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An Attentional Adaptation Account of Spatial Negative Priming: Evidence from Event-Related Potentials

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Abstract

Negative priming (NP) refers to a slower response to a target stimulus if it has been previously ignored. To examine theoretical accounts of spatial NP, we recorded behavioral measures and event-related potentials (ERPs) in a target localization task. A target and distractor briefly appeared, and the participant pressed a key corresponding to the target's location. The probability of the distractor appearing in each of four locations varied, while the target appeared with equal probability in each location. We found that reaction times (RTs) were fastest when the prime distractor appeared in its most probable (frequent) location and when the prime target appeared in the location that never contained a distractor. Moreover, NP effects varied as a function of location: they were smallest when targets followed distractors in the frequent distractor location – a finding not predicted by episodic retrieval or suppression accounts of NP. ERP results showed that the P2, an ERP component associated with attentional orientation, was smaller in prime displays when the distractor appeared in its frequent location. Moreover there were no differences between negative prime and control trials in the N2, which is associated with suppression processes, nor in the P3, which is associated with episodic retrieval processes. These results indicate that the spatial NP effect is caused by both short- and long-term adaptation in preferences based on the history of inspecting unsuccessful locations. This paper is dedicated to the memory of Edward E. Smith and we indicate how this study is inspired by his research career.

Keywords

negative priming; attentional adaptation; ERPs; P2; N2; P3

1. Introduction

This paper uses event related potentials (ERP) to address an issue related to cognitive control; specifically, how implicitly varied base-rates of information in the environment affect covert shifts of attention in a spatial localization task. The work builds on previous research for which the primary dependent measure was response times (RT) (Reder, Weber, Shang, & Vanyukov, 2003). The third author's first and most influential advisor, Ed Smith, was a leader in using RT (Smith, 1968) and he had a keen interest in how the human mind

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selectively processes rapidly presented information. That work on selective attention (Smith, Haviland, Reder, Brownell, & Adams, 1976) was just one of Smith's many research projects addressing cognitive control and selective attention. He remained interested in attention throughout his career, and frequently returned to the question of how do humans come to focus on some features of a stimulus and to ignore others (e.g., Polk, Drake, Jonides, M. Smith & E. Smith, 2008).

One of Smith's many strengths was his tendency to use converging measures to address questions of interest. He did not shy away from challenging existing interpretations and theories and excelled at finding alternative explanations for data sets. He was an early adopter of new methodologies, RT being his first foray into new methods, and neuroimaging being one of his last. This paper is written in the spirit of Ed Smith's approach to science. The paper attempts to discriminate among multiple theories related to allocation of attention in a spatial localization task. This paper can be construed as challenging current theories. The arguments rely on several methodologies, the first being the methodology Ed Smith promoted when he was a young academic (RT) and the other being of the class of neuroimaging methods that Ed promoted later in life.

The paradigm we use to explore theories of selective attention in a spatial localization task involves presenting targets and distractors in an array simultaneously, after which participants must press a key to indicate the location of the target. Performance is degraded when the target is in a position that contained a distractor on the previous display. There have been a number of competing theories to explain this *Negative Priming* (NP) effect. NP refers to a slower response to a target stimulus if it has previously been ignored. In the typical NP paradigm, participants view a prime display followed by a probe display. Both displays contain a distractor, which participants must ignore, and a target, which they must attend to. NP has spawned a large body of research (Fox, 1995; May, Kane, & Hasher, 1995; Neill & Valdes, 1992; Neill & Valdes, 1996; Neill, Valdes, Terry, & Gorfein, 1992; Tipper, 1985; Tipper, Brehaut, & Driver, 1990). The phenomenon has been studied in different experimental paradigms such as letter naming (Tipper & Cranston, 1985), picture naming (Tipper, 1985), and target localization (Neill et al., 1992; Tipper et al., 1990). This paper will primarily focus on NP effect in a target localization task. Most research on the spatial NP effect has centered on two theories – the *suppression account* (Banks, Roberts, & Ciranni, 1995; Driver, Mcleod, & Dienes, 1992; Houghton, Tipper, Weaver, & Shore, 1996; Tipper & Cranston, 1985) and the *episodic retrieval account* (Neill & Valdes, 1992; Neill et al., 1992).

The suppression account has been implemented as a neural network model (Houghton & Tipper, 1994; Houghton et al., 1996). When a distractor appears, the activation value of the mental representation of that distractor increases above its baseline level. Distractor activation interferes with target processing. When the external presentation of the distractor is terminated, the internal representation of the distractor is suppressed to a sub-baseline level of activation. These states of inhibition remain when the probe is displayed. Consequently, in a target localization task, responses to targets that occupy the former distractor location are impaired relative to targets that appear in novel locations.

The episodic retrieval account provides a qualitatively different explanation of NP (e.g., Neill, 1997; Neill & Valdes, 1992). Episodic retrieval posits that, as a byproduct of ignoring a distractor stimulus, a tag is associated with the representation of the distracting information. This “ignore me” tag competes with other associated tags (e.g., “attend to me”) when the system needs to decide whether to process a stimulus further. According to Neill, the “ignore me” tag produces maximal interference in NP trials due to its recent occurrence making the tag salient.

