Oddball distractors demand attention: Neural and behavioral responses to predictability in the flanker task

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Abstract

Predictable and unpredictable distractors may differentially affect attention. We adapted the Eriksen flanker task by manipulating the probability with which specific flankers occurred. Subjects reported the orientation of briefly-presented targets while attempting to ignore four flanking items. Flankers had either standard (90% of trials) or oddball (10%) orientations. Congruent and incongruent configurations were equiprobable, as were target orientations. Oddball flanker orientations substantially enhanced congruency effects: performance was best when the target was congruent with oddball flankers and worst when it was incongruent. We recorded scalp EEG while subjects performed the task, and later computed ERPs timelocked to stimulus onset. Oddball flanker orientations evoked a visual mismatch negativity (vMMN). Subjects' temperament predicted individual differences in vMMN magnitude. Orientation sensitivity predicted larger vMMNs; attential selectivity predicted smaller. Behavioral and vMMN results indicate that subjects exploit distractor predictability to support more-effective active inhibition; oddballs disrupt this strategy. Despite subjects' attempts to ignore the flankers, unexpected distractors strongly influence neural responses and behavioral performance.

Highlights
- We modified flanker frequency, creating Standard and Oddball flankers.
- Oddball flankers enhance the flanker congruency effect on reaction time and accuracy.
- Oddball flankers elicit a visual mismatch negativity (vMMN).
- Individual differences in temperament predict individual vMMN magnitudes.

The natural environment's predictable spatial and temporal regularities allow the human brain to operate in a predictive, feedforward mode (Bar, 2009). This ability to extend environmental structure to predict forthcoming stimuli facilitates many cognitive tasks, from identifying objects (Biederman, Mezzanotte, & Rabinowitz, 1982) to planning and executing behaviors (Maryott, Noyce, & Sekuler, 2011) to appropriately allocating attention (Posner, 1980). Most research into predictive processing has considered the impact of regularities among a task's targets, a focus which is entirely understandable, as such regularities clearly facilitate cognitive performance. However, little work has been done on regularities among task-irrelevant distractors. Everyday experience suggests that, for example, it is easier to ignore a train whistle that blows at the same time every day than to ignore one that occurs at random. Further, we know that attention plays two complementary roles in cognition. We direct attention to targets and we withdraw attention from, or perhaps actively inhibit, distractors (James, 1890). If predictable distractors facilitate such inhibition, we should find enhanced attentional selectivity when distractors are predictable, and impaired selectivity when they are irregular. In order to investigate this proposition, we measured the behavioral and neural consequences of both predictable and oddball distractors.

Our study adapted the Eriksen flanker task (Eriksen & Eriksen, 1974), which entails interference between conflicting visual information. Specifically, the flanker task requires subjects to focus visual attention on a single target, such as a left-facing or right-facing chevron, while attempting to ignore surrounding items. The flanking distractors can either match or differ from the target, and the congruency between the flankers and the target influences the accuracy and reaction time with which subjects can report the target's orientation (e.g. Eriksen & Eriksen, 1974; White, Ratcliff, & Starns, 2011). Despite subjects' attempts to ignore the distractors, flankers that are incongruent with the central target interfere with processing, leading to reduced speed and accuracy on those trials (Schmidt & Dark, 1998). We modified the flanker task by manipulating the frequency with which different distractors appeared, creating predictable and oddball

flankers.

To supplement our behavioral measures, we drew on event-related brain potentials (ERPs), which provide a direct measure of neural activity time-locked to specific events (Luck, 2005). Because we were interested in the effects that oddball flankers might have, we focused on one particular ERP component, the visual mismatch negativity (vMMN). This is an early, negative-going deflection in the ERP that occurs in response to occasional deviant elements within a sequence of visual stimuli that obey some regularity (Czigler, 2007; Pazo-Alvarez, Cadaveira, & Amenedo, 2003). The vMMN is analogous to the well-known auditory mismatch negativity (MMN), which is theorized to be generated in auditory cortex when a predictive signal from prefrontal areas is disconfirmed by incoming sensory information (Garrido, Kilner, Stephan, & Friston, 2009; Wacongne, Changeux, & Dehaene, 2012). The auditory and visual MMNs arise regardless of the focus of subjects' attention, and are even elicited when subjects are attending to stimuli in a different sensory modality (Näätänen, Paavilainen, Titinen, Jiang, & Alho, 1993; Stefanics, Kimura, & Czigler, 2011).

