Examining Cardiac and Behavioral Responses in a Modality Dominance Task

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Abstract

The current study examined cardiac and behavioral responses to changing auditory and visual information while using modified oddball tasks. When instructed to press the same button for auditory and visual oddballs, auditory dominance was found with cross-modal presentation slowing down visual response times and decreasing visual accuracy. When instructed to make separate responses to auditory and visual oddballs, visual dominance was found with cross-modal presentation slowing down response times and decreasing auditory accuracy. However, examination of cardiac responses that were time-locked to stimulus onset show cross-modal facilitation effects, with discrimination of oddballs and standards occurring earlier in the course of processing in the cross-modal condition than in the unimodal conditions. These findings shed light on potential mechanisms underlying modality dominance effects and have implications on tasks that require simultaneous processing of auditory and visual information.

Keywords: Cross-modal processing; Sensory Dominance; Attention.

Introduction

While most of our experiences are multisensory in nature, historically, most research has focused on processing within a single sensory modality. Over the last 40 years there has been a growing body of research examining how sensory systems process and integrate incoming information (see for example Driver & Spence, 2004; Posner, Nissen, & Klein, 1976; Spence, 2009; Wickens, 1984), with some multisensory environments facilitating learning (e.g., Alsius, Navarra, Campbell, & Soto-Faraco, 2005; Massaro, 1998) and others attenuating learning (Sloutsky & Napolitano, 2003; see also Robinson & Sloutsky, 2010a for a review). For example, intersensory redundancy, when the same information can be conveyed in different sensory systems, can often facilitate learning and speed up responses (Bahrick & Lickliter, 2000; Giard & Peronnet, 1999). However, in many situations, information presented to one sensory modality is irrelevant or may even conflict with information presented to a different sensory system. In these latter situations, modality dominance effects can be observed, with one modality attenuating encoding and/or responding to information in the other modality (see Spence, Parise, & Chen, 2012 for a review).

One commonly used paradigm to study modality dominance is the Colavita visual dominance task (Colavita, 1974; Colavita, Tomko, & Weisberg, 1976; Colavita & Weisberg, 1979; Egeth & Sager, 1977). In this task, participants are presented with auditory or visual information and instructed to quickly respond by pressing one button when they hear an auditory stimulus and a different button when they see a visual stimulus. On a small percentage of trials, the auditory and visual stimuli are presented at the same time. Participants often miss these cross-modal trials by only pressing the visual button, as opposed to pressing both buttons, or a third button associated with a cross-modal stimulus (see Sinnett, Spence, & Soto-Faraco, 2007). Research using variations of this task consistently points to visual dominance, with most of the sensory and attentional manipulations weakening but not reversing the effect (but see Ngo, Cadieux, Sinnett, Soto-Faraco & Spence, 2011). While visual dominance effects are robust and well-studied, underlying mechanisms are poorly understood (see Spence et al., 2012 for a review).

The current study expands on this literature in several important ways. Robinson, Chandra, and Sinnett (2016) recently demonstrated that it is possible to reverse modality dominance in an oddball paradigm by having participants make the same response to auditory and visual oddballs. More specifically, participants were repeatedly presented with the same sound, picture, or sound-picture pairing, and were required to inhibit responses to this stimulus (standard). They were also instructed to press a button on a keyboard as quickly as possible if the picture, sound, or both the picture and sound changed (visual, auditory, or cross-modal oddballs, respectively). While pairing the pictures and sounds together slowed down response times to visual oddballs, it often had no negative effect on auditory processing (i.e., response times to auditory oddballs did not differ when presented with or without the visual standard). The first goal of the current study was to test the generalizability of this finding by using a slightly different procedure with more salient and familiar visual stimuli. It is possible that auditory dominance was found because the visual stimuli used in Robinson et al. were monochromatic, unfamiliar images.

The second goal was to examine if auditory and visual dominance effects can be modulated by top-down attentional control, or if instead proceed with attention having no effect. While attentional manipulations often fail to reverse auditory and visual dominance (Napolitano &

Sloutsky, 2004; Ngo, Sinnett, Soto-Faraco, & Spence, 2010; Sinnett et al., 2007), it is possible that individual differences in attentional control modulate or reverse the effect. For example, one proposed mechanism underlying visual dominance is that participants strategically bias their attention in favor of visual input to compensate for the low alerting properties of visual input (Posner et al., 1976). Thus, it is possible that participants who are better at selectively attending to visual input are more likely to show visual dominance effects and/or less likely to be distracted by conflicting auditory information. At the same time, it has also been argued that auditory dominance may stem from auditory stimuli *automatically* grabbing attention and attenuating or delaying visual processing (Robinson & Sloutsky, 2010a). If auditory dominance effects stem from auditory stimuli automatically engaging attention, then individuals with high or low attentional control may show the same pattern of results. To examine effects of attentional control on modality dominance, we collected individual differences in resting Heart Rate Variability (HRV) prior to the experiment. The underlying idea is that the prefrontal cortex plays a significant role in executive functions such as selective attention and emotional regulation. HRV may serve as a proxy for individual variability in executive functions because parasympathetic activity adds short term variability to the heart beat via the vagus nerve and participants with higher HRV often perform better on a variety of executive function tasks (Hansen, Johnson, & Thayer, 2003; Thayer & Lane, 2000). They may also show a different pattern of results on modality dominance tasks.