Other theories have been offered to account for NP effects. For example, the Inhibition of Return (IOR) account describes a tendency to inhibit orienting toward visual locations that have been recently attended (Posner & Cohen, 1984). It has also been offered as an explanation for the spatial negative priming effect (Christie & Klein, 2001). In addition, the Feature-Mismatch account (Park & Kanwisher, 1994) claims that NP occurs because of the mismatch of features between prime and probe displays. The mismatch of features between prime and probe displays requires more time to analyze than when they match, thereby producing NP.

In the standard target localization task, targets and probes appear with equal frequency in each location. The suppression and episodic retrieval accounts have been largely successful in accounting for NP in this task. However, these theories have recently been challenged by a variant of the target localization task where the probability of the distractor varied by target location (Reder et al., 2003). In addition to replicating the standard NP result (*i.e.*, participants were slower to locate a target that appeared in a location that previously contained a distractor), Reder et al. (2003) found that when the distractor appeared in the location that frequently contained a distractor (frequent location), reaction times (RTs) were shortest. Conversely, when the distractor appeared in the location that infrequently contained a distractor (infrequent location), RTs were longest. More surprisingly, the size of the NP effect (difference of RTs between NP and control trials) was smallest in the frequent distractor location and was greatest in the infrequent distractor location.¹

According to the logic of episodic retrieval, NP effects should be greatest in locations where distractors dominate. Specifically, the more frequently distractors appear in a location, the more the episodic traces (“tags”) of ‘no response’ are associated with that location. Thus, the more often a distractor appears in a specific location, the stronger that association. A stronger association increases the conflict between the ‘no response’ tag and the requirement to respond to the probe display (containing a target), hence the prediction of a larger NP effect in the frequent distractor location. The results of Reder et al. (2003), however, showed that the size of NP effect was smallest in the frequent distractor location.

Tipper's original suppression account (1985) stated that NP was a short-term process and consequently, the effect of NP should not depend on the differential probabilities of distractors in different locations. This is because differential probabilities take time to be assimilated and a short-term process would not be sensitive to that. Similarly, according to

¹The NP effect was not due solely to the difference in RTs for Negative Prime trials compared to corresponding control trials: The absolute RTs for NP trials showed this pattern as well.

the feature mismatch account, NP should not vary as a function of distractor probabilities. In order to account for long-term negative priming, this theory was modified to enable memory to store the suppressed episodes (Tipper, 2001). The revised suppression theory seems to make the same predictions as the Episodic Retrieval Theory – when a distractor appears in a frequent distractor location, this location will be inhibited more strongly and the NP effect will be greatest. Again, this is the opposite of what we observed in several studies. As for the Inhibition of Return (IOR) account, studies have shown that IOR can be present at multiple locations and that its magnitude is largest for the location that was examined most recently (*e.g.* Snyder & Kingstone, 2000). As discussed in Reder et al. (2003), there was evidence that IOR contributed to the RT pattern, but the data clearly indicated that the attentional adaptation processes were dominant. As we noted there, whether IOR is observed or not may depend on the nature of the task. In our studies, it is clear that while IOR may be able to explain the behavioral data associated with the prime displays it cannot account for the differential negative-priming effect (see Reder et al., 2003, for a detailed discussion of this point).

More recently, there has been interest in determining whether differential probabilities affect attentional processes (Baker, Olson, & Behrmann, 2004; Druker & Anderson, 2010; Geng & Behrmann, 2002; Hoffmann & Kunde, 1999). These studies have demonstrated that people are sensitive to spatial probability distributions. Targets in frequent target locations are detected more quickly than targets in rare target locations, and targets are detected more slowly when a distractor appears in the location that frequently contains a target (Reder et al., 2003; Reder & Weber, 1997) demonstrated that differential probabilities of distractors in locations also influence attentional processes.

In this paper, we test an attentional adaptation account based on the role of spatial probability to explain the NP effect. Given that the allocation of attention among locations is biased by the spatial probability of the distractors, the results of Reder et al. (2003) can be explained in terms of long-term attentional adaptation based on the spatial distributions. The suppression and episodic retrieval accounts tacitly assume that both the target and distractor locations are inspected in parallel and allocation of attention to each location is equivalent. In contrast, we propose that a subject detects the locations of the two stimuli in parallel, but differentially *allocates* attention to each stimulus. This differential allocation of attention affects which location gets more attention. If a target occupies the location that gets the most attention, the response will be fast. Otherwise, the response will be slower.