We measured the visual mismatch negativity in order to characterize the neural response to infrequent distractors which subjects are actively attempting to ignore. We then assessed correlations between the neural responses, the behavioral effects of the frequent and infrequent distractors, and individual differences in temperament. We hypothesized that infrequent distractors would evoke a visual mismatch negativity, and that they would lead to an outsize flanker congruency effect, due to the difficulty of suppressing attention to unpredictable flankers.

An area of growing interest among cognitive neuroscientists is the nature and origins of individual differences in neural activity and behavioral effects. One potential source of such differences is variability in emotional, motor, and attentional reactivity (Kagan, 2003; Rothbart, 2007). Performance on the flanker task requires attentional separation of stimuli whose appearance and spatial selection are very similar. If occasional oddball flankers disrupt this separation, individual differences in sensitivity or reactivity to sensory input may predict the degree of such disruption. We thus hypothesized that differences in temperament would predict differences in the extent to which oddball flankers enhance the flanker congruency effect. Further, the vMMN
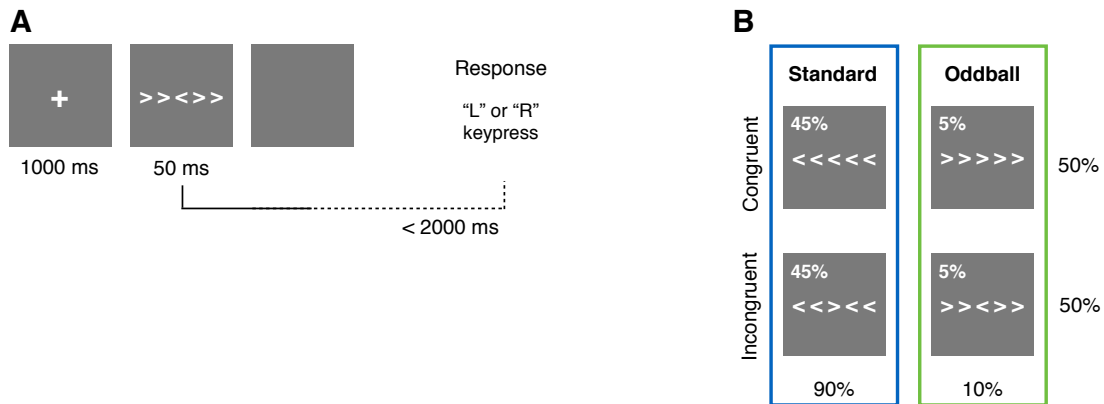
Figure 1. (A) The sequence of events within a trial. After fixation, the flanker stimulus was displayed for 50 ms, after which subjects had two seconds to report the orientation of the center chevron. (B) Diagram of the two-by-two trial design. One factor, **flanker orientation**, governed the orientation of the four flanker chevrons; the second, **congruency**, governed the relationship between the central target and its flankers. Whether the **Standard** flanker orientation was left or right was counterbalanced within subjects. 90% of trials incorporated the **Standard** flankers (45% **Congruent** and 45% **Incongruent**); 10% of trials incorporated the **Oddball** flankers (5% **Congruent** and 5% **Incongruent**).

indicates that oddball stimuli are being processed, despite attention being directed away from them (Stefanics et al., 2011; Näätänen, Paavilainen, Rinne, & Alho, 2007), and we thus hypothesized that individual differences in temperament would predict the magnitude of the vMMN response to deviant distractors.

Methods

Subjects

Twenty members of the Brandeis University community (15 female, age range 18–21) participated in this study. All were right-handed (mean score on the revised Edinburgh Handedness Inventory 89.49, SD = 12.85). Two other subjects completed one experimental session but did not return for the second; their data were discarded.

Experimental task

We developed a modified Eriksen flankers task using chevron stimuli (Eriksen & Eriksen, 1974). Chevron stimuli have frequently been used in the flankers task to minimize reliance on

verbal processes and literacy (e.g. Dye, Green, & Bavelier, 2009; Emmorey, Luk, Pyers, & Bialystok, 2008; Hajcak & Foti, 2008; Mayr, Awh, & Laurey, 2003; White et al., 2011; Wylie, Ridderinkhof, Eckerle, & Manning, 2007). The basic trial structure is shown schematically in Figure 1A. On each trial, subjects were presented with an array of five chevrons that were displayed for 50 ms and were not masked upon offset. They were instructed to report whether the central chevron was facing to the left or to the right. We will refer to this central chevron as the *target*, and the two chevrons on each side of it as the *flankers*. The four flankers were always consistently oriented, and the central chevron's orientation was equiprobably congruent or incongruent with its flankers. After a subject's response, a fixation cross was displayed for an inter-trial interval of 1000 ms before the next trial display appeared.

