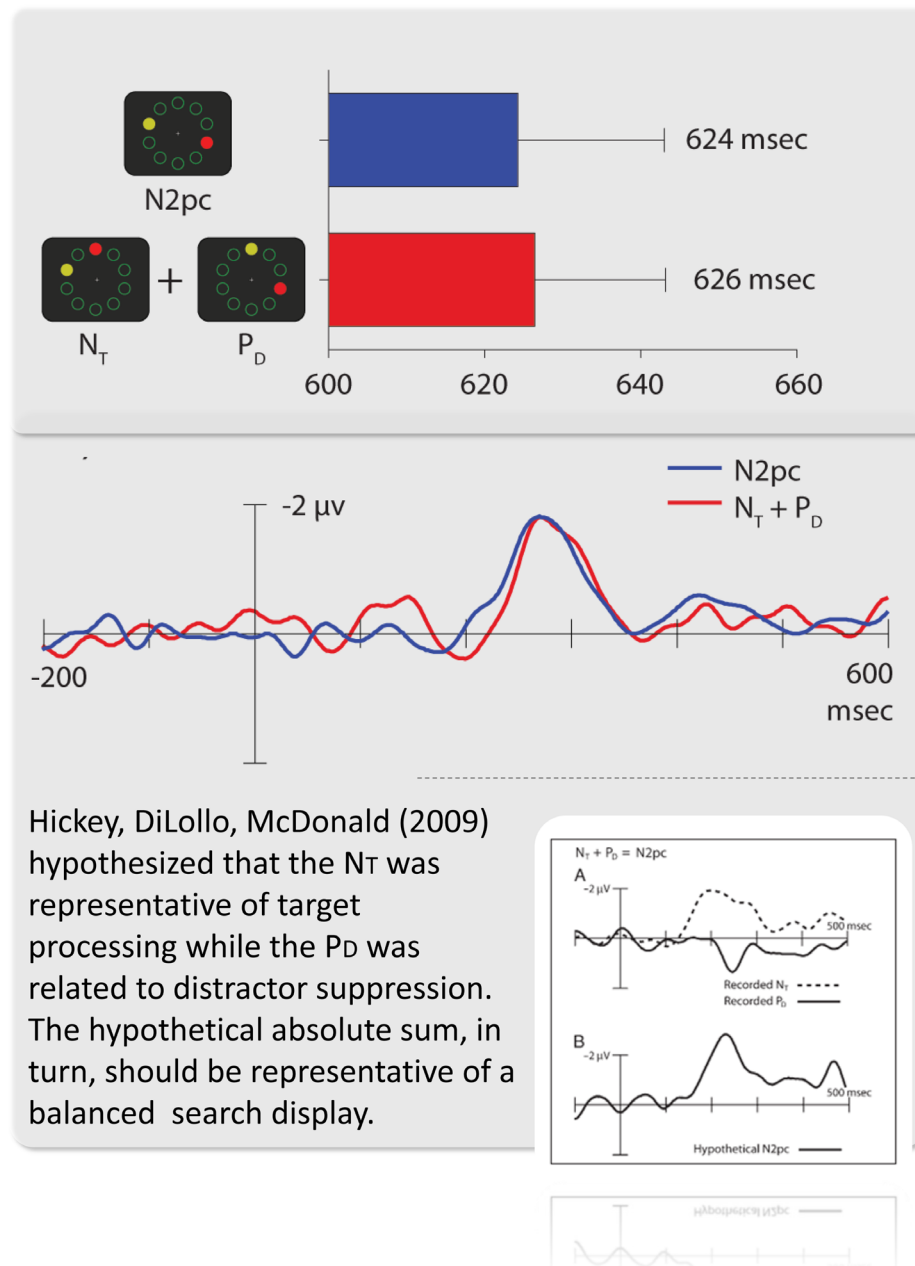
There was no evidence of an N2pc to any of the distractor singletons, demonstrating that observers do not automatically attend to the most salient item in the display. Several studies have now reported similar findings (e.g. Jannati, Gaspar, & McDonald, in preparation; Sawaki & Luck, 2010a, 2010b, Kiss, & Eimer, 2010; Hillmire, Mounts, Parks, & Corballis, 2009; Eimer & Kiss, 2008; Seiss, Kiss & Eimer, 2009). Despite this, Theeuwes has maintained that the absence of an N2pc in the fixed target-distractor search does not necessarily reflect the absence of capture since the N2pc does not represent an attentional shift but rather the post-selective processing of features at a specific location in space (see: Theeuwes 2010). Theeuwes contends that attentional processing at the location of the distractor occurs but its near instantaneous disengagement is insufficient to reveal the N2pc. Eimer and Kiss (2010) have vehemently refuted this interpretation, stating: “If there is no reason to assume that the N2pc is exclusively (or even primarily) linked to post-selective attentional processing,

there is no basis for arguing that the N2pc cannot be used to demonstrate the impact of top-down factors on the initial attentional selection of visual target objects” (p. 101).