The history of success and failure of inspection, based on where targets and distractors have previously appeared, affects the tendency to allocate attention to each location. Our theory relates to the attention-based rehearsal hypothesis (Smith & Jonides, 1998; Awh & Jonides, 2001), which states that spatial memory rehearsal is achieved by covert shifts of spatial selective attention to memorized locations. These covert shifts of attention enhance neural signals representing the attended location and/or decrease neural signals representing unattended locations (Postle, Awh, Jonides, Smith & D'Esposito, 2004). We propose that participants, based on their *actual* history of successes and failures, learn to allocate attention to locations that rarely or never contain a distractor. When the low-frequency distractor location contains a distractor during the prime display, the system is likely to

allocate attention to that location. Recent attentional allocation is weighted more heavily (in the short term), and thus there is a strong bias to ignore that location should something appear there in the next (probe) display. Conversely, when the frequent distractor location contains a distractor during the prime display, attention is not likely to be drawn there, and thus that location is unlikely to experience a (short-term) failure when the probe display appears. In other words, when distractors appear in the frequent location, participants are biased to ignore them. This minimizes the NP effect because the distractor on the prime display has not been processed.

1.1 Using ERPs as a converging measure

It is useful to employ converging methodological techniques to better understand the mechanisms underlying a phenomenon such as NP. ERPs represent a particularly useful tool for studying NP owing to their excellent temporal resolution. Several ERP components are relevant to adjudicating the underlying mechanism of NP. The *P2*, an ERP component that peaks about 200ms after stimulus onset, is typically elicited by visual stimuli and has primarily been associated with visual search and attention. The *N2* component, which peaks 200-350ms after stimulus onset, is associated with suppression and conflict monitoring (Eimer, 1993; Nieuwenhuis, Yeung, Van den Wildenbert, & Ridderinkhof, 2003). The *P3* component, typically observed between 250-500 ms after stimulus onset, is thought to reflect the degree of effort required to evaluate a stimulus (Donchin & Coles, 1988; Gibbons, Rammsayer & Stahl, 2006). Several recent ERP studies have enhanced our understanding of NP (Buchner & Naumann, 2006; Gibbons, 2006; Gibbons, 2009; Gibbons & Frings, 2010; Mayr, 2003; Mayr & Buchner, 2006). In the following section, we will describe ERP data used to support the suppression and episodic retrieval accounts of negative priming.

1.2 ERP evidence intended to support the suppression account

Although there have been many ERP studies of NP, only a few have examined NP in a spatial localization task. Ruge and Naumann (2006) found that the posterior N2 was larger for NP trials compared to control trials. This result is consistent with the suppression account of NP because the N2 is believed to be an index of attentional inhibition (Eimer, 1993; Nieuwenhuis et al., 2003). Likewise, Gibbons (2006) found that the posterior N2 component was larger for NP than control trials, indicating a persisting inhibition of the prime distractor location. In addition, Gibbons (2006) found a larger frontal N2 component that suggested inhibition of the prime response.

Although both studies found a larger N2 in the NP condition, they only compared NP to a control condition. Neither study included a positive priming (PP) condition (trials in which the location of the target on the probe display matches the location of the target on the prime display). Without a comparison with a PP condition, it is difficult to determine whether the N2 component reflects NP, or is merely a differential response to any stimulus that is repeated in a given location from prime to probe display.

1.3 ERP evidence intended to support the episodic retrieval account

Support for the episodic retrieval account comes from a different type of NP paradigm. Eriksen (1974) demonstrated NP in a flanker task where participants had to identify a centrally presented digit that was flanked by two other digits. The flanking digits were identical to one another but different from the target, (e.g., 6-4-6). In the NP condition, the flankers on the prime display served as the target on the subsequent probe display (e.g., 3-6-3). In the control condition, no prime digits were repeated on the probe display. In three ERP studies of NP that used the flanker task (Gibbons, 2006; Gibbons, 2009; Stahl & Gibbons, 2007), the P3 component was smaller for NP and PP trials than for control trials. The critical feature shared by these two conditions is that the probe target is a repeated prime stimulus; in other words, both conditions contain retrieval cues. Therefore, the smaller P3 amplitude was taken as support for the episodic retrieval account, according to which “a smaller P300 reflects a perceived prime–probe similarity which may correspond to a central concept of episodic retrieval theories, i.e., the ‘retrieval cue’” (Gibbons & Frings, 2010, pp. 340).

1.4 Using ERP to resolve the apparent inconsistencies

The ERP data reviewed above seem consistent with two different accounts of NP depending on which paradigm is used. Even though few studies provide direct ERP evidence for either the IOR or feature mismatch accounts, these accounts also make unique predictions based on the postulated underlying mechanisms. The feature mismatch account would predict a larger P3 amplitude on NP compared to PP trials. As stated earlier, P3 amplitude is thought to reflect the effort to evaluate a stimulus, and more effort is required for NP trials due to the mismatch between prime and probe displays. The IOR account would also predict larger N2 and P3 components for NP trials because participants need to overcome the *IOR* to return to a spatial location that previously contained an item.

However, as stated earlier, none of these theories can explain the behavioral findings of Reder et al. (2003). The goals of this paper are to determine whether the findings of Reder et al. will replicate in a modified ERP version of the experiment, and to test whether the ERP components will support the attentional adaptation account of those behavioral findings.

