

**Revisiting the Automaticity of Reading:  
Electrophysiological Recordings Show that Stroop  
Words Capture Spatial Attention**

**by  
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## Abstract

Interference in the Stroop task is reduced when the word and color patch are placed at different locations and is diluted further by the presence of another distractor that is response-neutral. Such dilution indicates that reading is not independent of an observer's attentional focus and thus is not a fully automatic process. So where does reading fall on the automaticity continuum? To address this question, we sought to determine whether an irrelevant word that appears abruptly in the field of view invariably draws attention to its location or whether observers can successfully ignore it while identifying a centrally presented target. In two experiments, electrical brain activity was recorded while healthy young adults participated in nonintegrated Stroop tasks. Irrelevant color words appearing randomly to the left or right of a target shape elicited an event-related potential (ERP) component that reflects the spatial focusing of attention (posterior contralateral N2; N2pc). This N2pc was observed when participants discriminated the color of the target and when they discriminated the shape of the target. These findings demonstrate that color words reflexively capture spatial attention even when their meaning is unrelated to the task at hand. We conclude that although reading is not fully automatic, skilled readers cannot ignore words that appear abruptly in their field of view.

**Keywords:** Stroop; Automaticity; Attention Capture; Reading; Event-Related Potentials (ERPs); N2pc

## Dedication

I would like to dedicate my thesis to my Grandfather, Carman (Fudge Grampy) Smith.  
You will always be loved.



## **Acknowledgements**

I owe many thanks to my senior supervisor Dr. John J. McDonald for all of his guidance and feedback that were integral to the completion of this work, and for his apparently limitless patience and understanding. I would also like to thank my secondary supervisor Dr. Richard D. Wright for the many of the comments and advice given over the years. Sincere thanks also go to my fellow grad students in the Department of Psychology and to my lab mates in the Human Electrophysiology Lab at Simon Fraser University past and present: Daniel Tay, Jennifer Hoffmeister, David McIntyre, Victoria Carriquiriborde, Andrea Smit, Bert Sager, Evan Caldbick, Elisabeth Kreykenbohm, Ashley Livingstone, Greg Christie and John Gaspar for their support, assistance and collaboration. And finally, above all, I express my most sincere gratitude to my family and friends for their love and patience. I could not have done this without all of your support.

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## List of Acronyms

$\mu\text{V}$	Microvolt
A-to-D	Analog-to-Digital
AFC	Alternative-forced choice
Ag/AgCl	Silver/silver chloride
CA	California
Cm	Centimeter
DAQ	Data acquisition
DC	Direct current
EEG	Electroencephalography
EOG	Electrooculography
ERP	Event-related potential
G $\Omega$	Giga-ohm
HEOG	Horizontal Electrooculogram
Hz	Hertz
k $\Omega$	Kilo-ohm
LCD	Liquid crystal display
LED	Light-emitting diode
LPD	Late positive deflection
ms	Millisecond
N1	First visual-evoked potential
N2pc	Posterior parietal N2
NSERC	Natural Sciences and Engineering Research Council of Canada
P1	First visual-evoked positivity
P <sub>D</sub>	Distractor positivity
RT	Reaction time
SFU	Simon Fraser University
SPCN	Sustained posterior contralateral positivity

# Chapter 1. Introduction

Human beings encounter innumerable situations in everyday life that demand their attention. People are able to allocate their attention to objects or actions of interest but they cannot attend to more than a small number of these objects or actions due to limitations in attentional and cognitive capacities (Shiffrin and Schneider, 1977). Fortunately, many cognitive and behavioral processes become automated with practice, thereby freeing up mental resources for tasks that require more attention and control. When we start to learn to ride a bike, for example, we must switch our attention between the actions required to operate the bicycle itself (e.g., balancing, pedaling and steering) and the objects in the surrounding environment. After continued practice, however, many of these individual actions and cognitive operations can be performed more effortlessly, requiring fewer attentional resources and less cognitive control. This shift from controlled processing to automatic processing allows human beings to perform many of the complex cognitive processes we encounter in everyday life, while effectively navigating an ever increasingly complex environment.

The defining characteristics for automaticity have been considered over the many decades since James (1890) pondered them. Although different researchers continue to focus on different criteria, there is a general consensus that automatic processes require no voluntary control or intention and are independent from the attentional state of the observer (Shiffrin and Schneider, 1977; Logan, 1978; Kahneman and Treisman, 1984). There is also agreement that automaticity is best conceived as a continuum rather than a strict dichotomy. The concept of an automaticity continuum enables characterization of processes that satisfy some criteria for automaticity but not all such criteria. In particular, several complex processes appear to be involuntary (that is, not require voluntary control) but still benefit from attention over inattention. Such processes are often considered to be *partially automatic* rather than fully automatic (Kahneman and Chajczyk, 1983, Kahneman and Treisman, 1984).

Findings from the Stroop paradigm indicate that reading may be one such partially automatic process. In the conventional Stroop color-word task, participants are slower to report the color of a word's lettering if that word spells a different color (incongruent trial; e.g., the word "**GREEN**" printed in red lettering) than if that word spells

the same color (congruent trial; e.g., “**GREEN**” printed in green lettering)(Stroop, 1935). This difference indicates that skilled readers process the meaning of the irrelevant word without any intention to do so. Accordingly, many researchers regarded reading as an automatic process because it appeared to satisfy the unintentionality criterion of automaticity (for review, see MacLeod, 1991). In the conventional Stroop task, however, participants are required to attend to the color word in order to identify the color of its lettering. Thus, although there may be no intention to read the word, paying attention to the word object may facilitate processing of all of its features, including word meaning, regardless of whether those features are relevant or not (Kahneman and Henik, 1981; Treisman, Kahneman, and Burkell, 1983).

A modified color-word task was developed to determine whether reading in the Stroop task was affected by the spatial allocation of attention (Kahneman and Chajczyk, 1983). This *nonintegrated* Stroop task involved two major modifications. First, the irrelevant color word (now printed in black lettering) and the to-be-identified colored stimulus (a horizontal bar) were separated and placed at different locations. Second, a response-neutral stimulus, such as a non-color word (e.g., **MOST**) or a string of Xs (e.g., **XXXX**) was added to the display on half of the trials. Participants were instructed to report the color of the bar, which appeared at a fixed location, and to ignore any and all words in the display. More time was required to name the color bar on incongruent-word trials than on congruent-word trials, although the magnitude of this interference was reduced compared to that observed in the regular Stroop task (121 ms in Experiment 1; vs. 202 ms in Kahneman and Henik, 1981, Experiment 2). More importantly, the addition of the neutral distractor reduced Stroop interference even further (by 46% with neutral-word distractors, and by 22% with neutral-XX distractors). The continued presence of Stroop interference indicates that fluent readers involuntarily read words presented outside the focus of their attention, but the dilution of the Stroop effect indicates that such involuntary reading is subject to interference.