Perhaps the most convincing argument to be made against the attentional capture hypothesis comes from the finding here that, when the proximity analysis was conducted for both experiments, there was no RT interference when the distractor was furthest from the target (see: Figure 5 for Experiment 1; Figure 9 for Experiment 2), versus when the distractor was all together absent. If capture of the most salient item (the distractor) must occur prior to its disengagement and redeployment to the target, one would expect that RT interference would in fact be greatest when the target and distractor were furthest in proximity. Instead the pattern is the complete opposite: interference was greatest when the target and distractor were closest in proximity (Experiment 1: 53.12 msec; Experiment 2: 27.28 msec) and completely absent when the distractor appeared furthest from the target (Experiment 1: -2.5 msec; Experiment 2: -5.19 msec). Rather than attentional capture, RT interference can be better explained in terms of ambiguity resolution (Luck, Girelli & McDermott, 1997). Ambiguity resolution theory proposes that when multiple objects fall within the same receptive field of a neuron, the coding of features can become ambiguous. In turn, the role of selective visual attention is to resolve this ambiguity, which is done so by suppressing inputs from unattended items. This would account for both the increased RT interference observed as the distractor nears the target, as well as the differences observed in the ERP analysis. When the target and distractor existed within the same feature dimension (Experiment 1) a large  $P_D$  component was elicited to a lateralized distractor. Here, this  $P_D$  component appears to represent the spatial suppression of the salient within-dimension distractor. As the distractor (and in turn the  $P_D$  it elicits) nears the target (and the N2pc it elicits), the positive voltage of the  $P_D$  summates with the negative voltage of the N2pc. Since the N2pc is the dominant, larger component, its amplitude is directly and linearly lessened as the distractor nears in proximity and amalgamates with the  $P_D$ . Furthermore, this change in amplitude is accompanied by a linear increase in performance: the further away the distractor is, the larger the N2pc is, and the faster a subject is to report a correct response (See: Figure 4).

The presence of proximity ERP differences support the notion that the N2pc reflects attentional mechanisms relating to both the location of the target and the

suppression of the distractor. Luck et al. (1997) proposed a theory to account for the ostensible relationship between the N2pc and distractor-suppression. The *Ambiguity Resolution Theory* proposes that the suppression of unattended items is necessary for the successful and efficient coding of attended objects in the visual field. As receptive fields in the visual cortex are organized as a hierarchical structure, neurons at higher-level visual areas with larger receptive fields code for more complex stimuli (Desimone & Ungerleider, 1989). As the target and distractor near one another, they fall into the same receptive field, and ambiguities in the perceptual representation of object features can occur. Attentional mechanisms are then necessary to solve this inherent ambiguity between the attended and unattended stimuli by suppressing the inputs of to-be-ignored stimuli. Luck and colleagues took the N2pc to be an index of this attentional suppression, since the presence of distractors was necessary to elicit an N2pc (Luck & Hillyard, 1994b). However, Hickey, DiLollo, and McDonald (2009) have proposed that attentional mechanisms required for selection may instead rely on both target representations as well as distractor representations. They argued that the N2pc in a balanced array could rather characterize an aggregate of distinct mechanisms indexing the enhancement of target processing ( $N_T$ ) and distractor suppression ( $P_D$ ). By parsing the N2pc into its respective  $N_T$  and  $P_D$  components, they hypothesized that the absolute algebraic sum of these two components would equal the balanced N2pc array. Figure 10 offers the first empirical evidence in support of this proposition. Here, the averaged N2pc difference waves of the  $N_T$  and the flipped  $P_D$  are added together to derive the absolute sum. Plotted against the lateral target, contralateral distractor configuration N2pc, the components overlap sharing near identical amplitudes (-1.62 versus -1.72) and peak latencies (~280 msec). A repeated measures ANOVA found no significant difference between the  $N_T + P_D$  versus the N2pc difference waves [ $F(1, 15) = 0.121$ ,  $p = 0.733$ ]. When RTs for the averaged N2pc difference wave are compared, differences in RT interference can also be accounted for within 2 msec.