The final goal of the current research was to examine real-time psychophysiological responses to changing auditory and visual information to possibly gain insight into the time course of cross-modal interference effects. It is well documented that infants' heart rates slow down when actively processing visual information (see Richards & Casey, 1992 for a review), and using a modified oddball task, heart rate also appears to slow down to novel, less frequent sounds than to more frequent sounds (Robinson & Sloutsky, 2010b). By time-locking heart rate with the onset of standard and oddball items, the current study examined the feasibility of using changes in adults' cardiac responses as a measure of auditory, visual, and cross-modal processing. It was hypothesized that cardiac responses would differ for standards and oddballs; thus, potentially providing an additional measure of discrimination. We also examined if comparing cardiac responses to auditory and visual oddballs when presented cross-modally with the respective unimodal baselines would provide converging evidence of modality dominance effects.

Experiment 1

Experiment 1 employed a cross-modal oddball task and participants made the same response to auditory and visual oddballs. It was hypothesized that cross-modal presentation would have a greater cost on visual processing.

Method

Participants Thirty-eight adults (23 Females, M = 19.1 years) participated in Experiment 1. Participants were undergraduate students at The Ohio State University Newark who received course credit in exchange for participation.

Apparatus A Dell Latitude E6430 laptop computer with DirectRT software was used for stimulus presentation and to record response times and accuracies. Visual stimuli were presented on a Dell P2212hB monitor and auditory stimuli were presented via Kensington 33137 headphones at approximately 65 dB. A Dell Latitude E6430 laptop computer with Mindware software was used to record electrocardiograms. Two Ag-AgCl electrodes were placed on the participants' right collarbone and left lower rib, and a reference electrode was placed on the participants' right lower rib. Electrocardiograms were collected using a BioNex acquisition unit with a BioNex Impedance Cardiograph and GSC amplifier. DirectRT on the stimulus presentation laptop sent event markers to Bionex; thus, time-locking electrocardiograms with stimulus presentation.

Materials The stimulus pool consisted of five visual and five auditory stimuli. Visual stimuli (see Figure 1) were approximately 400 x 400 pixels and pulsated centrally on a computer monitor for 750 ms, with a random 600-900 ms Inter-Stimulus Interval (ISI). The auditory stimuli consisted of bear, frog, elephant, cat, and dog sounds, which were taken from Marcell et al. (2000) and were shortened to 750 ms using Audacity software. As in basic oddball paradigms, one stimulus was frequently presented (approximately 90%, standard) and other stimuli were less frequent (approximately 10%, oddballs). The standard was a dog bark, an image of a dog, or the dog and bark were paired together. The auditory and visual oddballs were an elephant, frog, cat, and bear.

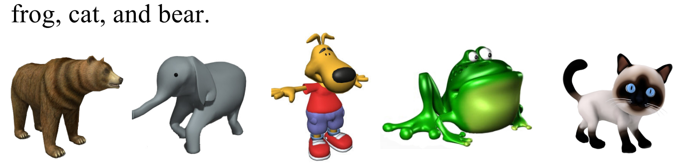

Figure 1. Visual stimuli used in Experiments 1 and 2

Procedure The study consisted of four phases. In the first phase, participants sat still for five minutes while the computer recorded resting HRV. Participants then completed three different oddball tasks on the computer, while their heart rate was monitored. The current study deviated from traditional oddball paradigms in that a trial was defined as a series of stimuli with either a standard or oddball at the end of the series (e.g., 5 standards → oddball), as opposed to each stimulus being a trial. This manipulation gave the heart at least 6 s to respond to an oddball before encountering another oddball (assuming two short oddball sequences were presented back to back).

In the auditory oddball condition, there were 16 standard trials and 16 oddball trials. On auditory oddball trials, a dog bark was presented either four or five times, followed by one of the other animal sounds (oddball). On auditory standard trials, participants heard four or five dog barks, followed by another dog bark (standard). Half of the trials consisted of four standards followed by a standard or oddball, and the remaining trials consisted of five standards followed by a standard or oddball. DirectRT sent an event marker to Bionex at the onset of the last standard or oddball in each trial. The unimodal visual condition was similar to the auditory condition, with the exception that standard and oddballs were pictures, not sounds. Thus, for each condition, we measured how quickly participants pressed a button when they encountered an oddball and how quickly the heart differentiated standards and oddballs.

In the cross-modal condition, the trials consisted of four or five standard image-sound pairs (dog-dog bark) followed by another image-sound pair that was either a standard or an oddball. Each participant had a total of 96 trials (48 standard and 48 oddball). Sixteen of the oddball trials had only a visual change (visual oddball), while an additional 16 trials only had an auditory change (auditory oddball). Lastly, there were also 16 double oddball trials, where both auditory and visual stimuli changed. As in the unimodal conditions, each stimulus was presented for 750 milliseconds, with a 600-900 ms ISI.