To account for these findings, Kahneman and Chajczyk (1983) proposed that involuntary reading requires focused attention and that the magnitude of Stroop interference depends on how much attention is focused on the color word. By this account, Stroop interference is (1) maximal in the regular (integrated) color-word task because attention can be tightly focused on the word itself, (2) intermediate on single-word trials of the nonintegrated task, because the word often draws attention to its

location, and (3) smallest on additional-distractor trials of the nonintegrated task, because attention is sometimes captured by the response-neutral distractor rather than the color word. Accordingly, Kahneman and Chajczyk (1983) concluded that reading is only partially automatic because it fails to satisfy the attentional-independence criterion for automaticity. According to those researchers, “the finding of dilution implies that reading isolated words requires some attention, though not much of it. If reading were strongly automatic it would demand none at all” (p. 508).

The behavioral results from the nonintegrated Stroop task indicate that reading is not fully automatic, but beyond that, the strength of automaticity is unknown. It may be the case, for example, that skilled readers can largely ignore irrelevant words that are in the field of view but that any overlap with the response-relevant dimension causes them to capture attention contingently (Folk, Remington, and Johnston, 1992). In this case, reading would be seen as a weakly automatic process. In contrast, reading would be seen as a more strongly automatic process if a clearly visible word invariably captures an observer’s attention to its location. In other words, the degree of automaticity depends not only on whether attention is required for reading but also on the ability of a word to capture a reader’s attention.

Researchers have long debated whether the orienting of visual attention is automatically driven by stimulus salience or is under the control of the observer. The salience-driven selection hypothesis posits that attentional orienting is initially driven by stimulus salience and only later influenced by an observer’s intentions (Theeuwes, 1991a, 2010). According to this perspective, the most salient object within the visual region of interest will invariably draw attention to its location, irrespective of an observer’s goals. Other competing hypotheses are based on the idea that orienting is under top-down control associated with the intentions and experiences of the observer. For example, the contingent capture hypothesis (Folk et al., 1992) posits that salience-driven distraction can be prevented by selectively up-weighting features that are relevant to the current task. For example, if the task is to search for a blue square, features that are blue and/or square-like will be given a higher weight than those that are green and circular. Only those items that possess an up-weighted feature (blue or square-like) are predicted to capture attention. According to a related hypothesis, called the Dimensional Weighting Account (DWA), attentional upweighting is based on featural dimensions (e.g., color or orientation) rather than specific features within such dimensions (Found

and Müller, 1996; Liesefeld and Müller, 2019). More recently, researchers have hypothesized that salience-driven attention capture by can be prevented by actively suppressing salient stimuli (signal suppression hypothesis; Sawaki and Luck, 2013; Gaspelin and Luck 2018).

Behavioral and electrophysiological support for these latter top-down-control perspectives has been reported, first from a modified cuing paradigm (e.g., Eimer and Kiss, 2008; Folk et al., 1992) and more recently in the additional singleton paradigm (e.g., Gaspar and McDonald, 2014; Jannati et al., 2013). Much of the electrophysiological evidence comes from two event-related potential (ERP) components associated with attentional selection (the posterior contralateral N2, N2pc; Luck and Hillyard, 1994a, 1994b) or suppression (the distractor positivity, P<sub>D</sub>; Gaspar and McDonald, 2014; Hickey et al., 2009). Each of these components is maximal over the posterior scalp and is isolated by comparing voltages obtained at electrodes positioned contralateral or ipsilateral to some item in the display. The N2pc is elicited by task-relevant targets as well as to-be-ignored stimuli that resemble a target, whereas the P<sub>D</sub> is often elicited by salient nontargets that appear concurrently with a target. The weight of this ERP evidence indicates that observers reflexively orient their attention to objects that possess relevant features but that physically salient but irrelevant stimuli do not invariably capture attention unless they have some innate or learned salience (such as stimuli associated with financial reward; Anderson et al., 2011).

The present study was premised on the perspective that the degree of automaticity depends not only on whether attention is required for reading but also on the ability of a word to capture a reader's attention. In addition to measuring Stroop interference, the present study used ERPs to determine whether irrelevant color words reflexively capture spatial attention in a nonintegrated Stroop task. To provide a strong test of the automaticity of attention capture, we aimed to dilute the Stroop effect by presenting a response-neutral distractor (a string of Xs) concurrent with the color word and a separate to-be-attended color target. In Experiment 1, participants were instructed to discriminate the color of a central rectangle that was flanked by distractors to the left and right. One distractor was a color word, and the other was a string of Xs. We predicted that the color word would elicit an N2pc based on the behavioral findings from Kahneman and Chajczyk's (1983) study and on the related hypothesis that the color word captured attention on the majority of trials. In Experiment 2, the shape of the target

was varied orthogonally to its randomly changing color, and participants were instructed to discriminate the target's color or its shape in different blocks. Thus, in Experiment 2, the color word was response-relevant (congruent or incongruent) in the Report-Color condition but was response-neutral in the Report-Shape condition. If words capture attention automatically then the color word should elicit N2pc in both conditions of Experiment 2. By contrast, if words capture attention contingent upon some association with a task-relevant dimension, then the color would should elicit N2pc in the Report-Color condition but not in the Report-Shape condition.

## **Chapter 2. Experiment 1**

### **2.1. Method**

The Office of Research Ethics at Simon Fraser University (SFU) approved the research protocol for this study. All experimental procedures were performed in accordance with guidelines and regulations outlined by SFU and the Natural Sciences and Engineering Research Council of Canada (NSERC).

#### **2.1.1. Participants**

Thirty-six neurologically healthy volunteers participated after giving informed consent. All subjects reported normal or corrected-to-normal visual acuity and were tested for normal color vision using Ishihara color plates prior to participation. Data from eight participants were excluded from further analyses because their ocular artifacts exceeded our standard laboratory limits (>25% of the trials were contaminated by ocular artifacts or averaged horizontal electrooculogram, EOG, deflections > 3.2  $\mu$ V). Of the remaining 28 participants (mean age: 19.9 years), 20 were female and 25 were right handed. The sample size was determined a priori to yield sufficient power ( $1 - \beta = .80$ ) to detect a moderate-sized effect ( $d = .60$ ) in pairwise t tests (using G\*Power 3.1). The effect size was based on N2pc effects obtained from our lab in recent years (e.g., Tay et al., 2019).

#### **2.1.2. Apparatus**

Experiments were conducted in a dimly lit, sound-attenuated and electrically shielded chamber illuminated by DC-powered LED lighting. A 24-inch LED computer monitor operating at a resolution of 1920 x 1080 pixels and a 120 Hz vertical refresh was used to present visual stimuli. Participants viewed the monitor at a distance of approximately 57 cm and made their responses using a commercially available gamepad (Logitech). A Windows-based computer running Presentation (Neurobehavioral Systems Inc., Albany C.A., U.S.A.) controlled the stimulus presentation and registered the participants' button presses, while a second Windows-based computer running custom software (Acquire) controlled EEG acquisition. The

acquisition computer housed an A-to-D board (PCI-6071e, National Instruments, Austin TX, U.S.A) connected to an EEG amplifier with a 1G $\Omega$  input impedance (SA instruments, San Diego, CA, U.S.A). The EEG amplifier was housed in the chamber, and the computers were situated outside of the chamber.