**Figure 10.** *Comparison of hypothetical N2pc and observed N2pc for Experiment 2. (Top) Mean correct RT (msec) with SEM for the lateral target, contralateral distractor display (associated with the N2pc) and the average of the mean RTs for the lateral target, vertical distractor display (associated with the N<sub>T</sub>) and the vertical target, lateral distractor display (associated with the P<sub>D</sub>). (Bottom) Contralateral-minus-ipsilateral difference waves for the N2pc and the algebraic sum of the N<sub>T</sub> and P<sub>D</sub> using the displays described above.*

In Experiment 2, a small yet significant  $P_D$  was also elicited; however, significant differences in the amplitude of the N2pc were not observed. This may, in turn, suggest that the more salient distractor, when it resides in a feature dimension different from that of the target, requires less direct suppression for efficient search. This difference in search strategy is perhaps best exemplified by the pattern of negative priming observed in the cross-dimensional experiment (Experiment 2). In visual search, the greater the weight assigned to the to-be-attended target dimension, the more rapid the observer will orient to this target; however, both negative and positive position priming can occur across successive trials (Found & Müller, 1996). As such, previous ( $n-1$ ) trials can be used to assess the costs and benefits of carry-over effects and, in turn, determine whether the search strategy used by the observer involves target enhancement, distractor suppression, or both. When the distractor appeared in the location previously occupied by the target (T-D), there was a significant increase in RT interference, whereas, when the target appeared in the location previously occupied by the distractor (D-T), there was no significant RT interference. This pattern of cross-over effects suggests that participants were tracking the location of the target but not the distractor in the cross-dimension search task (Experiment 2). These findings are the opposite of what was observed in the within-dimension experiment: no significant cost for condition T-D and a significant cost for condition D-T. In the within-dimension experiment, distractor suppression was seemingly paramount for efficient search and, in turn, the previous location of the distractor was carried over from trial to trial. However, it would appear that in the cross-dimension experiment the observer adopted a strategy wherein suppression was less necessary, and the presence of the distractor, less detrimental to efficient search. Rather, carry-over for the location of the target impaired performance when the distractor appeared at this location. It is possible that on trials where this negative T-D priming is occurring, the distractor singleton may elicit an N2pc.

Based on the paradigm used here, there are unfortunately insufficient trials to assess the presence of an N2pc component. Further research may elucidate this proposal. Worth noting, while negative priming for targets subsequently presented at the location of distractors has been previously reported (Kim & Cave, 1999; Klein, 1988; Kumada & Humphreys, 2002; Watson & Humphrey, 2000), this is the first known

evidence for negative priming for distractors subsequently presented at the location of targets.

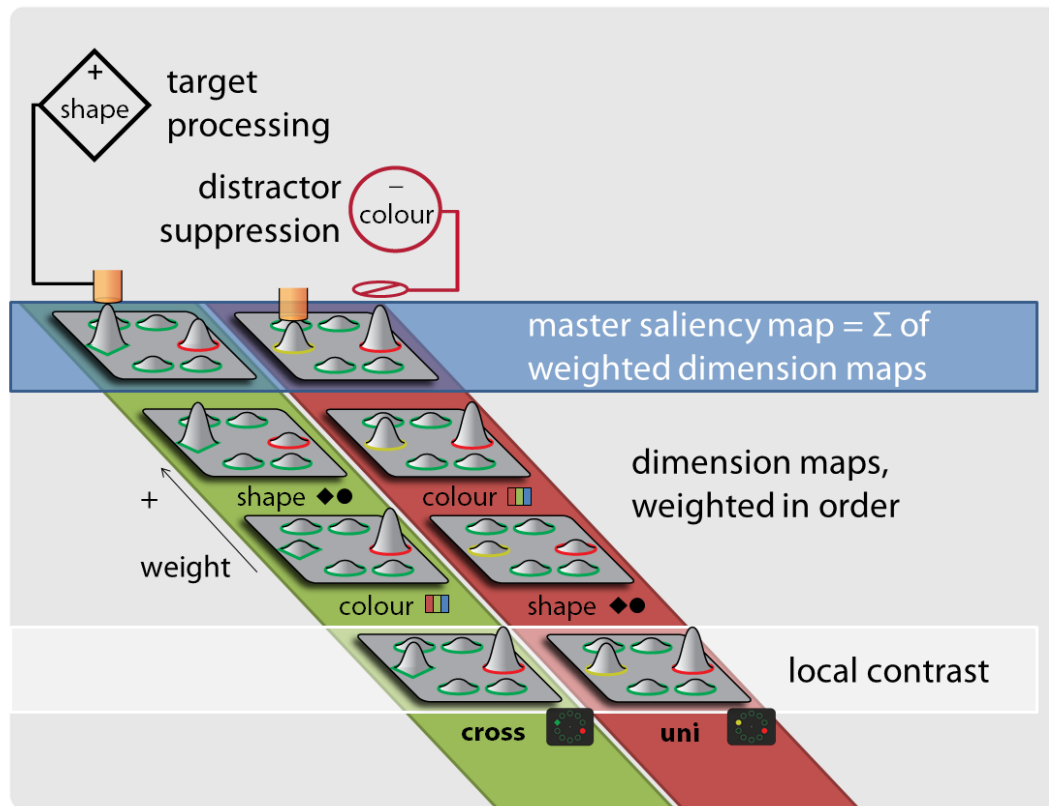
Overall, the present results can be interpreted in the context of the dimensional weighting account (DWA, e.g., Müller, Heller & Zeigler, 1995; Found & Müller, 1996). DWA assumes that observers can adjust the weight assigned to a given dimension by up-modulating the weight for the target dimension and/or down-modulating the weight for the distractor dimension. This modulation would enhance the saliency signal produced by the target at the master map level, while attenuating the signal generated by the distractor, resulting in the target being the most likely object to win the competition for attention. In the present experiments, over successive trials, a target resides in the same, unique feature dimension, and observers can set a dimensional weight based on the target singleton; however, this only offers a benefit to search in Experiment 2. In the cross-dimension experiment, up-weighting of the relevant feature dimension allows for the *pop-out* of the to-be-attended target. In the within-dimension experiment, since the *colour* dimension map is the more heavily weighted, both target and distractor *pop-out*. Since these maps are thought to simply be a basic salience calculation and carry no information pertaining to specific target features, subsequent attentional processing must occur in order to successfully identify the target. In turn, it takes longer to successfully orient to a target competing with a distractor in the same feature dimension. Therefore, the increased interference comes from the competition of the initial salience calculation on the dimensional salience map.