Subjects viewed the display from a difference of approximately 57 cm, and were instructed to maintain fixation on a central cross. Each chevron subtended approximately 1.4° visual angle, and the full array extended to an eccentricity of 4.7° to the left and right of the fixation point..

In order to maintain more-consistent error levels across subjects and conditions, subjects received feedback about their performance after every thirty trials (after Hajcak & Foti, 2008). If the subject had responded correctly on between 75% and 90% of those trials, the feedback was "You're doing great!" If accuracy was lower than 75%, the feedback instructed the subject to increase their accuracy; if it was above 90%, the feedback instructed the subject to respond more quickly.

Trials were randomly distributed among four conditions in a two-by-two design, as shown in Figure 1B. The first factor governed the orientation of the four flanker chevrons. On ninety percent of trials, the flanker chevrons had one orientation (the **Standard** orientation) and on ten percent of trials they had the other (the **Oddball** orientation). The second factor governed the relationship between the central target and the flankers. On half of trials, the target was **Congruent** with the flankers, and on half it was **Incongruent**. Left-facing and right-facing targets were equally frequent, and the orientations comprising **Standard** and **Oddball** flankers were counterbalanced within subjects.

On approximately 13% of trials, a burst of auditory white noise was presented after either

stimulus presentation or after response, to elicit startle reactions. Startle blink was measured via electromyography; however, we observed no effects of timing or trial type on startle blink magnitude and those data are not presented here.

Procedures and Analyses

Each recording block comprised 510 trials, with the first thirty discarded as practice. Each subject completed two blocks with left-facing flankers as the **Standard** orientation and two with right-facing flankers. These four blocks were completed in two separate recording sessions; the order of blocks was counterbalanced across subjects. By the end of the experiment, each subject had completed 2,040 trials, 1,920 of which were included for analysis.

Subjects filled out an anonymous questionnaire after each recording session, confirming that they got reasonable amounts of sleep, were not under the influence of any psychoactive substances, and had no medical history, such as a head injury or neurological diagnosis, that would lead us to exclude their data.

Behavioral measures. Subjects' reaction times and responses were recorded from each trial and analyzed. We computed accuracy and median reaction time for each of **Congruent Standard**, **Incongruent Standard**, **Congruent Oddball**, and **Incongruent Oddball** conditions as well as Vincentile reaction times and accuracy for each condition (Vincent, 1912; Ratcliff, 1979).

After the end of their final experimental session, subjects completed the Adult Temperament Questionnaire Short Form (ATQ). This instrument's 77 items form several self-report scales describing temperament factors (Evans & Rothbart, 2007). We selected two factors that seemed likely to capture task-relevant aspects of temperament: Attentional Control and Orienting Sensitivity. Attentional Control refers to the capacity to focus attention, and to shift attention as desired. "It's often hard for me to alternate between two different tasks," is an example of a reverse-scored Attentional Control item. Orienting Sensitivity refers to awareness of low-intensity environmental and self-generated stimuli and experiences. "I often notice visual details in the environment," is an example of an Orienting Sensitivity item. We hypothesized that the Attentional Control would account for some variability in people's task performance, and that both would

relate to variability in the ERPs elicited by **Oddball** and **Standard** stimuli.

EEG recording and analyses. A high-density EEG system (Electrical Geodesics, Inc., Eugene, OR) with 129 electrodes sampled scalp electroencephalographic signals at 250 Hz using a high-impedance amplifier. Signals were recorded for later, off-line analysis. At the start of each experimental session, all channels were adjusted for scalp impedance below 50 kΩ impedance; after one experimental block, channel impedences were measured and, if needed, returned to at most 50 kΩ scalp impedance before the subject completed the session.

After recording, EEG data were preprocessed using the EEGLAB Matlab toolbox (Delorme & Makeig, 2004). Continuous EEG signals were bandpass filtered to between 0.25 and 100 Hz using a first-order Butterworth filter. A 60 Hz notch filter was also applied to the continuous data, to reduce line electrical noise. Stimulus onset flags were shifted by 36 ms to correct for delay introduced by the amplifier's antialiasing filter. The data were then broken into epochs that were time-locked to stimulus onset and lasted from 236 ms before stimulus onset to 464 ms after. Epochs containing muscle artifacts, eye movements, and bad channels were identified by visual inspection and rejected. Independent components analysis allowed us to isolate eye blink activity, which was subtracted from the data. Data were again visually inspected for artifacts not corrected by the previous two processes. The number of trials per condition remaining after data cleaning are shown in Table 1. Finally, data were re-referenced to the average voltage, and averaged across trials and sessions to create a subject average ERP for each condition.

