Momentary reductions of attention permit greater processing of irrelevant stimuli

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A R T I C L E   I N F O

A B S T R A C T

Momentary reductions of attention can have extremely adverse outcomes, but it remains unclear whether increased distraction from irrelevant stimuli contributes to such outcomes. To investigate this hypothesis, we examined trial-by-trial relationships between brain activity and response time in twenty healthy adults while they performed a cross-modal selective attention task. In each trial, participants identified a relevant visual letter while ignoring an irrelevant auditory letter, which was mapped either to the same response as the visual letter (congruent trials) or to a different response (incongruent trials). As predicted, reductions of attention (i.e., increases of response time) were associated not only with decreased activity in sensory regions that processed the relevant visual stimuli, suggesting a failure to enhance the processing of those stimuli, but also with increased activity in sensory regions that processed the irrelevant auditory stimuli, suggesting a failure to suppress the processing of those stimuli. Reductions of attention were also linked to larger increases of activity in incongruent than in congruent trials in anterior cingulate regions that detect response conflict, suggesting that failing to suppress the sensory processing of the irrelevant auditory stimuli during attentional reductions allowed those stimuli to more readily activate conflicting responses in incongruent trials. These findings indicate that heightened levels of distraction during momentary reductions of attention likely stem, at least in part, from increased processing of irrelevant stimuli.

Introduction

Although often innocuous, momentary reductions of attention can have dire outcomes. For example, when experiencing a reduction of attention drivers take longer to step on the brake when an unexpected event occurs (Beede and Kass, 2006). Reductions of attention also profoundly disrupt behavior in numerous clinical syndromes, such as attention-deficit and hyperactivity disorder (ADHD) (Castellanos et al., 2005; Reimer et al., 2005), Alzheimer's disease (Berardi et al., 2005), and drug addiction (Hendricks et al., 2006). Understanding and minimizing reductions of attention therefore has tremendous theoretical and clinical importance.

Current models provide important clues as to which processes might be adversely affected by momentary reductions of attention. Specifically, they posit that attention facilitates performance not only by enhancing the processing of relevant stimuli, but also by limiting the processing of irrelevant stimuli (Desimone, 1998; Handy et al., 2001; Hasher and Zacks, 1988; Lavie et al., 2004). Thus, attentional reductions should both impair the processing of relevant stimuli and permit greater processing of irrelevant stimuli.

Using functional magnetic resonance imaging (fMRI), we recently investigated the effects of momentary reductions of attention on the processing of relevant stimuli in an intramodal visual selective attention task (Weissman et al., 2006). Natural variations in response time can serve as good dynamic markers of variations in attention (Castellanos et al., 2005). When a person experiences a reduction of attention, their responses to external stimuli become slower, and the degree of slowing depends on the severity of the reduction. Therefore, in our prior study we investigated the neural bases of momentary reductions of attention by correlating brain activity with response time (RT) on a trial-by-trial basis. Our findings provided strong evidence that reductions of attention (i.e., increases of RT) impair the processing of relevant stimuli. For example, reductions of attention were associated with reduced activity in sensory regions that processed behaviorally-relevant stimuli, suggesting that attention had failed to enhance the perceptual processing of those stimuli (Weissman et al., 2006).

In the present study, we used fMRI to investigate whether reductions of attention permit greater processing of irrelevant stimuli in a multisensory audiovisual selective attention task (Fig. 1). In each trial, participants identified a visual letter (X or O) while ignoring a simultaneously-presented auditory letter (X or O). The irrelevant auditory letter was equally likely to be congruent with the visual letter (i.e., both letters were Xs or Os; Fig. 1a), in which case the relevant and the irrelevant letters were mapped to the same response, or incongruent (i.e., one letter was an X, the other was an O; Fig. 1b), in which case the irrelevant letter was mapped to a different response than the relevant letter. Participants responded to the identity of the

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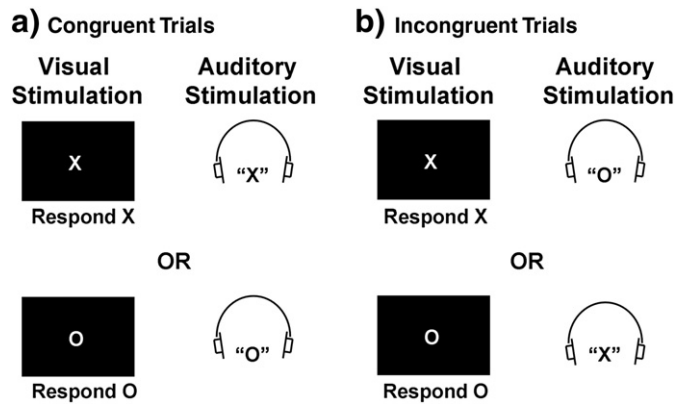E-mail address: danweiss@umich.edu (D.H. Weissman).

Fig. 1. Experimental stimuli. In each trial, participants identified a visual letter (X: 1.66° × 1.81° or O: 1.75° × 1.84°) while ignoring an irrelevant, simultaneously-presented auditory letter (X or O) that was mapped to either (a) the same response as the visual letter (congruent trials) or (b) a different response (incongruent trials).

visual letter via a button press with either the left or the right thumb. Because low-level sensory aspects of visual and auditory stimuli are processed in mostly nonoverlapping regions of the cerebral cortex (Kandel et al., 2000), we were able to distinguish sensory activity for the irrelevant auditory letter from sensory activity for the relevant visual letter.