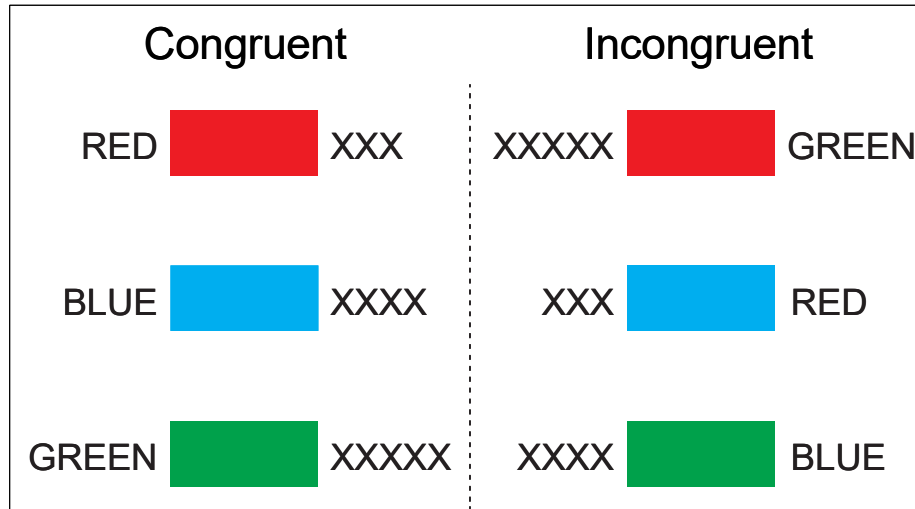
### 2.1.3. Stimuli and Procedure

All stimuli were presented against a uniformly black background. A small (0.4° dia), white disk served as a fixation point. A filled, color rectangle (3.0° x 1.5°) served as the response-relevant target. Color words and strings of Xs presented in white font served as irrelevant flankers (distractors). The target fill color was randomly selected to be red ( $u' = .455$ ,  $v' = .517$ ), blue ( $u' = .163$ ,  $v' = .290$ ), or green ( $u' = .126$ ,  $v' = .570$ ) with equal probability. The red, blue, and green targets were 15 cd/m<sup>2</sup>, 40 cd/m<sup>2</sup>, and 30 cd/m<sup>2</sup>, respectively. Target colors were not equated for luminance because we were measuring attention capture effects of the achromatic flankers. All flanker letters were printed in upper-case Arial with height fixed at 1°. The target rectangle appeared at fixation, superimposed on the fixation point, and the flankers appeared to the left and right of the rectangle. The distance between the fixation point and the nearest edge of the words and letter strings was 2.25°. Color words were either “RED”, “BLUE”, or “GREEN”, and the letter (X) strings were “XXX”, “XXXX”, or “XXXXX”.

Participants viewed an otherwise empty display with a central fixation point at the beginning of each trial. After an 800–1200-ms interval, a flanker display was presented until a manual response was registered or until a maximum of four seconds passed. The flanker display consisted of a central target rectangle, a color word on one side, and a letter string on the other side (**Fig. 1**). On any given trial, the color of the rectangle was determined randomly (with replacement), and the color word was determined randomly to be congruent (50%) or incongruent (50%) with the color of the rectangle. For example, 33 percent of congruent trials involved presentation of a red rectangle and the word “RED” on one side, and 33 percent of incongruent trials involved presentation of a red rectangle and either of the words “BLUE” or “GREEN”. The color word was always paired with a letter string of equal length on the other side of fixation (i.e., “RED”, “BLUE”, and “GREEN” paired with “XXX”, “XXXX”, and “XXXXX”, respectively). An equal number of left- and right-side color words were presented, and the side was determined randomly with replacement on each trial. Participants was instructed to press



one of three colored buttons on the gamepad to indicate the color of the target rectangle (that is, make a three-alternative-forced choice, 3AFC, manual response). They were encouraged to respond as quickly and as accurately as possible and were told that the words and letter strings were irrelevant and were not predictive of target color. The entire experiment was comprised of 40 blocks of 24 trials for a total of 960 trials, with participant-controlled rest periods between blocks.



**Figure 1** Examples of congruent-word and incongruent-word flanker displays used in Experiment 1, showing each of the three rectangle colors

### 2.1.4. Electrophysiological Recording and Pre-processing

The electroencephalogram (EEG) was recorded continuously from 25 sintered Ag/AgCl electrodes mounted in an elastic fabric cap (Electrode Arrays, El Paso Texas). Electrodes were placed at standard locations (FP1, FPz, FP2, F7, F3, Fz, F4, F8, T7, C3, Cz, C4, T8, P3, Pz, P4, POz, P7, PO7, O1, Oz, O2, PO8, P8, and left mastoid). During recording, all EEG signals were referenced to an electrode placed on the right mastoid; the ground electrode was positioned at AFz. The horizontal EOG was recorded bipolarly using a pair of electrodes positioned 1 cm lateral to the left and right external ocular canthi. Eye blinks and vertical eye movements were monitored using a scalp electrodes positioned on the forehead (FP1) referenced to the right mastoid. All electrode impedances were below 10k  $\Omega$  immediately prior to the experimental session, and the EEG and EOG were monitored during the experiment for electrode malfunction and artifacts (including blinks, eye movements, excessive muscular activity and

drowsiness). The EEG and EOG signals were amplified using a gain of 20,000, sampled at 500 Hz, and band-pass filtered during recording using two-pole Butterworth filters with 0.01 Hz and 100 Hz cutoffs.

A semi-automated procedure was performed to remove epochs of EEG that were contaminated by horizontal eye movements, blinks, or amplifier blocking. Specifically, differences between minimum and maximum voltages on the HEOG (horizontal eye movements) and FP1 (vertical eye movements and blinks) were compared to pre-set thresholds (in DAQ units, not  $\mu\text{V}$ ). An epoch was excluded from subsequent averaging procedures when the difference between the minimum and maximum voltages exceeded the threshold for at least one type of artifact. Thresholds were determined by visually inspecting the continuous EEG and EOG to determine values that would produce rejections of all clearly visible artifacts but of few artifact-free epochs. The minimum and maximum voltages were selected within a 700-ms time window within the recording epoch that started 200 ms before the onset of the search display. Following artifact rejection, ERPs elicited by flanker displays were constructed. ERPs were averaged separately for congruent and incongruent color word trials. Using conventional methods, the ERPs for each trial type were collapsed across the specific color word (RED, BLUE, GREEN), side of color word (left visual field, right visual field) and electrode lateralization (left hemisphere, right hemisphere) to produce waveforms recorded contralaterally and ipsilaterally with respect to the color word. ERPs were digitally low-pass filtered with a half-power cutoff at 30 Hz to remove residual higher-frequency noise from nearby electrical sources and muscle artifacts. The digitally filtered ERPs were then re-referenced to the average of the left and right mastoids to remove lateralized ERP activity associated with the lateral recording reference. Positive voltages were plotted downward by convention.