Table 1
Mean number of trials per subject in the final ERPs.

Flanker Orientation	Congruency		Total
	Congruent	Incongruent	
Standard	729.05 (105.05)	727.70 (109.43)	1,456.75 (214.10)
Oddball	79.05 (15.34)	78.50 (14.61)	157.55 (29.44)

Note. Standard deviations are given in parentheses.

To compare ERPs evoked by trials with Oddball flankers to those evoked by trials with Standard flankers, we used a data-driven, non-parametric clustering approach to select time windows and electrodes for analysis (Maris & Oostenveld, 2007). The FieldTrip toolbox includes

software implementing this approach (Oostenveld, Fries, Maris, & Schoffelen, 2011). It first quantifies the difference between two conditions at each electrode, at each time point, using Student's t. Then, clusters of time- and/or space-adjacent electrodes with $|t| > t_{\text{criterion}}$ are identified. Criterion t-values were selected by the experimenters after considering several factors, including the degrees of freedom of the comparison, the magnitude of the difference between the conditions, and the degree of spatial and temporal specificity desired.

To test significance, the t-scores of each cluster's member electrodes and time-points were summed, giving a cluster score that reflected both the extent of the cluster (in space and time) and the magnitude of the difference between the conditions at those electrodes and time points. A reference distribution of test statistics was generated by randomly permuting the data across the two conditions being compared, computing such scores for each resulting cluster, and taking the largest such cluster score on each of 1,000 permutations. Where cluster-wise p-values are reported, they have been derived by comparing the empirically-obtained cluster score to such a reference distribution. Grand average ERPs were created by averaging across subjects and across the electrodes identified as part of the cluster.

Using this clustering algorithm, we analyzed each trial's data in an epoch from 86 ms before stimulus onset to 284 ms after. This time window was restricted so that the reliable, although small, vMMN effect was not drowned out by a larger, centralized, response-related component that peaked around 340 ms after stimulus onset. The data-driven nature of the clustering algorithm makes it sensitive to large components such as this, and the smaller time window allowed us to isolate our component of interest.

Given this large response-related ERP component, we ran a control analysis on a subset of trials, matched for reaction time. This allowed us to rule out two potential confounds: response-preparation effects, and trial-number artifacts. We identified trials that survived the cleaning process and, for each trial with **Oddball** flankers, we selected a matched trial from the same subject and session, with **Standard** flankers and a similar (within 8 ms) reaction time. When more than one trial met those criteria, we selected one at random. Subject-average and grand-average ERPs were then computed from those trials.
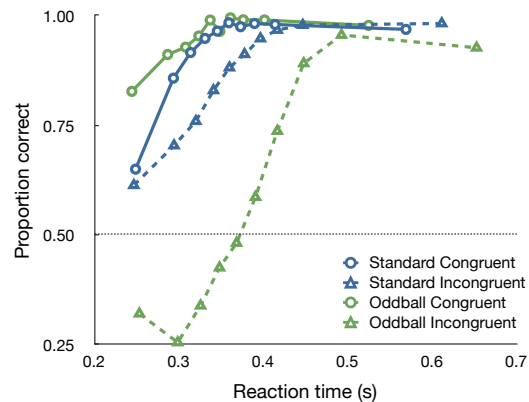
Results

Behavioral measures

Figure 2. Reaction time and proportion correct for each decile of Standard (blue) and Oddball (green) trials, when the flankers are Congruent (solid lines) and Incongruent (dashed lines).

Figure 2 shows the effects of congruency and flanker orientation on subjects' speed and accuracy in the flanker task. On trials in which the flankers had the **Standard** orientation (presented in blue in Figure 2), subjects were faster and more accurate on **Congruent** trials (proportion correct 0.93, SD = 0.04; median correct reaction time 356 ms, SD = 33) than on **Incongruent** trials (proportion correct 0.86, SD = 0.05; median correct reaction time 378 ms, SD = 37), with larger accuracy differences occurring on trials where subjects responded quickly. This effect was exaggerated when the flankers had the **Oddball** orientation (presented in green in Figure 2). On **Oddball Congruent** trials, subjects were faster and more accurate (proportion correct 0.95, SD = 0.04; median correct reaction time 343 ms, SD = 31) than on **Standard Congruent** trials, and on **Oddball Incongruent** trials, subjects were slowest and least accurate (proportion correct 0.59, SD = 0.16; median correct reaction time 427 ms, SD = 47).