The adaptation of attention account predicts that P2 amplitudes of prime displays will be smallest when distractors appear in the frequent distractor location. Davis (1964) found that P2 was larger for relevant than irrelevant stimuli. Posner and colleagues (1998) have proposed a network for visual selective attention that involves both frontal and posterior cortices and may provide a framework for interpreting the cognitive correlates of the P2. The P2 component is thought to reflect automatic stimulus processing that is influenced by early allocation of attention and attentional shifts in processing (Eimer, 1993; Hillyard et al., 1973; Naatanen & Picton, 1987). This component is also associated with the evaluation of task-relevant stimuli (Potts, 2004; Potts, Martin, Burton & Montague, 2006) and reorientation of attention from non-targets to targets (Ofek & Pratt, 2004). When one of the stimuli appears in the frequent distractor location, attention will not be drawn there because of the prior history of failure (i.e., the stimulus rarely turns out to be the target, invariably a distractor). Therefore, when distractors appear in the frequent distractor location, less

attentional-switching and reorientation processes will be involved, as participants are more likely to first look elsewhere to find the target. Unlike other accounts of NP, the attentional adaptation account does not predict differences between NP and control trials for either the N2 or P3 components in probe displays.

In summary, we will vary the probability of the distractor by location in a target localization task. We expect to observe smaller P2 amplitudes when the prime distractor is in the frequent distractor location due to fewer shifts of attention. That is, when the distractor is in the frequent location, attention will likely be drawn to the correct location, thereby obviating the need to shift attention.

2. Method

2.1 Participants

Nineteen right-handed participants (9 males and 10 females with a mean age of 21) were recruited from Carnegie Mellon University. All participants had normal or corrected-to-normal vision, and none had a known history of neurological disorder. Each participant received \$15. Written informed consent was obtained from participants prior to the experiment.

2.2 Materials and Design

For each trial, participants viewed a prime display followed by a probe display. Each display contained four locations, one of which contained a target and one of which contained a distractor. For NP trials, the probe target appeared in the location that previously contained the prime distractor. For PP trials, the probe target appeared in the location that previously contained the prime target. The probe distractor in these trials did not appear in the location that contained the prime distractor. For control trials, the probe target appeared in a location that was previously unoccupied.

The probability of distractors varied across the four locations: 0, 20%, 20% and 60% for both prime and probe displays (Figure 1).² The assignment of location to probability was randomly determined for each participant with the constraint that the 0% and 60% probability locations were always on opposite sides of the screen. Targets appeared in each location with equal probability (25%). The absolute number (for all displays) of distractors appearing in each location was 510, 170, 170, 0 for the frequent, medium frequent-side (medium frequency distractor location in the same hemifield as the frequent distractor location), medium never-side (medium frequency distractor location in the same hemifield as the location that never has a distractor) and never locations, respectively. The absolute number of targets was 212 or 213 in each location. The experiment contained 205 control trials, 110 NP trials and 110 PP trials occurring in random order and determined separately for each participant. There were 425 trials presented in all.

²The design was modified from Reder et al. (2003) in order to address the need for many observations per condition in ERP research. We omitted the rare condition due to insufficient trials. Instead, we included two bi-lateral medium frequency locations, one in the same hemi-field as the frequent distractor and the other in the same hemi-field as the never distractor location.

As shown in Figure 1, the four positions in which targets and distractors appeared formed a V-shape. A horizontal bar was displayed at each location below where a stimulus would appear and remained on the screen at all times. The widest horizontal distance between two positions (the top of the V) measured 45 mm and subtended approximately 5.16° of visual angle. The smallest horizontal distance measured 17 mm (subtending 1.94°), and the vertical distance measured 12 mm (subtending 1.38°). The stimuli (a white O and a white X) subtended 0.4° vertically and 0.22° horizontally. A small white cross (a '+' sign), subtending 0.32° horizontally and vertically, was centered in the middle of the display and served as a fixation point. The background was black.

2.3 Procedure

Participants responded to the location of the target on a computer keyboard using four response keys (D, C, K, M) that mapped spatially onto the four stimulus locations. This procedure was also used in Reder et al. (2003). The keys were marked with yellow stickers. Participants were instructed to position their left index finger and middle finger on the C and D keys respectively, and their right index finger and middle finger on the M and K keys respectively, for all trials. Participants were informed that every display would contain a target (O) present in one of four locations, and a distractor (X) present in one of the remaining three locations. Participants were instructed to respond to the target as quickly and as accurately as possible. At the start of each trial, the word "Ready?" appeared at the center of the screen (Figure 2). The participant pressed the space bar to continue and the prompt disappeared. After a delay of 1500ms, a fixation cross appeared at the center of the screen for 500ms, followed by the prime display for 150ms. The screen turned blank and the participant responded to indicate the target location. Immediately following the participant's response, another fixation cross appeared for 500ms followed by the probe display, again for 150ms. The participant then indicated the location of the target in the second display. After the participant responded, the next trial began.

2.4 ERP recording

Participants sat in an electrically shielded booth. Stimuli were presented on a standard CRT monitor situated behind radio-frequency shielded glass. ERP recordings were made using 32 Ag–AgCl sintered electrodes (10–20 system) and a bio-amplification system (Neuroscan Inc., Sterling, VA). Impedances were adjusted to be less than 5 kΩ. Data were sampled at a rate of 1 kHz with a band pass filter of 0.1–200 Hz. Vertical eye movements were recorded using electrodes placed above and below the orbit of the left eye. Horizontal eye movements were monitored with an additional pair of electrodes placed at the external canthi. The right mastoid served as the reference electrode, and scalp recordings were algebraically re-referenced offline to the average of the right and left mastoids.

