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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), σ_V: the uncertainty of visual representation (or more specifically, the standard deviation of the visual likelihood function), σ_A: the uncertainty of audition (or more specifically, the standard deviation of the auditory likelihood function), Δx_V: the bias in the visual sensory representation (i.e., likelihood mean bias), Δx_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, σ_p: the mean and variance, respectively, of the prior bias for localizing stimuli towards the central

Table 1
Mean optimized parameter values across participants in Experiment 1. *** Indicates a significant difference in the parameter between the two conditions ($p < 0.001$). The difference in all other parameters was statistically insignificant.

	p_c	σ_v***	σ_A	Δx_v	Δx_A	$\Delta\sigma_v$	x_p	σ_p
Unisensory attention	0.41	0.91	11.68	−0.50	3.65	0.58	0.01	25.25
Bisensory attention	0.35	1.23	11.65	−0.58	3.15	0.60	−1.96	26.03

Table 2
Mean optimized parameter values across participants in Experiment 2. ** Indicates a significant difference in the parameter between the two conditions ($p < 0.01$). The difference in all other parameters was statistically insignificant.

	p_c	σ_v**	σ_A	Δx_v	Δx_A	$\Delta\sigma_v$	x_p	σ_p
Unisensory attention	0.45	1.15	12.26	−0.55	2.60	0.48	−0.13	26.33
Bisensory attention	0.44	1.32	11.06	−0.68	3.39	0.55	−0.27	17.73

location (see Supplemental materials for additional details about the model).

2.3. Results

After the parameters were fitted to individual subjects' data for the unisensory attention and bisensory attention datasets, we compared the model parameters between the two attention conditions. Planned comparison analysis was performed using paired two-tailed *t*-tests to determine whether there were any significant differences in parameters between the two conditions, and these tests were corrected for multiple comparisons using Bonferroni correction for eight tests ($\alpha = 0.00625$). The results for all parameters are summarized in Table 1.

The binding tendency (i.e., "prior probability of a common cause" or p_c), did not significantly differ between the two attention conditions ($t(23) = 1.518$, $p > 0.05$). In regards to the question of whether attention can affect the precision of sensory representations, the standard deviation of the visual likelihood (σ_V) in the unisensory attention condition was found to be significantly smaller than that of the bisensory attention condition ($t(23) = -4.161$, $p < 0.001$). No significant difference was observed in auditory likelihood (σ_A) between the two conditions ($t(23) = .061$, $p > 0.05$) (see Supplemental materials for additional behavioral analyses).

3. Experiment 2

While the findings from Experiment 1 provided evidence for selective attention improving the precision in visual sensory representations, there remained the possibility that the observed differences in precision were not due to the influence of attention per se, but rather the difference in working memory demands. In other words, requiring only *one* response in the unisensory attention condition but *two* responses in the bisensory attention condition could result in differences in the amount of time the responses had to be retained in memory before report. Thus, Experiment 2 was conducted to eliminate these differences in memory requirements by a modification of the task in the bisensory attention condition: while participants were still required to pay attention to both stimuli, they were no longer required to make two responses on each of these trials, and instead were prompted immediately to report only one of the percepts, either visual or auditory.

3.1. Materials and methods

All of the methods were identical to those of Experiment 1 except for the following. Twenty-eight volunteers participated in the experiment. Two participants were excluded from analyses due to negligence with the response device during the task.

As in Experiment 1, in the unisensory attention condition, participants knew ahead of time which modality they needed to report. In contrast to Experiment 1, in the bisensory attention condition, participants did not know which modality to report until after the stimuli were presented. Bimodal blocks now only required *one* response per trial. Thus, twice as many bisensory trials were included to gather sufficient responses to both visual and auditory stimuli in a given condition, totaling 1950 trials altogether. See Supplemental materials for additional comments on the design of Experiment 2.

3.2. Results

As in Experiment 1, planned comparison analysis was performed using paired two-tailed *t*-tests to determine whether there were any significant differences in parameters between unisensory and bisensory attention conditions, and these tests were corrected for multiple comparisons using Bonferroni correction for eight tests ($\alpha = 0.00625$) (Table 2).

