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Research paper

# The effects of selective and divided attention on sensory precision and integration

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## HIGHLIGHTS

- Selective attention does not seem to alter the probability of integrating.
- Selective attention improves precision of visual spatial representations.
- Auditory spatial representations are not impacted by selective attention.
- Selective attention improves temporal numerosity precision in both modalities.

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## ABSTRACT

In our daily lives, our capacity to selectively attend to stimuli within or across sensory modalities enables enhanced perception of the surrounding world. While previous research on selective attention has studied this phenomenon extensively, two important questions still remain unanswered: (1) how selective attention to a single modality impacts sensory integration processes, and (2) the mechanism by which selective attention improves perception. We explored how selective attention impacts performance in both a spatial task and a temporal numerosity judgment task, and employed a Bayesian Causal Inference model to investigate the computational mechanism(s) impacted by selective attention. We report three findings: (1) in the spatial domain, selective attention improves precision of the visual sensory representations (which were relatively precise), but not the auditory sensory representations (which were fairly noisy); (2) in the temporal domain, selective attention improves the sensory precision in both modalities (both of which were fairly reliable to begin with); (3) in both tasks, selective attention did *not* exert a significant influence over the tendency to integrate sensory stimuli. Therefore, it may be postulated that a sensory modality must possess a certain inherent degree of encoding precision in order to benefit from selective attention. It also appears that in certain basic perceptual tasks, the tendency to integrate crossmodal signals does not depend significantly on selective attention. We conclude with a discussion of how these results relate to recent theoretical considerations of selective attention.

## 1. Introduction

In our daily lives, our capacity to selectively attend to information from a single sensory channel is very important as we attempt to accurately process information from the surrounding world. For instance, in order to effectively read and comprehend passages in a book, one needs to allocate attentional resources exclusively toward processing the visual information on the page. However, if one wants to listen to a lecture in audio podcast format and fully comprehend what is being discussed, one needs to exclusively attend to the auditory information at the expense of sensory stimuli in other modalities. This process of selectively attending to a single sensory modality is critical for being able to quickly and effectively navigate a busy world in which important information could come from different sensory channels at any given time.

Previous research indicates that selective attention improves processing in the attended modality. Behaviorally, selective attention to a single sensory modality has been shown to improve sensory discriminations in the attended modality [1], decrease reaction time to targets [2], and improve spatial discrimination

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(left vs. right) judgments [3]. Neuroimaging studies indicate that selective attention to either visual or auditory stimuli in multisensory environments can increase activity in the corresponding sensory cortices, while dividing attention across those two modalities results in only a slight, simultaneous activation of both brain regions [4–8]. This general idea is consistent with several ERP studies indicating that the effect of selective attention to one type of sensory input is to enhance activity in the applicable cortical area [9–11]. Thus, studies indicate that processing is improved for the attended modality, but the *mechanism* involved remains unclear.

Computationally, models assuming optimal Bayesian integration of sensory cues have successfully captured observer's performance on a number of multisensory tasks [12–14]. However, as noted in a recent review, Bayesian models' abilities to account for the effects of attention remain unclear [15]. Therefore, we aim to provide insight into *how* selective attention exerts its beneficial effects in a Bayesian framework by employing a Bayesian Causal Inference model [12,13,16,17] and comparing conditions of selective and divided attention. Because the effect of attention could potentially differ in separate modalities, tasks, or domains, we explore these questions systematically by implementing both a spatial task and a temporal numerosity judgment task, and testing how attention to the visual or auditory modality alone differs from conditions where attention is allocated to both modalities at the same time.

Most previous studies investigating selective attention indicate that it improves processing of an attended feature [18–21]. However, this could be due to improving the sensory representations (reducing noise), or due to improving expectations about when and where things will occur in the environment. Using our computational model, we aim to establish whether selective attention exerts effects on the sensory representations or *a priori* expectations by quantitatively estimating both of these components in each observer in each task.