These results were confirmed by two-way repeated measures ANOVAs with factors **congruency** and **flanker orientation**. There was a main effect of **congruency** on proportion correct (F(1,19) = 94.211, $p < .0001$), a main effect of **flanker orientation** on proportion correct (F(1,19) = 80.019, $p < .0001$), and a **congruency** × **flanker orientation** interaction (F(1,19) = 101.809, $p < .0001$). There was a significant main effect of **congruency** on median correct reaction time

(F(1,19) = 92.244, p < .0001), no main effect of **flanker orientation** on median correct reaction time (F(1,19) = 0.026, p = .8747), but a significant **congruency** × **flanker orientation** interaction (F(1,19) = 30.917, p < .0001).

Post-hoc t-tests on accuracy and reaction time confirmed that each condition was significantly different from the others. Subjects were faster and more accurate on **Oddball Congruent** trials than on **Standard Congruent** trials (accuracy: paired $t(19)$ = 6.304, p < .0001; reaction time: paired $t(19)$ = 5.781, p < .0001), faster and more accurate on **Standard Congruent** trials than on **Standard Incongruent** trials (accuracy: paired $t(19)$ = 9.984, p < .0001; reaction time: paired $t(19)$ = 11.733, p < .0001), and faster and more accurate on **Standard Incongruent** trials than on **Oddball Incongruent** trials (accuracy: paired $t(19)$ = 9.688, p < .0001; reaction time: paired $t(19)$ = 10.077, p < .0001).

On average, subjects scored near the center of the ATQ's range for both factors of interest. The mean Perceptual Sensitivity score was 5.00 (SD = 0.86), and the mean Attentional Control score was 4.03 (SD = 0.91). Temperament scores did not correlate convincingly with overall proportion correct, overall reaction time, or the interaction effect on either measure.

ERPs

Figure 3 illustrates the neural activity that accompanied the presentation of **Standard** and **Oddball** flanker directions. A data-driven clustering and permutation analysis identified the cluster of electrodes that best captured (p < .001) the difference in scalp voltage topographies between **Standard** and **Oddball** flankers. This cluster was derived with $t_{criterion}$ = 3.883, the critical t-value at α = .001 and df = 19. The cluster was composed of 16 posterior electrodes that were more negative-going on **Oddball** than on **Standard** trials during an interval from 144–284 ms after stimulus onset. The negativity at these posterior electrodes continues past 284 ms, but those time points were not considered by the cluster analysis algorithm, as discussed under Methods. Figure 3A depicts the locations of the electrodes making up the cluster and the distribution of t-scores between ERPs to the two flanker orientations during that time window. The traces in Figure 3B show ERPs at the cluster, time locked to stimulus onset, to **Standard** (blue) and **Oddball**
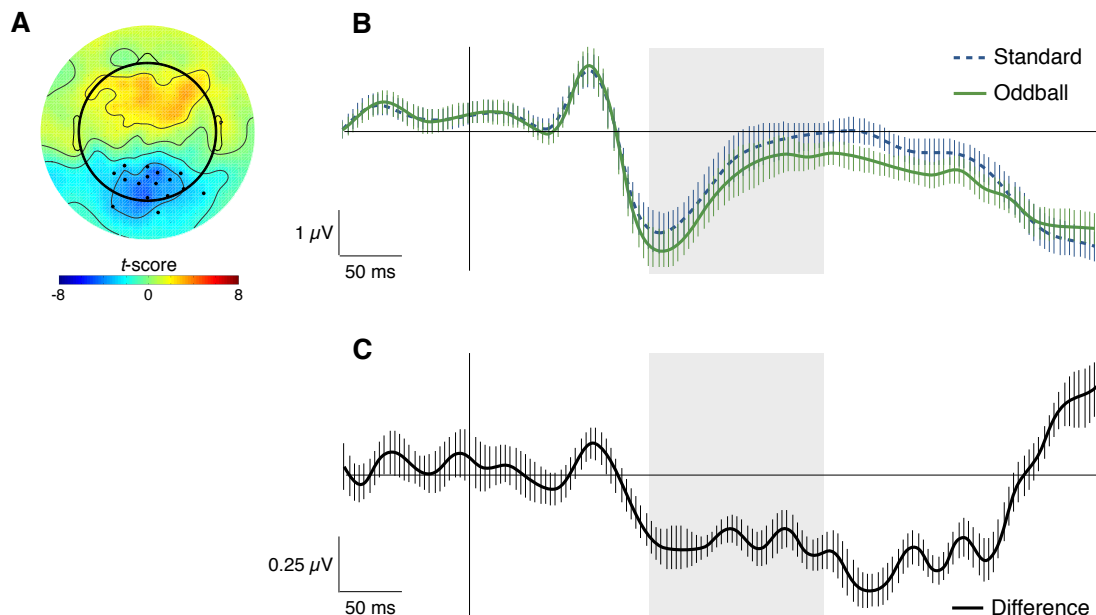
Figure 3. ERPs to **Standard** and **Oddball** flanker orientations at a cluster of posterior electrodes. A: Topographical plot showing the locations of the 16 electrodes making up the cluster, and the distribution across the scalp of t-values at 144–284 ms after stimulus onset. B: Traces show ERPs time locked to stimulus onset for **Standard** (shown in blue) and **Oddball** (green) flankers, at the cluster of electrodes shown in panel A. Error bars are within-subject s.e.m.; gray boxes denote the time window identified by the clustering algorithm. C: Trace depicts the difference between the two traces shown in panel B. Negative values occurred when ERPs to **Oddball** flankers were more negative-going than those to **Standard** flankers.