Following construction of the ERPs, event-related EOG waveforms were inspected for each participant to make a final determination whether data from that participant were sufficiently free of ocular artifacts associated with horizontal saccades.

## 2.1.5. Analysis

### ***Behavior***

Median response times (RTs) were computed for congruent and incongruent trials, separately for each participant. A paired-samples *t*-test was performed to determine if RTs differed significantly across the two trial types, using the conventional alpha level for evaluating the statistical outcome ( $\alpha = .05$ ). A one-tailed test was performed because we had a directional hypothesis based on numerous prior Stroop studies (i.e. shorter RTs for congruent trials than for incongruent trials and expected a small (i.e., “diluted”) effect due to the presence of the neutral distractor (Kahneman and Chajczyk, 1983).

### ***ERPs.***

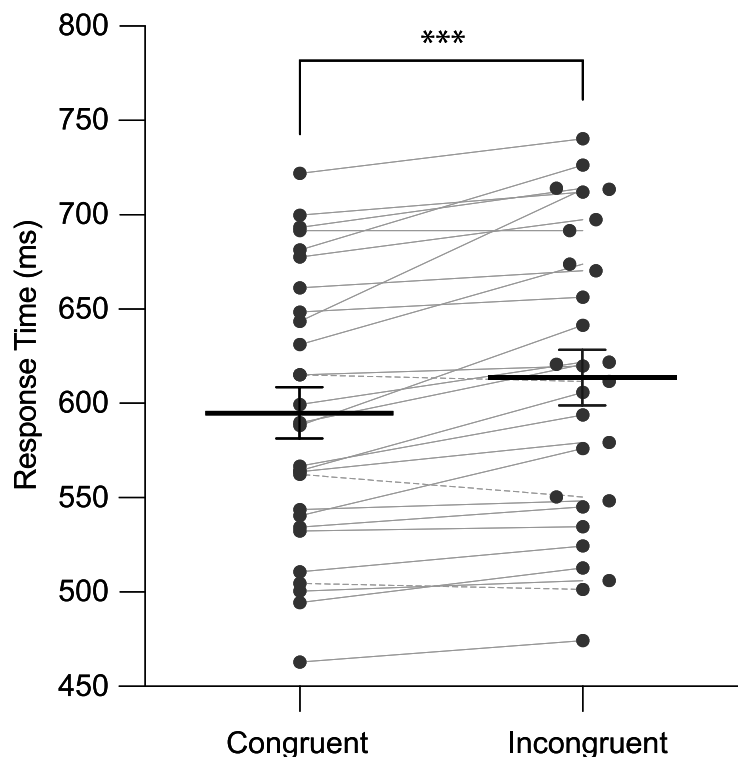
The N2pc was measured using a single pair of occipital electrodes (PO7 and PO8) because prior studies have demonstrated that N2pc is largest at or near these sites (e.g., Eimer, 1996; Luck & Hillyard, 1994a; Tay et al., 2019). To help visualize the N2pc, the ipsilateral ERP waveforms were subtracted from the corresponding contralateral ERP waveforms to produce contralateral-minus-ipsilateral difference waves. N2pc measurements were taken from this difference wave, separately for congruent trials and for incongruent trials. N2pc onset latencies were defined and measured as the time at which the amplitude of the N2pc rose to 50% of its peak amplitude. Differences in N2pc onset latency across trial types were evaluated statistically using a conventional Jackknife approach (Miller et al., 1998). N2pc magnitude was then quantified as the mean amplitude within a 75-ms window that began at the onset latency, relative to a 100-ms baseline interval immediately preceding appearance of the flanker display. A one-sample *t*-test was performed to determine whether the N2pc was significantly different from zero in each of the two trial types. Despite having a directional hypothesis (N2pc mean amplitude would be more negative than zero), these tests were done with two tails to enable conclusions about the presence of a lateralized ERP positivity called the Distractor Positivity ( $P_D$ ), which occurs at the same electrodes at around the time as the N2pc. Whereas the N2pc has been linked to attentional selection (Luck & Hillyard, 1994a, 1994b), the  $P_D$  has been linked to suppression (Hickey et al., 2009; Gaspar and McDonald, 2014; Gaspelin and Luck, 2018). A two-tailed, paired-samples *t*-test was performed to determine whether mean

amplitude within the N2pc measurement interval differed across congruent and incongruent trial types.

## 2.2. Results

### 2.2.1. Behavior

Fewer than 1.5 percent of trials were trimmed from the analysis because participants responded too quickly (RT < 100 ms) or too slowly (RT > 1500 ms). On the remaining trials, the mean RT across participants was shorter for congruent trials (594 ms) than for incongruent trials (613 ms),  $t(27) = 5.25$ ,  $p < .001$ ,  $d = 0.99$ . All but four participants showed this pattern of Stroop interference (**Fig. 2**); three participants exhibited the reverse numerical difference, and one participant showed no difference. Response accuracy did not differ significantly across trial types (84.0% and 84.5% for congruent and incongruent trials, respectively),  $t(27) = 1.55$ ,  $p = .132$ ,  $d' = 0.29$ .



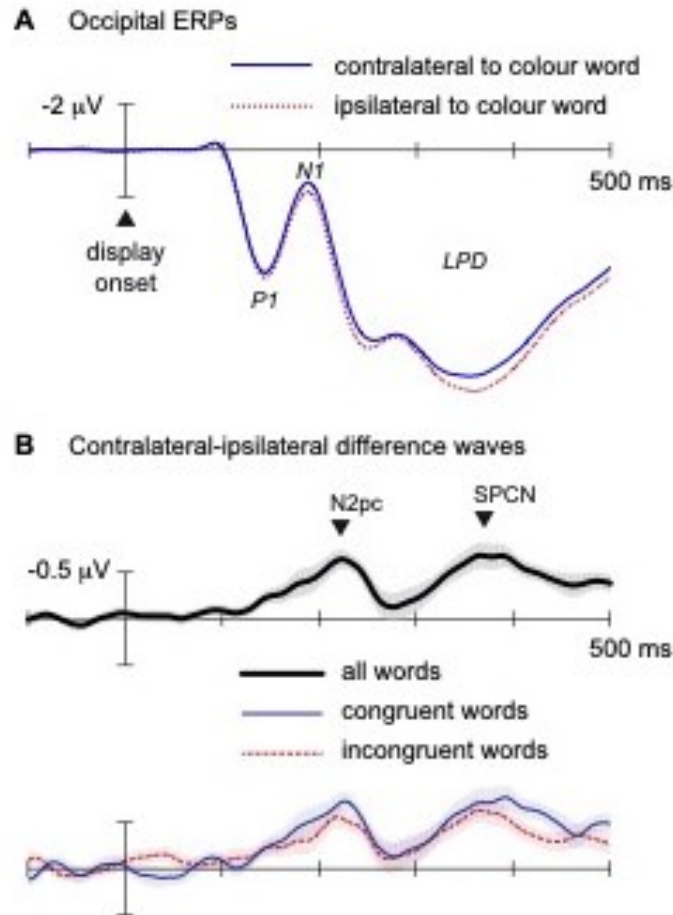
**Figure 2** Response times (RT) in Experiment 1.