Finally, while the question of attention's impact on integration has been explored extensively by previous research and thoroughly discussed in several recent reviews [15,22,23], studies investigating the question of how (or if) attention can influence the integration of sensory signals have yielded heterogeneous results. For instance, depending on the paradigm, it has been shown that selective attention does not influence integration [24–26], increases integration [27], or even reduces integration [28,29]. One of the main problems with some of the previous studies examining this question is that the measure of integration is confounded with unisensory processing; therefore, a change in unisensory processing (improved reliability, for example) could result in a change in interaction between the two modalities and be misinterpreted as a change in integration. Our Bayesian model provides a measure of integration tendency, which we call "binding tendency," that is not confounded by unisensory precision (or noise), and therefore can provide a clearer picture of whether attention influences unisensory precision, multisensory integration or both. Therefore, utilizing the causal inference model, we quantitatively estimated the binding tendency for each individual subject in both selective and divided attention conditions, and in both spatial and temporal tasks to address this question more rigorously.

## 2. Experiment 1

The goal of this experiment was to compare sensory representation noise (or alternatively, sensory representation reliability) and the binding (i.e., integration) tendency under the conditions of selective attention to a single modality vs. divided attention to both auditory and visual modalities in a spatial task.

### 2.1. Materials and methods

Twenty-five research volunteers at the University of California—Los Angeles participated in Experiment 1. One participant was excluded from analyses due to negligence with the response device during the task. Participants sat at a desk in a dimly lit room with their chins positioned on a chinrest 52 cm from a projection screen. The screen was a black, acoustically transparent cloth subtending much of the visual field (134° width × 60° height). Behind the screen were 5 free-field speakers (5 × 8 cm, extended range paper cone), positioned along azimuth 6.5° apart, 7° below fixation. The middle speaker was positioned below the fixation point, and two speakers were positioned to the right and two to the left of fixation. The visual stimuli were presented overhead from a ceiling mounted projector set to a resolution of 1280 × 1024 pixels with a refresh rate of 75 Hz, and could be displayed at any of the five positions that overlapped with the centers of the speakers. For additional details about the screening procedures, stimuli, eyetracker, response device, practice period, and stimulus timing, please see the Supplemental materials.

The stimulus conditions included five unisensory auditory locations, five unisensory visual locations, and all 25 combinations of auditory and visual locations (bisensory conditions). Three different blocks were implemented three times each in the experiment in a Latin-square design, and in a given block, participants were given one of three possible instructions: localize only the auditory stimulus, localize only the visual stimulus, or localize *both* the auditory and visual stimulus. It is important to note that in the unisensory attention blocks, participants could be presented with either unisensory or bisensory stimuli, but were consistently required to report only one modality throughout the block. In bisensory attention blocks, the exact same trial types as unisensory attention blocks were used, but participants were asked for either one report in response to unisensory stimuli, or two reports (the location of the auditory stimulus and the location of the visual stimulus in sequential order) for bisensory stimuli. The order of these two responses was consistent throughout the session, and was counter-balanced across participants.

### 2.2. Model

We employed a variant of a Bayesian Causal Inference model [12,13,16,30] with eight free parameters [17] to model localization responses from both the unisensory and bisensory attention conditions for each individual participant; thus, the perceived location of auditory and/or visual stimuli on each trial for each condition was used as the dependent variable. Previous studies have shown that the Bayesian Causal Inference model is superior to other models [12] and that this variant (with 8 parameters) is superior to other tested variants of the Bayesian Causal Inference in the spatial localization task used here [17]. This model allows us to quantitatively characterize each observer's binding tendency (prior), sensory representation parameters (likelihoods), and spatial biases (priors) in each attention condition. The parameters in the model used in Experiment 1 were as follows: $p_c$: the binding tendency (a.k.a., prior probability of a common cause), $\sigma_V$: the uncertainty of visual representation (or more specifically, the standard deviation of the visual likelihood function), $\sigma_A$: the uncertainty of audition (or more specifically, the standard deviation of the auditory likelihood function), $\Delta x_V$: the bias in the visual sensory representation (i.e., likelihood mean bias), $\Delta x_A$: the bias in the auditory sensory representation, $\Delta\sigma_V$: the change in visual likelihood variance as a function of eccentricity, and $x_p, \sigma_p$: the mean and variance, respectively, of the prior bias for localizing stimuli towards the central