(green) flankers. Figure 3C shows the difference between the two traces in Figure 3B. Negative values reflect **Oddball**-evoked ERPs that were more negative-going than **Standard**-evoked ERPs.

Figure 4 illustrates the results of a control analysis. To confirm that the sustained negativity seen in response to **Oddball** flankers was not response-related, we down-sampled the trials with **Standard** flankers to a reaction-time-matched subset. The median correct reaction time for both **Standard** and **Oddball** trials in the down-sampled dataset was 360 ms (SD = 38 ms in both conditions), and the mean number of trials per condition was 151.3 trials (SD = 30 trials). The traces in Figure 4A show ERPs at the same cluster of electrodes as in Figure 3, time locked to stimulus onset, to **Standard** (shown in blue) and **Oddball** (green) flankers. Figure 4B shows the differences between the two traces in Figure 4A. These traces are not substantially different from those shown in Figure 3, and allayed our concerns about artifacts due to reaction time
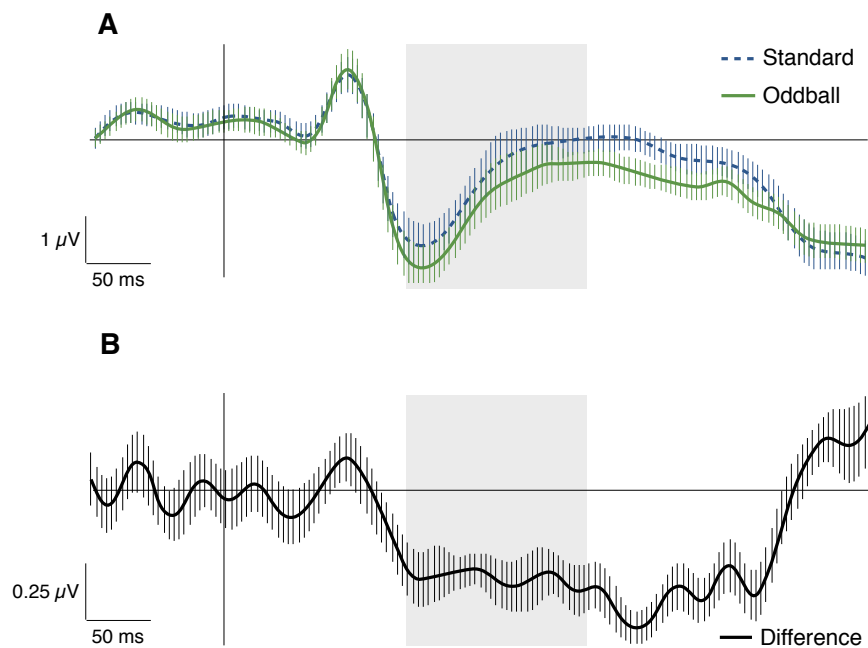
Figure 4. ERPs to **Standard** and **Oddball** flanker orientations at the same cluster of posterior electrodes, on a subset of trials matched for reaction time. B: Traces show ERPs time locked to stimulus onset for **Standard** (shown in blue) and **Oddball** (green) flankers, at the cluster of electrodes shown in Figure 3, panel A. Error bars are within-subject s.e.m.; gray boxes denote the time window identified by the clustering algorithm. B: Trace depicts the difference between the two traces shown in panel A. Negative values occurred when ERPs to **Oddball** flankers were more negative-going than those to **Standard** flankers. After matching trials on reaction time, the vMMN appears quite similar to that seen in Figure 3; if anything, the difference between conditions is increased.

differences or numbers of trials.