Each dot represents one participant's RT, and each line connects one participant's RT from the two trial types. Solid gray lines represent longer RTs for incongruent-word trials (or no numerical difference), and dashed gray lines represent shorter RTs for incongruent-word trials. Thick

horizontal lines represent the means for the two trial types and the error bars show the standard errors for those means. \*\*\* $p < .001$ .

### 2.2.2. ERPs

Flanker displays elicited a typical pattern of ERP peaks over the posterior scalp, including a positive voltage (P1) peaking at 140 ms, a negative voltage (N1) peaking at 190 ms, and a late positive deflection (LPD) lasting beyond the plotting interval (see Mangun and Hillyard, 1991). Figure 3 shows waveforms recorded contralaterally and ipsilaterally with respect to the side of the color word, averaged over congruent and incongruent trials (all-words ERPs). The contralateral and ipsilateral waveforms overlapped initially but began to diverge within the later phase of the P1. From that point onwards, the contralateral waveform appeared to be more negative than the ipsilateral waveform. Contralateral-minus-ipsilateral difference waves were computed to better isolate the lateralized difference(s) and to help determine when the difference was largest. The all-words difference wave contained two negative voltage maxima, with the first one peaking within the time range of the N2pc (220–230 ms post stimulus; Luck & Hillyard, 1994a, 1994b) and the second one peaking within the early phase of the SPCN (300–400 ms post stimulus; Jannati et al., 2013; Jolicoeur et al., 2008; Mazza et al., 2007)(**Fig. 3b**, top). The onset latencies of the N2pc and SPCN (defined as the times at which the components reached half of their peak amplitudes) were 168 ms and 316 ms, respectively. The mean amplitude of the N2pc ( $-0.51 \mu\text{V}$  within the 168–243 ms time window) was significantly different from that predicted on the basis of the null hypothesis (i.e., zero  $\mu\text{V}$ ),  $t(27) = 5.54$ ,  $p < .001$ ,  $d = 1.05$ . The mean amplitude of the SPCN was nearly identical ( $-0.52$  within the 350–500 ms time window) and was also significant,  $t(27) = 6.02$ ,  $p < .001$ ,  $d = 1.14$ .



**Figure 3. ERP results from Experiment 1.**

Negative voltages are plotted upwards by convention. (a) Grand-averaged ERPs recorded at occipital electrodes (PO7/PO8) positioned contralateral and ipsilateral to the color-word (independent of word congruency). Typical visual evoked components (P1, N1 and LPD) are labeled. (b) Grand-averaged contralateral-minus-ipsilateral difference waves from lateral occipital electrodes (PO7/PO8). Shaded areas around the difference waves represent standard error bars.

Next, contralateral-ipsilateral difference waves were computed separately for congruent- and incongruent-word trials (**Fig. 3b**, bottom). Analyses of these waveforms revealed two key groups of findings. First, the individual N2pc and SPCN components were significantly different from zero volts for each trial type: N2pc,  $t_s(27) \geq 4.50$ ,  $p_s < .001$ ,  $d_s \geq 0.85$ ; SPCN,  $t_s(27) \geq 4.37$ ,  $p_s < .001$ ,  $d_s \geq 0.89$ . Second, both components were larger on congruent-word trials than on incongruent-word trials: N2pc,  $t(27) = 2.71$ ,  $p = .012$ ,  $d = 0.51$ ; SPCN,  $t(27) = 2.40$ ,  $p = .024$ ,  $d = 0.45$ .

## 2.3. Discussion

A small but significant Stroop effect was observed in Experiment 1. The magnitude of the effect was predicted to be small because the color word appeared a few degrees away from the to-be-named color rectangle and was accompanied by a response-neutral visual distractor (the string of XXs) on the opposite side. Given that the target rectangle always appeared at the location of the fixation point, one might assume that the participants would be able to ignore the color word entirely, but the observation of RT interference here and in prior nonintegrated versions of the Stroop color-word task (e.g., Kahneman and Chajczyk, 1983) suggest that they cannot. The ERPs obtained in Experiment 1 provide compelling evidence that participants covertly orient their attention to the location of the irrelevant color word (as indexed by the N2pc) and process its identity (as indexed by the subsequent SPCN). Moreover, the onset latency of the N2pc was on the shorter end of the spectrum. Several factors affect the timing of the N2pc, including stimulus intensity (Brisson et al., 2007) and local contrast (i.e., salience; Gaspar & McDonald, 2014). Thus, the results of Experiment 1 indicate that words appearing sufficiently close to the relevant region of visual space capture attention in a bottom-up manner, irrespective of an observer's intention and the current demands of the task at hand. In other words, the color words may have captured attention automatically.

There is, however, an alternative explanation for the word-elicited N2pc in Experiment 1. Namely, participants might have inadvertently attended to the color words only because they were set to identify the color of a concurrent object. This alternative explanation is consistent with the contingent-capture hypothesis outlined in the Introduction. According to this perspective, an observer will reflexively orient attention to any item that is in possession of a task-relevant feature. Such contingent capture is often based on low-level visual features, such as color and motion (Folk et al. 1994), but it can also be triggered by items that overlap with the target in a less direct way, such as when it is part of the same high-level category of objects (e.g., amusement park rides; Wyble et al., 2013). Thus, the color word might have attracted attention not because words are inherently salient for skilled readers but because the meaning of every word was related to the category that was relevant for the response.

Experiment 2 was designed to test this alternative explanation. As in Experiment 1, a central target shape was presented at fixation and was flanked by a color word on one side and a string of XXs on the other. In Experiment 2, however, the shape of the target varied randomly across trials. In separate conditions, participants were instructed to make a 3AFC manual response to report either the target's color (report-color condition) or the target's shape (report-shape condition). All shapes were white in the report-shape condition to prevent an unintended match between target and distractor. If words capture attention automatically, the color word should elicit the N2pc in both conditions. If, however, words capture attention contingently upon a match between the word category and the relevant target dimension, then the color word should fail to elicit N2pc in the report-shape condition.



## Chapter 3. Experiment 2

### 3.1. Method

The Office of Research Ethics at Simon Fraser University (SFU) approved the research protocol for this study. All experimental procedures were performed in accordance with guidelines and regulations outlined by SFU and the Natural Sciences and Engineering Research Council of Canada (NSERC).