The results qualitatively replicated the results of Experiment 1. The standard deviation of the visual likelihood (σ_v) in the unisensory attention condition was again found to be significantly smaller than that of the bisensory attention condition ($t(25) = -3.16$, $p = 0.005$). In summary, Experiment 2 replicated the findings from Experiment 1 and ruled out the possibility that the initial findings were due to differences in the demands caused by localizing either one or two stimuli (see Supplemental materials for additional behavioral analyses).

4. Experiment 3

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

4.1. Materials and methods

Twenty-five subjects completed the experiment, but only twenty-four were included in data analysis (one participant's data were excluded due to negligence during the task). Participants rested their chins on a chinrest 57 cm away from a CRT monitor, which was flanked on each side by two speakers. Before each trial in the experiment, subjects were required to have their eyes fixated on a white cross, displayed at the center of the computer monitor. Visual stimuli consisted of a white disc flashed for one frame, which was approximately 10 ms in duration. The flash was presented 7° below the fixation point on an otherwise dark screen. Auditory stimuli were ramped noise bursts of 10 ms duration. The center of the visual and auditory stimulus trains were temporally aligned. The number of flashes and beeps varied from one to four, and following presentation of the stimuli, subjects had to first view an instruction about which modality to report (this changed depending on the attention condition), and then respond using the numbers 1–4 on the computer keyboard. For additional details about the stimulus timing, response device, instructions, practice period, and design, please see the Supplemental materials.

The presentation of the blocks followed a Latin-square design, with each subject receiving a unique ordering of the blocks. It is important to note that in the unisensory visual block, there was always at least one flash presented on every trial, and in the unisensory auditory block, at least one beep was always presented. In the

Table 3
Mean optimized parameter values across participants in Experiment 3. ** Indicates a significant difference in the parameter between the two conditions ($p < 0.01$). The difference in all other parameters was statistically insignificant.

	p_c	σ_V **	σ_A **	σ_P
Unisensory attention	0.52	0.85	0.38	0.93
Bisensory attention	0.48	1.01	0.44	0.95

bisensory block, participants were never asked to provide a report for a modality that was not presented with stimuli.

4.2. Model

The Bayesian Causal Inference model with four free parameters, which is the best existing model for accounting for observers' performance in this task [31], was used to model the data. Compared to previous studies of this task using this model, one modification was implemented based on previous findings in order to render the model more parsimonious and the parameter optimization more reliable: the mean for the prior μ_P was now fixed at 1.38, based upon the optimal value found by Wozny et al. [13] in a numerosity judgment task (see Supplemental materials for additional details regarding the model).

4.3. Results

Planned comparison analysis was performed using paired two-tailed *t*-tests to determine whether there were any significant differences in parameters between attention conditions, and these tests were corrected for multiple comparisons using Bonferroni correction for four tests ($\alpha = 0.0125$) (Table 3).

Similarly to the previous experiments, the visual precision was superior in the unisensory attention condition ($t(23) = -2.954$, $p < 0.01$). Interestingly, the auditory representation also exhibited superiority in precision in the unisensory attention condition ($t(23) = -3.378$, $p < 0.01$, alpha = 0.0125). The binding tendency p_c did not show a significant difference (paired-samples *t*-test $t(23) = 0.894$, $p > 0.05$). The spatial prior bias, $\sigma_{P,}$ did not exhibit a difference between the two conditions either ($t(23) = -0.269$, $p > 0.05$).

5. Discussion

Many studies have investigated the role of attention in multisensory integration. The results have been mixed, no clear picture has emerged, and as a result, hypotheses involving complex relationships have been proposed [22,23]. Therefore, the question of how selective attention influences sensory integration has yet to be illuminated. Even more, studies have investigated the role of attention on visual and auditory perception, but again a clear computational characterization of the effect of attention on perceptual processing has remained elusive.