We tested whether vMMN magnitude reflected subjects' susceptibility to interference from unexpected flanker orientations. To account for differences in neural function and anatomy that are unrelated to such susceptibility, we first regressed vMMN magnitudes on the N2 magnitudes elicited by **Standard** flankers. N2 magnitude was operationalized as each subject's mean amplitude of the ERP from 144–184 ms after stimulus onset on **Standard** trials, averaged across the 16 electrodes in our cluster of interest. Residual vMMN magnitudes after this regression gave us a measure of neural responses to unexpected events after correcting for individual variation in scalp signal.

Residual vMMN values were correlated with proportion correct on **Oddball Congruent**
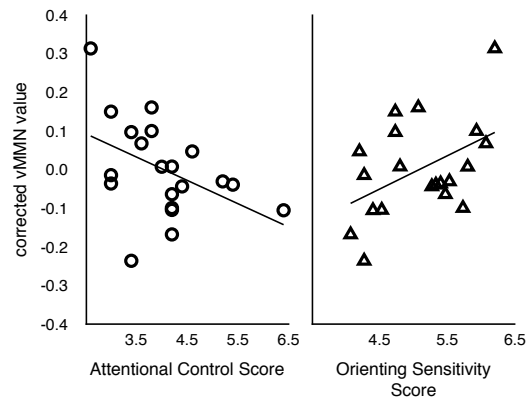
Figure 5. Two self-report temperament factors, attentional control and orienting sensitivity, are significantly correlated with individual differences in vMMN magnitude. Higher scores on attentional control predict larger (more negative) vMMNs; higher scores on orienting sensitivity predict smaller vMMNs.

trials ($r = -0.448$, $p = .048$), such that those subjects who were most accurate on these trials had larger (negative) vMMNs. However, residual vMMN magnitude did not correlate convincingly with proportion correct on **Oddball Incongruent** trials, ($r = 0.194$ $p = .412$), nor did it correlate with any reaction time measures ($|r| < .250$ for all relationships).

Figure 5 illustrates the relationship between temperament and vMMN magnitude. Residual vMMN values were marginally negatively correlated with Attentional Control score ($r = -0.439$ $p = .053$), but positively correlated with Orienting Sensitivity score ($r = 0.464$ $p = .039$). These results suggest that subjects who scored higher on Attentional Control tended to have larger (negative) vMMNs, while subjects who scored higher on Orienting Sensitivity tended to have smaller vMMNs. Combining Attentional Control and Orienting Sensitivity in a multiple linear regression significantly predicted N2-corrected vMMN magnitude ($R^2 = 0.35$, $p = .026$).

Discussion

We modified the Eriksen flanker task by manipulating flanker frequency to create Standard and Oddball flanker directions. We replicated the usual flanker congruency effect: subjects were faster and more accurate when flankers were congruent with the target. As we hypothesized, this effect was strongly modulated by the predictability of the flankers. On trials with Oddball

flankers that were congruent with the target, subjects were fastest and most accurate, while on trials with Oddball flankers that were incongruent with the target, subjects' performance was markedly impaired.

This result is consistent with previous work demonstrating that unexpected or poorly-predicted events capture attention in associative learning tasks (Wills, Lavric, Croft, & Hodgson, 2007), and that deviant events in an unattended location or sensory modality impair target detection (Ljungberg & Parmentier, 2012; Nöstl, Marsh, & Sörqvist, 2012). While there have been some prior investigations into the effects of predictability in the flankers task, these have been restricted to manipulations of the frequency of incongruent trials (e.g. Gratton, Coles, & Donchin, 1992; Purmann, Badde, Luna-Rodriguez, & Wendt, 2011), and the frequency of particular flanker/target combinations (Lehle & Hübner, 2008; Wendt & Luna-Rodriguez, 2009). Those investigations have suggested that when incongruent trials are likely, people adjust their level of cognitive control and are less influenced by flankers (Gratton et al., 1992).

Several mechanisms for that adjustment have been proposed. One is that the presence of conflict on an incongruent trial leads to an activation of cognitive control mechanisms, such that reaction times on subsequent trials are increased and the flanker congruency effect is decreased (Gratton et al., 1992). This effect occurs on both a trial-by-trial timescale and a more global timescale, such that blocks with frequent incongruent trials have reduced flanker congruency effects relative to blocks with infrequent incongruent trials. Another proposed mechanism is that short-term priming effects facilitate responses to repeated stimuli (Mayr et al., 2003; Wendt & Luna-Rodriguez, 2009) and repeated responses (Mordkoff, 1996). Neither of these can entirely explain our behavioral results.