#### 3.1.1. Participants

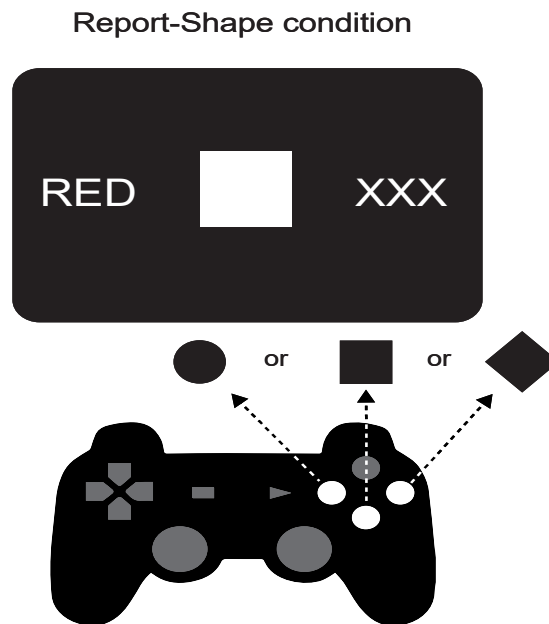
Thirty-five neurologically healthy volunteers participated after giving informed consent. All subjects reported normal or corrected-to-normal visual acuity and were tested for normal color vision using Ishihara color plates prior to participation. Data from ten participants were excluded from further analyses because too many trials were contaminated by ocular artifacts or because their averaged horizontal EOG contained deflections in excess of  $3.2\mu\text{V}$  (as in Experiment 1). Of the remaining 25 participants (mean age: 20.0 years), 16 were female and all were right handed. Once again, the sample size was determined a priori to yield sufficient power ( $1 - \beta = .80$ ) to detect a moderate-sized effect ( $d = .60$ ) in pairwise t tests (using G\*Power 3.1).

#### 3.1.2. Apparatus, Stimuli and Procedure

Flanker displays contained the same color words and letter (XX) strings as in Experiment 1, but the features of the central target were changed. The shape of the target varied randomly across trials, with circles ( $1.5^\circ$  diameter), squares ( $1.5^\circ \times 1.5^\circ$ ) and diamonds (squares rotated  $45^\circ$ ) occurring with equal probability. Each subject participated in two types of trial blocks (conditions). In half of the blocks, the target color varied randomly across trials, and participants were instructed to report the target color by means of a 3AFC manual response (red, blue, green). Thus, as in Experiment 1, the color words were either congruent or incongruent with the response in this report-color condition. In the other half of blocks, the target was white, and participants were instructed to report the shape of the target using the same three gamepad buttons (**Fig.**

4). Thus, whereas the color words overlapped with the response dimension in the report-color condition, they were completely response-neutral in the report-shape condition.

There were 21 blocks of 24 trials of each type. Half of the participants completed all report-shape blocks first and then switched to report-color blocks midway through the experiment; the other participants ran in the report-color blocks first. All other aspects of the stimuli and procedure were the same as those in Experiment 1.



**Figure 4.** An example of the flanker displays used in the report-shape condition of Experiment 2, with the shape-button mapping shown.

### 3.1.3. Electrophysiological Recording and Pre-processing

These were the same as in Experiment 1, except that ERPs were now averaged separately for the report-shape condition and the congruent-word and incongruent-word trials from the report-color condition.

### 3.1.4. Analysis

#### *Behavior*

Mean RTs were submitted to a one-way repeated-measures ANOVA with three levels corresponding to report-shape trials, and the two trial types from the report-color

condition (congruent-word and incongruent-word). This Omnibus ANOVA was followed by a single planned comparison to determine whether Stroop interference occurred in the report-color condition (that is, incongruent trials vs. congruent trials). Accuracy was computed for these two trial types and compared by planned t-test to determine whether a speed-accuracy trade-off might have occurred.

### ***ERPs***

The sample size was nearly as large as that in Experiment 1, and so Experiment 2 had nearly the same power to detect moderate-sized effects by conventional measures. However, the number of report-color trials was roughly cut in half in Experiment 2 so that each participant could also perform in the report-shape condition. Thus, the effective power to detect differences between ERPs obtained on congruent- and incongruent-color trials was expected to be lower (Boudewyn et al., 2018). Those statistical tests were still performed, as they were in Experiment 1, but the main goals were to determine whether the N2pc and SPCN were present (statistically more negative than zero, by one-tailed t tests) in each of the two conditions. Mean amplitudes were measured as they were in Experiment 1. The N2pc measurement window was based on the onset (i.e., 50% fractional peak) latency of the grand-averaged N2pc, averaged over the two conditions (186–261 ms post-stimulus). Onset latencies were not analyzed to reduce the number of statistical tests (and because there was no a priori hypothesis about a latency difference). Amplitude differences between report-color and report-shape conditions were analyzed using two-tailed, paired-samples t tests.

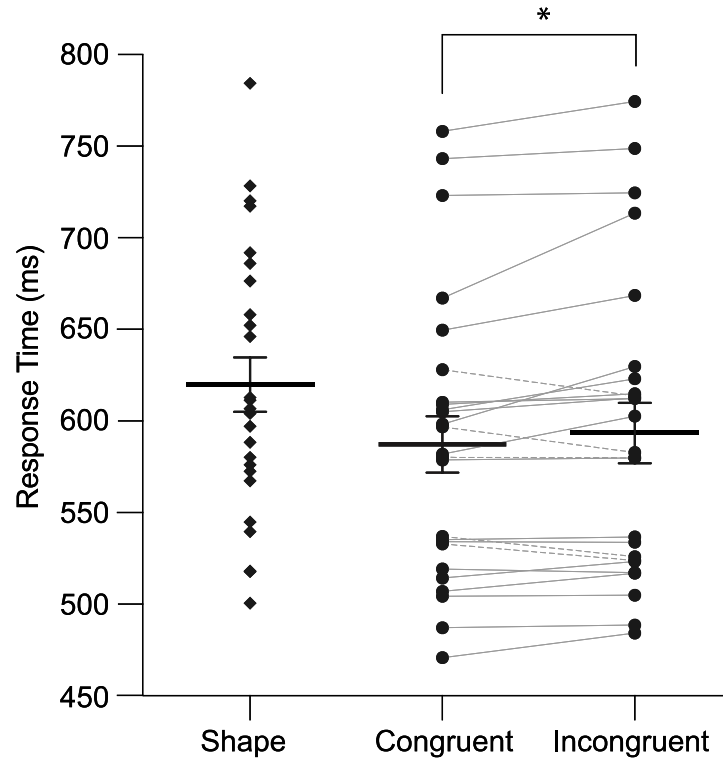
### ***Correlations.***

Neither experiment had sufficient power to analyze correlations between Stroop interference and the N2pc amplitudes. However, the combined sample size ( $N = 53$ ) from the two experiments ( $N = 28$  and  $N = 25$ , respectively) had sufficient power (.80) to detect a moderately large correlation ( $r = .38$ ). Accordingly, we performed an exploratory analysis of the correlation between Stroop interference (mean RT on incongruent trials minus mean RT on congruent trials) and N2pc amplitude in the report-color condition of both experiments. The N2pc amplitude measure for each participant was collapsed across congruent- and incongruent-color trials to maximize the signal-to-noise ratio of the measure and to minimize the probability of making a Type 1 error.