2.5 ERP analysis

The continuous data were segmented from -200 to 1000ms relative to trial onset for stimulus-locked analyses, and from -500 to 500ms for response-locked analyses. Data were corrected for ocular artifacts using a regression analysis (Semlitsch, Anderer, Schuster, & Presslich, 1986). Epochs were baseline corrected over the pre-stimulus interval for stimulus-locked analyses, and over the entire epoch for response-locked analyses (Luck & Hillyard,

1990). Trials contaminated with voltages above 100 V or below -100 V were excluded from further analyses. The segmented data were then averaged across trials within participants for each condition and smoothed using a 30Hz low pass filter. For statistical analyses, 32 electrodes were divided into anterior (F1, FPZ, F2, F7, F3, FZ, F4, F8), central (FT7, FC3, FCZ, FC4, FT8, T7, C3, CZ, C4, T8, TP7, CP3, CPZ, CP4, TP8) and posterior (P7, P3, PZ, P4, P8, POZ, O1, OZ, O2) regions. The dependent measures in the ERP analyses were the mean amplitudes of the ERP components in the given time ranges and electrode regions. Amplitudes were compared using repeated measures ANOVAs with electrode region, distractor location, and trial types as factors. The Greenhouse-Geisser correction was used when the assumption of sphericity was violated. All post-hoc tests were evaluated with a Bonferroni correction to protect against alpha slippage.

3. Results

3.1 Behavioral Results

3.1.1 Prime Displays

Effects based on distractor location: We first analyzed the effect of distractor location on performance for prime displays. Figure 3 presents mean RTs for correct responses as a function of distractor location. This graph collapses over the location of the target for each of the three possible distractor locations.³ There was a significant effect of distractor location on response times, $F(2, 36) = 3.45, p < .05, \eta_p^2 = .16$. RTs were reliably faster when the distractor was in the frequent distractor location than in medium never-side location, $t(18) = 3.03, p < .01, d = .70$, but not when the distractor was in the medium frequent-side location, $t < 1.5$. When the two medium probability distractor locations were collapsed, RTs were reliably faster when the distractor was in the frequent distractor location, $t(18) = 2.23, p < .05, d = .51$. There was no significant difference in accuracy for prime displays as a function of distractor location (frequent location: 98%; medium frequent-side location: 98%; medium never-side location: 97%), $F < 2$.

Effects based on target location: Although targets were equally probable in all four locations, previous research has demonstrated that the time to identify a target in a given location is strongly affected by the probability of a distractor being shown in that location (Reder et al., 2003). Figure 4 presents mean RTs for correct responses as a function of target location. The effect of target location was significant, $F(3, 54) = 3.68, p < .05, \eta_p^2 = .17$, such that RTs were faster when targets appeared in the never distractor location compared to in the medium never-side location, $t(18) = 4.05, p < .001, d = .96$. RTs were marginally faster when the target appeared in the medium frequent-side location compared to when the target appeared in the frequent distractor location, $t(18) = 1.87, p < .1, d = .44$. Participants responded faster to targets when they appeared in the medium frequent-side location as compared to the medium never-side location, $t(18) = 2.52, p < .05, d = .60$. No other comparisons for RTs were reliable and there were no reliable effects on accuracy (frequent location: 0.98%; medium frequent-side location: 0.96%; medium never-side location: 0.98%; never location: 0.98%), all $F_s < 2.0$.

³There are only three locations because distractors could not be in the never distractor location.

3.1.2 Probe Displays—Figure 5 presents mean RTs as a function of trial types. An ANOVA revealed a significant effect of trial type on accuracy, $F(2, 36) = 12.72, p < .01, \eta_p^2 = .41$, and correct RTs, $F(2, 36) = 24.25, p < .001, \eta_p^2 = .57$. Participants responded more slowly on NP trials than control trials, $t(18) = 6.30, p < .001, d = 1.46$, and PP trials, $t(18) = 5.55, p < .001, d = 1.31$. RTs did not differ between PP and control trials, $t < 1.5$. The accuracy of PP trials (99%) were significantly higher than NP (96%), $t(18) = 5.50, p < .001, d = .75$, and control trials (97%), $t(18) = 3.00, p < .05, d = .57$. Accuracy did not vary between NP and control trials, $t < 1.55$.

Next, for each of the three locations that could contain a distractor we computed the difference in mean correct RTs between NP and control trials for probe displays (NP costs), and we examined these NP costs by target location, shown in Figure 6. An ANOVA revealed a significant main effect of location on the size of NP effect for RTs, $F(2, 36) = 3.26, p < .05, \eta_p^2 = .153$. NP costs were greater in the medium frequent-side distractor location than for either the frequent distractor location $t(18) = 2.66, p < .05, d = .58$, or the medium never-side location, $t(18) = 2.13, p < .05, d = .51$.