We made two predictions. First, we predicted that reductions of attention (i.e., increases of RT to correctly identify the relevant visual stimulus) would be associated not only with reduced activity in sensory regions that processed the relevant visual stimuli (Weissman et al., 2006), but also with increased activity in sensory regions that processed the irrelevant auditory stimuli. Second, we predicted that increased sensory processing of the irrelevant auditory stimuli during reductions of attention would allow those stimuli to more strongly activate the responses to which they were associated, thereby leading to greater conflict-related activity (i.e., activity that is greater in incongruent than in congruent trials) in anterior cingulate regions that detect response conflict (MacDonald et al., 2000; Weissman et al., 2004).

Materials and methods

Participants

Twenty-two healthy participants (12 male, age range: 19–29, all right-handed) took part in the study. All had normal or corrected-to-normal vision with no history of serious neurological trauma or disorders. Furthermore, none reported any problems with their hearing. Two participants were excluded due to excessive head motion leaving twenty participants in the final analyses (10 male, age range: 19–29 years, all right-handed). Participants gave informed consent prior to the experiment in accordance with the Duke University Medical Center human subjects institutional review board. Before the MR session, each participant briefly practiced the task. Participants were paid $20 per hour for their participation, which lasted approximately 2 h.

Task

As discussed earlier, participants performed a cross-modal audio-visual selective attention task (Fig. 1). In each 2.5-second trial, participants identified a visual letter (X or O) while ignoring a simultaneously-presented auditory letter (X or O), which was equally likely to be congruent with the visual letter (i.e., both letters were Xs or Os; Fig. 1a) or incongruent (i.e., one letter was an X, the other was

an O; Fig. 1b). Participants identified the visual letter via a button press with either the left or the right thumb.

Within each of six runs, there were a total of 96 trials (48 congruent and 48 incongruent; stimulus duration, 350 ms). Congruent and incongruent trials were presented in a first-order counterbalanced order such that each trial type was preceded equally often by every trial type in the design. Moreover, the inter-trial-interval (ITI) ranged from 0 to 4 TRs following a roughly exponential distribution that favored short ITIs. Such jittering of the ITI increases the efficiency with which response estimates for distinct trial types are made in a multiple regression framework (Miezin et al., 2000).

Data acquisition

We used a PC running Presentation software (Neurobehavioral Systems, Inc.) to present the animations to participants through an MR-compatible goggle system. Structural images for each participant were collected using a T1-weighted spin echo sequence on a 4-Tesla GE whole-body scanner (TR = 500 ms, TE = 14 ms, flip angle = 90°, 24 contiguous 5-mm-thick slices — in-plane resolution = 0.94 mm × 0.94 mm). Functional images, which measured the blood oxygenation level-dependent (BOLD) signal, were collected using a spiral imaging sequence (TR = 1.25 s, TE = 40 ms, flip angle = 90°, 24 contiguous 5-mm-thick slices — in-plane resolution, 3.75 mm × 3.75 mm). Each participant completed six runs of the experimental task. During each run, 297 brain volumes were collected. The first six functional images of each run contained no trials and were discarded.

Data analysis

SPM2 (Friston et al., 1995) was used to correct for asynchronous acquisition of functional images, to correct the functional images for head motion, to normalize the functional images to standard Montreal Neurological Institute (MNI) space, and to spatially smooth the functional images with a three-dimensional Gaussian filter (FWHM = 8 mm). The time series for each functional run was analyzed using customized software, which implements a version of the general linear model that makes no assumptions about the shape of the blood oxygen level-dependent (BOLD) response. This linear regression approach, sometimes called the finite impulse response (FIR) model, estimates the average stimulus-locked fMRI response associated with each trial type and has been validated in numerous prior studies (Miezin et al., 2000; Shulman et al., 1999; Weissman et al., 2004). The linear model for each run included 18 regressors to model the average response for each trial type, beginning 7.5 s (6 TRs) prior to stimulus presentation and ending 15 s (12 TRs) following stimulus presentation.

RT regressors

We also included 18 additional regressors for each trial type to determine whether and how the magnitude of the fMRI response in each trial varied with RT. These parametric regressors, which we term RT regressors, modeled trial-to-trial variance in the average fMRI signal for a trial type that scaled linearly with trial-to-trial variance in correct RTs for that trial type. Relative RT for each trial was measured as the mean-subtracted RT score: RT for that trial (in seconds) minus the mean RT for correct trials of that trial type in that functional run. In the linear model, every time a trial type was presented and a correct response was made, we included not only 18 regressors of unit value (i.e., 1), which corresponded to each time point of the average fMRI response, but also 18 RT regressors with a value of the mean-subtracted RT for that trial. Each of the 18 RT regressors for a particular trial type modeled the effect of RT on fMRI activity at one time point of the relevant trial type's average fMRI response.

Since the average of any distribution from which the mean is subtracted is zero, the regressors that coded the mean-subtracted RT