We examined both of these questions in two complementary domains: a spatial task and a temporal task. While these tasks involved different response dimension characteristics (i.e., spatial task responses were continuous, while temporal task responses were discrete), previous work using Bayesian Causal Inference has demonstrated that the parameters' estimates are quite consistent across different response spaces [12,16,32,33]. Interestingly, the findings of both tasks regarding both questions (unisensory processing and integration) were qualitatively consistent. In both tasks, we found that sensory representations benefited from selective attention by a reduction of noise (reduced variability) in sensory representation [34,35]. However, while this benefit was present in both modalities in the temporal numerosity task, it was only present for the visual modality in the spatial task. We hypothesize that this may be related to the reliability of the signal for the task: when the sensory signals were relatively reliable they became even better (less noisy) with attention, in contrast, when the signal was very poor (auditory signal in the spatial task) it did not appear to benefit from attention. Thus, our findings suggest that the "rich get richer" when it comes to the influence of attention on processing, as sensory modalities that are already reasonably skilled at a task see a benefit, but modalities that exhibit noisy encoding in a given domain (e.g., the auditory system in the spatial domain) are not enhanced by attention.

Our next question focused on sensory integration. The literature has been very mixed in this regard. Some investigations have found that attention has no effect on multisensory integration [24,25], while other studies have reported that selective attention can increase integration [27], or reduce integration [28,36,37]. Here, in both tasks we found no evidence of an influence of attention on binding tendency. However, the possibility that there is a small effect, which was not detected by our experiments due to insufficient power, cannot be ruled out. Based on the number of subjects in each experiment, our power to detect a mid-size effect (0.5 standard deviation shift in the parameter distributions) was reasonable for all three experiments (65%, 69%, and 65%, respectively), but there remains the possibility that a small effect exists that was missed. Some have argued that power analyses are limited compared to alternative Bayesian methods, as the frequentist approach assumes that lack of a significant finding is evidence for the null hypothesis, when in reality, any obtained difference in means can be interpreted along a *spectrum* of evidence for the null hypothesis vs. evidence for the alternative hypothesis [38]. To this end, we also computed Bayes' factors for our three experiments, which yielded 0.36 for Experiment 1, 0.06 for Experiment 2 and 0.19 for Experiment 3, all of which provide stronger evidence for the null hypothesis (i.e., that the binding tendency was not changed) compared to the alternative hypothesis.

From a theoretical perspective, our results inform current ideas about attention in a Bayesian framework [15,23]. One recent account has focused on how attention may impact perception in environments where inference problems may be computationally intractable. In this framework, rather than simply serving as a prior, attention serves as a mechanism to refine perceptual accuracy by approximating the inference to be performed [35]. Here, we used a simple task to determine which elements of a Bayesian model (i.e., likelihoods or priors) are impacted by modality-specific attention in a spatial and a temporal task.

One recent study [39] investigated mechanisms impacting causal inference with a task requiring selective attention; in this study, subjects localized auditory signals in an audiovisual environment, and the relative sensory reliability was shown to be an influential factor in the inference process. Here, we extend these recent findings by not only probing *selective* attention processes, but *divided* attention as well, and comparing optimized parameter values across conditions. We did not find evidence that attention impacts the integration process in any way, but we did find that it enhances the precision of sensory representations of the visual modality in both the spatial and temporal domains, and the auditory modality exclusively in the temporal domain. Additionally, we found that auditory spatial representations were *not* enhanced, which introduces the question of how and when auditory spatial processes may be impacted by attention, if at all.

Future studies should aim to probe an important question that we are unable to address in the current paradigm: what happens to the *unattended* modality in conditions of selective attention? For example, we cannot compare the precision of the auditory modality when the subjects are attending to the sound, versus when they are attending to vision. Our model currently assumes that the variance in both of these conditions is the same, which may not be the case. This is a simplification for computational convenience, and future studies should explore this question further using alternative experimental paradigms that would allow for investigations of representations for the unattended modality. Finally, future research should also continue to investigate how and when attention can influence integration or segregation of higher-level features in more realistic settings, and probe how its allocation and deployment can be more effectively cultivated and implemented.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.neulet.2015.12.039.

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