In order to rule out the possibility that differences in NP costs across locations are driven exclusively by differences in RTs for control trials, we examined the absolute RTs for NP and controls trials as a function of the target's location. An ANOVA revealed a significant main effect of location on RTs for control trials, $F(2, 36) = 4.27, p < .05, \eta_p^2 = .192$. RTs were longer in the medium never-side distractor location than for either the frequent distractor location, $t(18) = 11.82, p < .1, d = .43$, or the medium frequent-side location, $t(18) = 2.43, p < .05, d = .57$. For NP trials, there was a marginally significant effect of location on RTs, $F(2, 36) = 2.63, p < .1, \eta_p^2 = .127$. While the effect of target location for NP trials was only marginally significant, the specific contrasts were reliable. The RTs were significantly longer in the medium frequent-side distractor location than in the frequent distractor location, $t(18) = 2.24, p < .05, d = .53$ and the medium never-side distractor location, $t(18) = 2.06, p < .05, d = .46$.

3.2 ERP Results

3.2.1 Prime displays—Figure 7 presents stimulus-locked waveforms in each region for prime displays based on the location of the distractor, collapsed over the location of the target. The P2 component was analyzed in the range from 150 – 270ms. There were significant main effects of distractor location, $F(2, 36) = 12.31, p < .001, \eta_p^2 = .406$, and electrode region, $F(2, 36) = 20.11, p < .001, \eta_p^2 = .528$. P2 amplitude was greater when distractors were in the medium frequent-side location than either the frequent, $t(18) = 4.41, p < .001, d = 1.04$, or the medium never-side locations, $t(18) = 3.59, p < .01, d = .84$.

P2 amplitudes were greater in the anterior region than the central region, $t(18) = 4.21, p < .01, d = .99$, and the posterior region, $t(18) = 5.26, p < .001, d = 1.25$. P2 amplitudes were also greater in the central region than the posterior region, $t(18) = 3.27, p < .05, d = .77$. The interaction between distractor location and electrode region was also significant, $F(4, 72) = 5.37, p < .01, \eta_p^2 = .23$. Although the effect was present over all regions, it was maximal at anterior sites. The mean amplitudes when distractors were in medium frequent-side

locations were significantly (or marginally significantly) higher than frequent and medium never-side locations. (Anterior region: $t(18) = 4.98, p < .001, d = 1.77, t(18) = 4.23, p < .001, d = .99$; Central region: $t(18) = 4.47, p < .001, d = 1.06, t(18) = 3.49, p < .01, d = .83$; Posterior region: $t(18) = 2.74, p < .05, d = .64, t(18) = 1.99, p < .1, d = .47$).

3.2.2 Probe displays—We analyzed probe displays as a function of trial type. Figure 8 shows waveforms for probe displays based on trial types. The N2 component was analyzed in the range from 220 – 310ms. An ANOVA revealed no effect of trial type, $F < 1$ and no interaction between trial type and electrode region, $F < 2$.

Because the latency of the P3 component appeared to differ by trial type, we analyzed P3 latencies to determine whether a response-locked analysis was justified. The latency of P3 was defined as the time point at which the P3 reached the peak within the time window between 300 – 500ms. The repeated measures ANOVA showed an effect of trial type, $F(2, 36) = 9.36, p < .001, \eta_p^2 = .34$, such that P3 latencies were delayed for NP trials relative to control, $t(18) = 3.89, p < .005, d = .92$, and PP trials, $t(18) = 3.28, p < .05, d = .77$. There was no reliable difference in peak latency between control and PP trials, $t < 1.5$.

To reduce the influence of latency differences on P3 amplitude, we used a response-locked analysis to compare P3 amplitudes among conditions (Figure 9). This approach has been used elsewhere when the time to categorize a stimulus and to subsequently respond varies among conditions (Luck & Hillyard, 1990). The P3 component was analyzed in the range between -100 – 100ms (surrounding each response). The main effect of trial type was significant, $F(2, 36) = 6.30, p < .005, \eta_p^2 = .26$, as was the interaction between trial type and electrode region, $F(4, 72) = 6.66, p < .001, \eta_p^2 = .27$. P3 amplitude was significantly larger during PP trials than during control or NP trials in the anterior (control: $t(18) = 4.06, p < .01, d = .97$; NP: $t(18) = 3.85, p < .01, d = .91$) and central regions (control: $t(18) = 3.17, p < .05, d = .75$; NP: $t(18) = 3.01, p < .05, d = .71$). P3 amplitude did not vary by trial type over the posterior region, $t < 1$. There was no reliable difference between NP and control trials, $t < 1$. The results were basically consistent with the patterns we observed in stimulus-locked waveforms (Fig. 8).⁴

We did not find significant differences for either N2 or P3 when comparing NP with control trials. Given the theoretical importance of these null results, we examined whether these null effects were due to a lack of statistical power by conducting a post hoc power analyses using GPower (Faul, Erdfelder, Buchner & Lang, 2009; Faul, Erdfelder, Lang, & Buchner, 2007) with power $(1 - \beta)$ set at 0.80 and $\alpha = .05$. The recommended effect sizes used for this assessment are as follows: small ($\eta_p^2 = .01$), medium ($\eta_p^2 = .06$), and large ($\eta_p^2 = .14$) (Cohen, 1992). The post hoc analyses revealed that the statistical power for this study was .20 for detecting a small effect, .93 for detecting a medium effect and .99 for detecting a large effect. Thus, there was more than adequate power (i.e., power = .80) at the moderate to large effect size level.