Based on a culmination of the aforementioned findings, Figure 11 presents our model of visual selection based on dimensional weighting, neural ambiguity resolution, and attentional capture and distractor inhibition. The visual search arrays used in the current experiments required observers to identify a target, while ignoring a distractor singleton. From a local-contrast standpoint, the distractor singleton was always the most salient item in the search array. If the initial attentional selection is determined solely by physical salience, we should expect local contrast to be sufficient for the capture and deployment of attention across every trial. The data presented here, however, do not support this supposition. Instead, we propose that at a pre-attentive perceptual stage of processing, feature dimensions relevant to the goal-driven task are up-weighted (while irrelevant dimensions may be down-weighted). The salience of each item is ultimately



computed across all such features on a 2-dimensional topographical saliency map of the entire visual field. Importantly, while this pre-attentive stage can motivate an attentional orienting response, it contains no precise feature or dimension information.

In the case of the cross-dimension search experiment, shape is the up-weighted feature dimension. As such, activation on the master saliency map results in peak activation for the location of the shape singleton. This is sufficient for rapid processing of the target stimulus. Once attention has been oriented to the target location, focal attention then allows for the identification of the line inside the singleton. In the within-dimension experiment, colour is the up-weighted dimension; however, both the target and distractor reside in this feature dimension. As a result, dimensional weighting does not ultimately lead to the selection of the target, as the relevant target singleton cannot be up-weighted any more so than the irrelevant distractor. The distractor singleton, which had the higher local contrast, remains the most salient item in the array. As a result, it is proposed that responses here would require subsequent processing of the irrelevant, to-be-ignored distractor in order for target to be efficiently processed. It is likely that the  $P_D$  reflects this processing, suppressing the location of the irrelevant yet salient distractor. Furthermore, as these peaks activations on the master saliency map near one another in proximity, target ambiguity begins to arise, slowing identification of the target. Seen in both experiments, participants were slower to respond to targets the closer the distractor appeared. Ambiguity resolution theory predicts this added interference. As the peak salience activations near one another in proximity, the more receptive fields overlap, and the more difficult it is to discern the location of the target from that of the distractor. This is further evidenced by the lack of RT interference observed when the target and distractor are furthest from one another.



**Figure 11.** *Model of visual attentional selection based on dimensional weighting of stimuli.*

In summary, the results reported here are not in compatible with the salience-driven capture hypothesis, as there is no evidence to support the involuntary orienting of attention to a salient-but-task-irrelevant distractor singleton. Distractor singletons did not elicit an N2pc in either experiment. Furthermore, RT interference, while small in general, is all together absent when the target and distractor appeared furthest from one another in the search array in both experiments. Rather, these results demonstrate that top-down control can bias attention in line with the behavioural goals the observer sets, making the contingent capture hypothesis the more viable alternative. Additionally, when dimensional weighting is not a viable selection strategy, suppression of the distractor location seems necessary for efficient search.

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