## 3.2. Results and Discussion

### 3.2.1. Behavior

Fewer than 1.5 percent of trials were trimmed from the analysis because participants responded too quickly ( $RT < 100$  ms) or too slowly ( $RT > 1500$  ms). RTs from the remaining trials are displayed in **Fig. 5** as a function of the three trial types (one from the report-shape condition, and two from the report-color condition). The one-way ANOVA revealed a significant main effect of Trial Type,  $F(2,48) = 13.51$ ,  $p < .001$ ,  $\eta_p^2 = 0.36$ . The sole planned comparison showed that the mean RT was shorter for congruent trials (587 ms) than for incongruent trials (594 ms),  $t(24) = 2.32$ ,  $p = .014$ ,  $d = 0.47$ . Response accuracy was not statistically different across congruent- and incongruent-color trials (82.2% and 82.7%, respectively),  $t(24) = 0.55$ ,  $p = .588$ . Thus, Experiment 2 replicated the small, “diluted” Stroop interference from Experiment 1. The magnitude of interference was numerically smaller in Experiment 2 than in Experiment 1, but this between-groups difference was not assessed statistically because the magnitude of interference was not the focus of the present study.



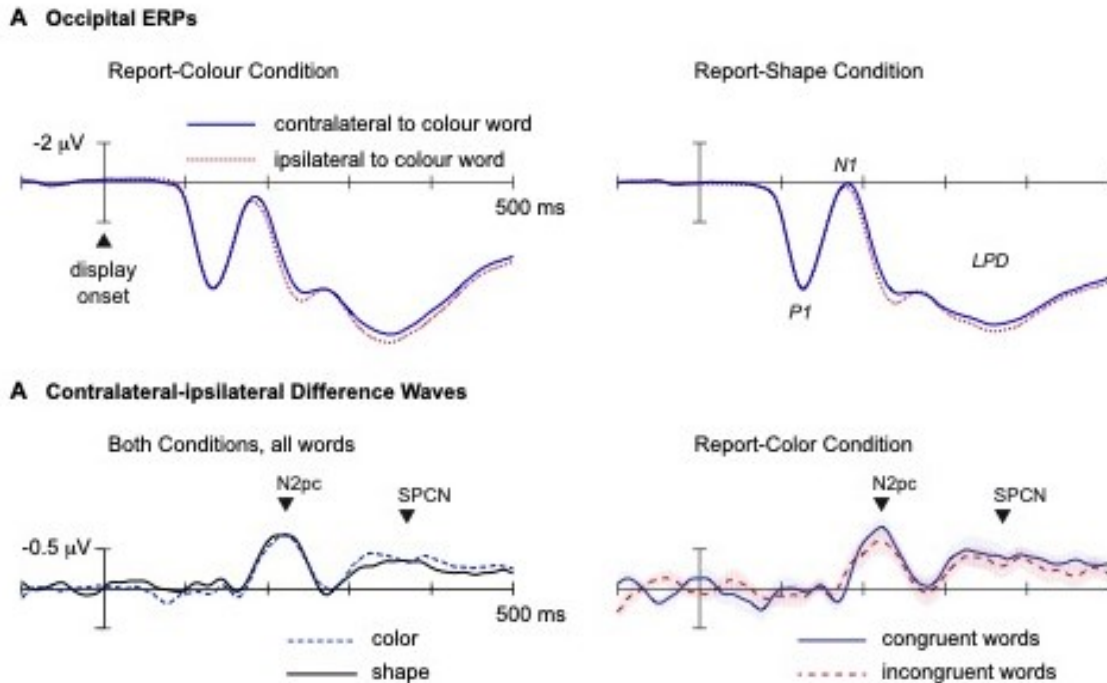
**Figure 5. Response times in Experiment 2.**

Each dot represents one participant's RT for each of the three trial types (report-shape trials and congruent- and incongruent-word trials from the report-color condition). Each line between congruent and incongruent columns connects RTs from an individual participant. Solid gray lines represent longer RTs for incongruent-word trials, and dashed gray lines represent shorter RTs for incongruent-word trials. Thick horizontal lines represent the means for the three trial types, and the error bars show standard errors of those means. \* $p < .05$ .

### 3.2.2. ERPs

Flanker displays elicited a typical pattern of ERP peaks over the posterior scalp in both conditions (**Fig. 6a**). The contralateral and ipsilateral waveforms overlapped initially but, in each condition, the contralateral waveform became more negative than the ipsilateral waveform from the time range of the N1. As in Experiment 1, the contralateral-minus-ipsilateral difference waves contained two negative voltage maxima, with the first one peaking within the time range of the N2pc and a later, more sustained negativity occurring within the time range of the SPCN (**Fig. 6b**, left). The mean amplitude of the N2pc was significantly more negative than that predicted on the basis of the null hypothesis (i.e., zero  $\mu\text{V}$ ) in the report-color condition,  $t(24) = 5.26$ ,  $p < .001$ ,  $d = 1.05$ . This replicates the main result from Experiment 1 and provides additional evidence that color words capture attention in the typical nonintegrated Stroop task. Critically,

N2pc amplitude was also found to be significantly more negative than zero in the report-shape condition,  $t(24) = 5.57$ ,  $p < .001$ ,  $d = 1.11$ , which indicates that the irrelevant flanker words captured attention even when their meanings did not overlap with the task-relevant response dimension. N2pc amplitude did not differ significantly across conditions,  $t(24) = 0.49$ ,  $p = .627$ , which suggests that there was no more or less capture in the report-shape condition than in the report-color condition.



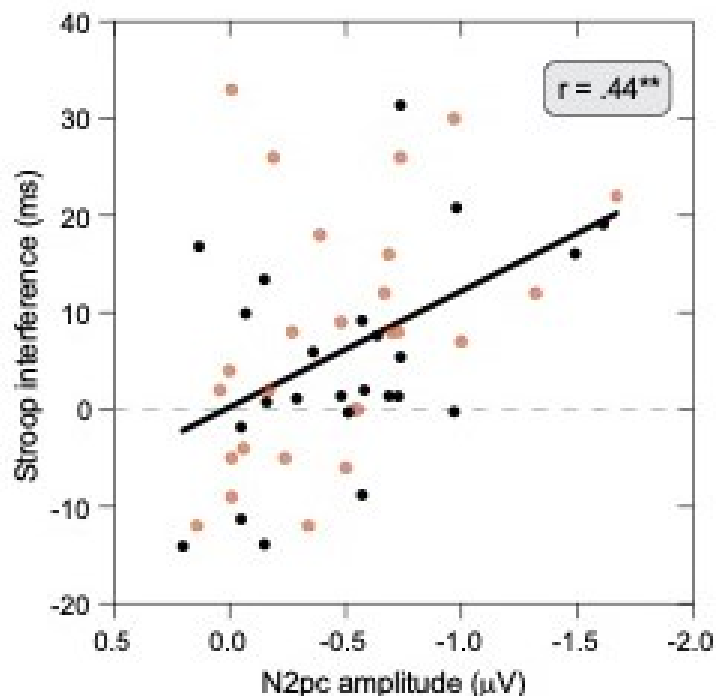
**Figure 6. ERP results from Experiment 2.**

Negative voltages are plotted upward, by convention. (a) Grand-averaged occipital ERPs recorded from lateral electrodes (PO7 and PO8) positioned contralateral and ipsilateral to the color word. (b) Contralateral-minus-ipsilateral difference waveforms recorded from lateral occipital electrodes (PO7/PO8). Shaded areas around the difference waves represent standard error bars.