We found a reduced flanker congruency effect of Standard (frequently-occurring) flankers and an enhanced effect of Oddball flankers, despite holding the probability of incongruent trials stable at fifty percent. Our data thus support active inhibition of predictable flankers. Previous work in a related Stroop task has shown that explicit cues as to the nature of the upcoming distractor can dramatically reduce interference, due to recruitment of an active inhibition process (Chao, 2011). Here, subjects may develop a template for probable flanker identities based on

previous trials. On a trial whose flankers match that template, subjects are more successful at inhibiting the flankers; on a trial whose flankers differ from the template, subjects are markedly less successful.

Another mechanism that could give rise to our behavioral results is adjustment of attentional selectivity in response to the target's identity. As target identity is correlated with congruency, subjects could use more stringent attentional selection when the target shares an orientation with the Oddball flanker orientation, and more relaxed selection when it shares an orientation with the Standard. This would account for the increased congruency effect on Oddball trials, but it requires that subjects first identify the target and only then adjust attention to appropriately filter the flankers. Such backwards-acting adjustment of attention seems implausible, and thus unlikely to account for the pattern of responses that we observed.

Our results also confirmed our hypothesis that Oddball flanker orientations would evoke a visual mismatch negativity. This ERP component is thought to reflect a potentiation of the neural response to stimuli that do not match a predictive feedback signal sent from higher cortical areas to the sensory cortices (Garrido et al., 2009; Wacongne et al., 2012). The presence of a vMMN to the Oddball flankers confirms that subjects' brains are sensitive to the regularity governing flanker direction, despite the long interval between successive trials and the occasional intervening feedback events. The memory system that gives rise to the vMMN is therefore more robust than has previously been demonstrated (Pazo-Alvarez et al., 2003). While previous work establishing the mismatch negativity in the visual domain has not demonstrated interactions between deviants in the unattended region and behavioral performance, here we've shown that human sensitivity to unexpected events elicits a reliable neural signature and interferes with spatially-precise attentional selectivity.

Interestingly, a recent study manipulated the relationship between background events and target events. Czigler and Sulykos (2010) found that reaction times were longer when background and target events were in the same task domain (e.g. orientation changes). They also found that vMMN evoked by background events was smaller when background and target events were in the same task domain. Czigler and Sulykos concluded that the overlap in task domain resulted

in cognitive resources being allocated to target events, reducing processing of task-irrelevant background events. In our task, the strong behavioral effects demonstrate that subjects are processing the flankers, despite (or possibly because of) their close similarity to the targets. The spatial layout or specific stimuli of our task may be responsible for this different result.

We also found, as hypothesized, that subjects' self-reported temperament could predict their neural sensitivity to Oddball flankers. Two factors—Attentional Control and Orienting Sensitivity—together predicted about a third of the variance in vMMN magnitude. High Attentional Control scores may reflect proficiency at predictive inhibition of distractors, leading to larger differences between the neural responses to Standards and to Oddballs. Similarly, high Orienting Sensitivity may lead to strong sensory responses to both Oddball and Standard flanker stimuli, reducing such differences. Attentional Control scores have previously been linked to increased conflict-related negativity at anterior electrodes (Kanske & Kotz, 2012), and to alpha-band activity in the parietal lobe (Alfonso, Miquel, Xavier, & Blanca, 2013), further supporting the link between self-reported temperament and neural markers of attention.

Neither temperament nor vMMN magnitude was related to individual differences in performance on the flanker task. It may be the case that the magnitude of the mismatch signal generated in visual cortex, as detectable by scalp EEG, is unrelated to the attentional capture elicited by such a mismatch. Future work should consider other approaches. We did not assess the latency of the vMMN, nor did we measure electrophysiological correlates of behavior, such as the lateralized motor potential. The null relationship between self-reported temperament and behavior is more surprising, especially given the relationship between temperament and vMMN. It is possible that the feedback subjects were given, which encouraged them to maintain their performance within a particular range of accuracy, has masked any underlying differences in behavior. Further work investigating neural versus behavioral susceptibility to attentional capture is called for.

Using a flanker task with predictable and oddball flanking distractors, we found that oddball flankers enhance the flanker congruency effect and elicit a visual mismatch negativity. Further, individual differences in vMMN magnitude correlate with individual differences in tem-

perament, such that temperament accounts for roughly a third of vMMN variation. Although a substantial body of previous work has demonstrated the fallibility of human attentional selection, these are the first results showing a dramatic interaction between the probability of a given distractor and its behavioral effects. The human brain exploits structure and predictability among distractors in order to support attentional selection.

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