⁴Although there appears to be a difference among the response-locked waveforms from -400 to -200ms, the effect of trial type was not significant in this time window, $F < 1.5$.

4 Discussion

The goal of this study was to advance a theoretical account of NP using behavioral and ERP measures. It follows from the Attentional Adaptation account that participants learn to allocate attention to locations that are likely to contain targets and less likely to contain distractors. It also follows that prime RTs should be fastest and the P2 component smallest when prime distractors appear in expected locations. Most important, this account predicts that NP costs will be smallest when targets follow distractors in the frequent distractor location. The reason for this prediction is that participants are less likely to allocate attention to the frequent distractor location and thus are also less likely to have processed the distractor in the prime display for those trials. Consistent with these predictions, RTs were fastest and the P2 was smallest when distractors appeared in the frequent distractor location. NP costs, in turn, were smallest when targets followed distractors in the frequent location. Predictions of the suppression and episodic retrieval accounts were not supported in that we failed to find differences between NP and control trials for either the N2 or P3 components.

A tacit assumption in our account is that adaptation occurs on two time scales. The first-order, distractor-location effects, arise from the gradual accumulation of information about the spatial distributions of targets and distractors over trials, whereas the second-order, NP effects, mainly reflect the transient impact of the prime display. Note, a single mechanism that discounted trial history in a negatively accelerated manner could produce adaptation on both time scales (Reder et al., 2003).

NP costs in spatial location paradigms are typically quite small, on the average of 20ms (Neill et al., 1992; Tipper et al., 1990). Our NP effects were much larger, on the order of 70ms when distractors appeared at the medium frequent-side distractor location. The allocation of attention account explains why we observed comparatively large NP costs (see Reder et al., 2003). In the typical spatial location paradigm, distractors and targets appear with equal frequency in all locations. Without the bias manipulation we employed, participants are equally likely to inspect a target or distractor first because there is no reason to prefer one location to another. When participants inspect the target first on the prime display there will be no NP effect for the subsequent probe display. Only when the distractor is examined first on a prime display does a NP effect occur. In our study, when the distractor appeared in a location that frequently contained a distractor, participants were less likely to inspect the distractor first resulting in a smaller negative priming effect on average. Conversely, when the distractor appeared in locations that less frequently contained a distractor, participants were more likely to inspect the distractor first, resulting in comparatively large NP costs. Based on this explanation, it is clear that RTs to locate targets on prime displays should be fast when they appear in the Never distractor location and slow when they appear in the frequent distractor location.⁵

The pattern that begs for an explanation is why targets at the medium frequent location in the same hemifield as the frequent distractor location are detected more quickly than targets

⁵This adaptation does not require explicit knowledge: Reder et al. (2003) found that participants were unaware of the distribution of distractors even though their performance was affected by it.

at the medium frequent location in the same hemifield as the never distractor location. To understand this pattern of results, consider four distractor/target configurations. First, if the target and distractor are both in the hemifield with the frequent distractor location (35% of all the trials), the subject will inspect the medium location first as it is more likely to contain the target. Thus, RTs will be fast when the target appears in the medium frequent-side location (22.5% of all the trials, 90% of trials when targets were in the medium frequent-side location). Second, if the target and distractor are both in the hemifield with the never distractor location (5% of all the trials, 20% of trials when targets were in the never location), the subject will inspect the never location first as it is certain to contain the target. Thus, RTs will be fast when the target appears in the never distractor location. Third, when the target appears in the medium never-side location (25% of all the trials, 100% of trials when targets were in the medium never-side location), the distractor cannot appear in the same hemifield. Participants will sometimes inspect the wrong hemifield first and will need to re-allocate attention to the other hemifield. Thus, RTs will be slow when the target appears in the medium never-side location. Fourth and finally, when the target appears in the medium frequent-side location and the distractor appears in the medium never-side location (2.5% of all the trials, 10% of trials when targets were in the medium frequent-side location), participants will sometimes inspect the wrong hemifield first. But because these configurations occur infrequently, average RTs remain low when the target appears in the medium frequent-side location.

This account also explains why the negative prime costs are largest when the distractor appears in the medium frequent-side location on the prime display. Because participants frequently encode the distractor at that location during the prime display, they exhibit strong negative priming effects when the target subsequently appears at that location. When the distractor appears in the medium never-side location on the prime display, however, participants are unlikely to inspect that location. Because participants rarely encode the distractor at that location during the prime display, they exhibit weaker negative prime effects when the target subsequently appears at that location.