Results of the SPCN analyses paralleled those of the N2pc: The SPCN was significantly more negative than zero in the report-color condition,  $t(24) = 3.62$ ,  $p = .001$ ,  $d = 0.72$ , and in the report-shape condition,  $t(24) = 3.42$ ,  $p = .002$ ,  $d = 0.69$ , with no significant difference between conditions,  $t(24) = 1.01$ ,  $p = .324$ . No amplitude difference was found between congruent- and incongruent-color trials for N2pc,  $t(24) = 1.02$ ,  $p = .32$ , or SPCN,  $t(24) = 0.92$ ,  $p = .37$ .

### 3.2.3. Correlation

A total of 53 adults participated in the report-color task across Experiments 1 and 2. Before submitting the combined dataset to a bivariate correlation analysis, the behavioral and ERP data were assessed for univariate outliers, which were defined as being more than 2.5 standard deviations away from the corresponding univariate means. In all, three outliers were removed from the correlation analysis, including two RT-interference outliers and one N2pc amplitude outlier. Figure 7 shows a scatterplot of the remaining 50 datasets along with the best-fitting linear regression line. For ease of interpretation, the N2pc amplitudes were reversed in polarity before a correlation was computed, so that a positive correlation would have a more straight-forward interpretation (larger amplitude N2pcs associated with greater magnitudes of RT interference). The resulting Pearson correlation coefficient,  $r$ , was .44,  $p = .0012$ . This significant correlation indicates that the magnitude of N2pc elicited by irrelevant color words is predictive of the magnitude of behavioral interference in the nonintegrated color-word Stroop task.



**Figure 7. Statistical relationship between the amplitude of the word-elicited N2pc and the magnitude of Stroop interference.**  
Solid black circles represent data from Experiment 1; Lighter circles (orange in PDF; gray in print) represent data from the report-color condition of Experiment 2.

## Chapter 4. General Discussion

The concept of automaticity has been at the center of two research streams for decades. In one, researchers have considered a cognitive process to be automatic only if it can be performed equally well with or without attention. In the other, researchers have sought to determine whether a salient-but-irrelevant stimulus automatically draws attention to its location. The present study integrates these two streams to determine whether irrelevant words automatically capture attention to their location. Using a nonintegrated variant of the Stroop task, Kahneman and Chajczyk (1983) demonstrated that Stroop interference is reduced—or “diluted”—by the presence of a response-neutral distractor that presumably pulls some attentional resources away from the color word. This dilution indicates that reading requires attention and is thus only partially automatic. Here, we asked whether these irrelevant, color-word flankers automatically capture attention to their location.

Experiment 1 was similar to Kahneman and Chajczyk’s (1983) seminal experiments, except that the color-word flanker appeared to the left or right of the target rectangle (rather than above or below it) and was always accompanied by a response-neutral letter string on the opposite side of fixation. This methodological modification enabled us to measure the N2pc (an ERP signature of attentional selection; Luck and Hillyard, 1994a, 1994b) on every trial and thus to determine whether the color word was attended over and above the neutral distractor. The word was found to elicit the N2pc as well as the subsequent SPCN, which has been associated with stimulus identification (Jannati et al., 2013; Jolicoeur et al., 2008; Mazza et al., 2007). Both the N2pc and SPCN persisted when the color word was made completely neutral to the task at hand (in the report-shape condition of Experiment 2), and the amplitude of the N2pc was even predictive of the magnitude of Stroop interference. Based on these findings, we conclude that although reading may require attention (and is certainly not independent of attention), skilled readers reflexively orient their attention to nearby words even when those words are task-irrelevant and response-neutral. Such reflexive shifts of attention are often considered to be automatic in the sense that they occur without intent (Theeuwes, 1991). Thus, a corollary of our conclusion is that reading is *nearly automatic* in the nonintegrated Stroop task. By this term, we mean that nearby words of sufficient



salience automatically capture attention (as evidenced by the N2pc), which leads to the obligatory processing of word meaning (as evidenced by the SPCN).

The present results add to the growing and often contentious literature on the capture of attention by objects in the visual field. For over two decades, a debated centered on whether covert orienting of visual attention was entirely determined by stimulus salience or by the intentions of an observer (e.g., Folk et al., 1992, 1994; Theeuwes, 1991a, 2010). Early research using the additional singleton paradigm, in which target and distractor singletons (i.e., unique-feature objects) appear among several identical nontargets, suggested that the most salient item in the visual field captures attention automatically (Theeuwes, 1991). Results of other studies indicated that people can ignore salient singletons as well as salient abrupt visual onsets when their attention is already actively engaged at a different location in the visual field (Belopolsky and Theeuwes, 2010; Theeuwes, 1991b; Yantis and Jonides, 1990). Although there was some initial ERP evidence for automatic attention capture (Hickey et al., 2006), subsequent ERP studies showed that salience-driven diversions of attention can be prevented (e.g., Gaspar and McDonald, 2014; Gaspelin and Luck, 2018; Jannati et al., 2013; McDonald et al., 2013; Sawaki and Luck, 2010). There are known limits to this top-down attention control, however. For example, individuals with low visual working memory spans appear to be less capable of preventing salient stimuli from automatically capturing their attention (Gaspar et al., 2016). Anxious individuals and individuals performing at non-optimal times of day (relative to their internal circadian rhythms) also appear to be less able to prevent salient distractors from capturing attention (Gaspar and McDonald, 2018; Smit et al., 2019). Furthermore, simple visual objects that have been associated with financial reward appear to capture attention automatically (Anderson et al., 2011; Qi et al., 2013). Here, we show that words also capture attention when they are irrelevant and share no feature with the to-be-attended target, even though their attention should be actively engaged elsewhere throughout the entire experiment (since the target always appeared at fixation).

Of course, future research will be necessary to determine whether attention capture by words is fully (i.e., strongly) automatic or only partially automatic. Although observers could not prevent flanker words from capturing attention in the present series of experiments, observers might be able to ignore the words when faced with a more challenging task. This possibility is in line with the perceptual load theory of visual

attention (Lavie, 1995). According to this theory, distractors are processed only when the relevant task does not consume all of the available attentional resources. Interestingly, results from flanker tasks such as the one used here have been interpreted in terms of perceptual load theory. Lavie (1995) even suggested that the dilution of Stroop interference in Kahneman and Chajczyk's (1983) study occurred because the addition of a response-neutral distractor increased perceptual load, thereby making fewer attentional resources available to process the color word. Consistent with this interpretation, and with Kahneman and Chajczyk's own interpretation, we suspect that a color-word flanker would receive greater selective processing when presented without an accompanying flanker on the opposite side of fixation. The present ERP findings demonstrate that the color word flanker was attended despite dilution of the behavioral interference. Future research is needed to determine whether the color-word N2pc and SPCN persist in experiments with higher perceptual load and/or a more attentionally demanding target task.

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