The ERP data provide converging evidence for this account of the processes engaged in this NP task. For the prime displays, we found that the P2 was reduced when distractors appeared in their frequent location or in the medium never-side location as compared with when distractors appeared in the medium frequent-side location. As we noted in the introduction, the P2 component is considered a signature of attention, orientation, or selective attention (Eimer, 1993; Hillyard et al., 1973; Naatanen & Picton, 1987). This discovery of a reduced P2 when distractors appeared in the frequent location and the medium never-side location is consistent with the proposal that participants were less likely to allocate attention to those locations.

In contrast to prior studies (Gibbons, 2006; Ruge & Naumann, 2006), and to the predictions of suppression theory, we found that the N2 component did not differ between NP, PP, and control trials. Those studies only compared NP and control trials. As such, it is not possible to determine whether the N2 was induced by NP or simply by the repetition of information at a spatial location.

Importantly, when the experimental design does not bias participants to expect targets to repeat in certain locations, NP effects can be explained in terms of IOR, as stated in the introduction (Christie & Klein, 2001; Milliken, Tipper, Houghton, & Lupianez, 2000; Tian, Klein, Satel, Xu, & Yao, 2011; Tipper, Driver, & Weaver, 1991). IOR postulates that attention is less likely to return to locations that were just explored. Therefore, the IOR account might explain the small behavioral positive effect⁶ and larger P3 amplitudes for PP trials observed in our study because IOR applies to both distractor and target locations. In previous studies (Gibbons, 2006; Ruge & Naumann, 2006), an N2 may have been evoked because participants needed to overcome IOR to return to a spatial location that previously contained an item. In our task, we did not find a larger N2 for NP trials because IOR is less likely to dominate processes when there is a strong bias in attentional allocation (see arguments for why in Reder et al., 2003).

Also, in contrast with previous studies (Gibbons, 2006; Gibbons, 2009; Stahl & Gibbons, 2007) and the predictions of the episodic retrieval account, we found that the P3 amplitude was *larger* for PP trials than for NP or control trials. As reviewed in the introduction, Gibbons found that the P3 was larger for control trials than for NP or PP trials. The P3 effect was taken as support for the episodic retrieval account, as a smaller P3 reflects higher prime-probe similarity. Perhaps the different pattern is due to the fact that Gibbons employed a flanker task. Conceivably, differences in the ERP component structures reflect underlying differences in the mechanisms engaged in the flanker versus the spatial localization task. Our ERP results are also inconsistent with the feature mismatch account. This account predicts larger P3 amplitudes for NP trials than control trials because feature mismatch requires more effort to analyze stimuli, a result that is the opposite of what we found. At the very least, the finding of an enhanced P3 for PP trials is inconsistent with the view that episodic retrieval or feature mismatch produce NP in a spatial localization task.

One possible concern with our ERP results is that we did not observe lateralized ERPs (*e.g.*, N1pc) associated with negative priming (Ruge & Naumanns, 2006). This may relate to aspects of our design that precluded certain analyses. That is, given that we varied the probability of distractors by location, certain trial types would have insufficient numbers of trials in some locations when further partitioned by hemisphere. The design we chose was motivated by our primary goal of providing converging evidence for the Attentional Adaptation Account. Therefore, the most important analysis in our study concerns attention allocation and the processes involved in switching locations. It is unfortunate that one cannot easily address laterality questions of NP when conducting ERP studies that vary base-rates.

To conclude, throughout his career, Ed Smith studied how the human mind selectively processes rapidly presented information. He used converging measures to challenge existing interpretations, and to advance new theories of cognitive control and attention. In much the same way, we used converging measures, reaction times (RTs) and event-related potentials (ERPs), to challenge existing interpretations of negative priming, and to advance a novel

⁶One might have expected faster reaction times in PP trials because of the response repetition. Motor savings may have been obscured by the requirement to overcome IOR at those spatial locations, however.

account of attentional adaptation. The behavioral results of our study support this account, but are inconsistent with other theories. Likewise, the neural results are in line with this account, but not with other theories. These converging sources of evidence make a compelling case for an attentional adaptation account of negative priming. Finally we note that Ed would not be content to ‘accept’ a theory – and nor are we. The more basic message of this paper is that alternate measures and targeted methodological departures from standard paradigms can force re-evaluations of existing theories. By following Ed’s example, we can continue to refine ours and others’ theories of negative priming.

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Figure 1.
The probability of the distractor in each location

Figure 2.
Trial procedure

Figure 3.

Mean correct response times (with standard error bars) for prime displays, based on position of distractor, collapsed over target location (note, distractors cannot occur in the never location).

Figure 4.

Mean correct response times (with standard error bars) for prime displays, based on target position (note, position is defined in terms of frequency of distractor in that location--targets are equally probable in all locations).

Figure 5.

Mean correct response times (with standard error bars) for probe displays, based on trial type.

Figure 6.

The negative priming cost (the difference in mean correct RTs between negative-prime and control trials for probe displays) for each possible location that could contain a distractor.

Figure 7.
ERP waveforms for prime displays, based on distractor position.

Figure 8.
Stimulus-locked ERP waveforms for probe displays, based on different trial types.

Figure 9.

Response-locked ERP waveforms for probe displays, based on trial type.