Results and Discussion

Behavioral Analyses Overall, participants correctly reported when the auditory component changed and when both modalities changed (hit rate > .99 across both unimodal and cross-modal conditions). However, cross-modal presentation interfered with visual oddball detection, with visual hit rate in the unimodal visual condition (M = .99) exceeding the cross-modal condition (M = .95), t (37) = 2.05, p = .048, suggesting that cross-modal presentation attenuated responding to visual but not auditory oddballs.

Additional analyses focused on response times in the cross-modal condition when only the auditory or visual component changed, and these response times were compared to the respective unimodal baselines. A 2 (Modality: Auditory vs. Visual) x 2 (Presentation Mode: Unimodal vs. Cross-modal) repeated measures ANOVA revealed an effect of Presentation Mode, F (1,37) = 33.63, p < .001, and a Modality x Presentation Mode interaction, F (1,37) = 10.91, p = .002. While auditory discrimination times in the unimodal condition (M = 459 ms, SE = 9.92) were faster than in the cross-modal condition (M = 474 ms, SE = 9.72), t (37) = 2.10, p = .042, the interaction suggests that the cost of cross-modal presentation was more pronounced in the visual condition, with visual discrimination in the unimodal condition (M = 443 ms, SE = 6.95) being faster than the cross-modal condition (M = 488 ms, SE = 8.84), t (37) = 7.17, p < .001. Thus, accuracy and RT data show that cross-modal presentation attenuated visual processing more than auditory processing, a finding consistent with auditory dominance. However, there was no slow down when both modalities changed (M = 424 ms, SE = 11.34). In fact, response times on these trials were faster than all trial types, ts > 2.26, ps < .05, suggesting that the slowdown occurs because of the conflicting information (e.g., auditory standard elicits no response; whereas, visual oddball elicits button press), as opposed to cross-modal presentation increasing task demands more generally.

HRV Analyses To examine the relationship between HRV and modality dominance, we calculated a measure of resting HRV for each participant during the five minute baseline phase. Mindware software was used to isolate the baseline phase and to detect and remove artifacts. Root Mean Square of the Successive Differences (RMSSD) was calculated for each participant, with higher values indicating more variability in resting heart rate. A median split was used to classify each participant as having low or high HRV. Response times broken up by HRV are reported in Figure 2. A 2 (HRV: Low vs. High) x 2 (Modality: Auditory vs. Visual) x 2 (Presentation Mode: Unimodal vs. Cross-modal) mixed-factors ANOVA revealed no significant effects or interactions with HRV, F's < 1.60, ps > .214, suggesting that both groups showed the same overall pattern.

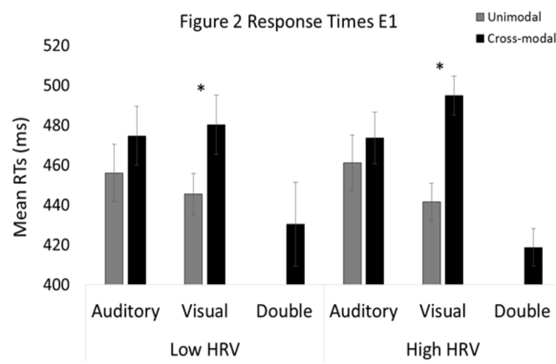

Figure 2. Mean response times across trial types, conditions, and HRV in Experiment 1. Error Bars denote Standard Errors and "*" denotes cross-modal RTs differ from unimodal RTs, ps < .001.

HR Analyses Weighted Inter-Beat Intervals (IBIs) were exported every second, and difference waveforms were calculated by subtracting pre-stimulus IBI (Weighted IBI from -1 s to stimulus onset) from each 1 s IBI bin post stimulus. Note that IBIs reflect the time between heartbeats; thus, increases in IBI reflect slowed heart rate, and difference IBIs greater than 0 reflect heart rate slowed compared to pre-stimulus levels. Paired t tests comparing standard and oddball IBIs were conducted each second to determine how quickly the heart differentiated oddballs from standards.

As can be seen in Figures 3A and 3B, cardiac responses to oddballs and standards differed at 4 s after stimulus onset in the auditory condition and 5 s after stimulus onset in the visual condition. Note that these effects were primarily driven by heart rate acceleration to oddballs; whereas, infants show slower heart rate to less frequent oddballs (Robinson & Sloutsky, 2010b). One explanation for this difference may stem from using passive looking time tasks with infants and speeded response time tasks with adults.

However, it is also worth noting that the discrimination of auditory and visual oddballs occurred earlier in the cross-modal condition (2 s after stimulus onset) compared to the unimodal conditions. Thus, behavioral data point to cross-modal interference with cross-modal presentation slowing down visual response times, but changes in time-locked cardiac responses show facilitation, with discrimination occurring earlier in the course of processing when information is presented to both sensory modalities.

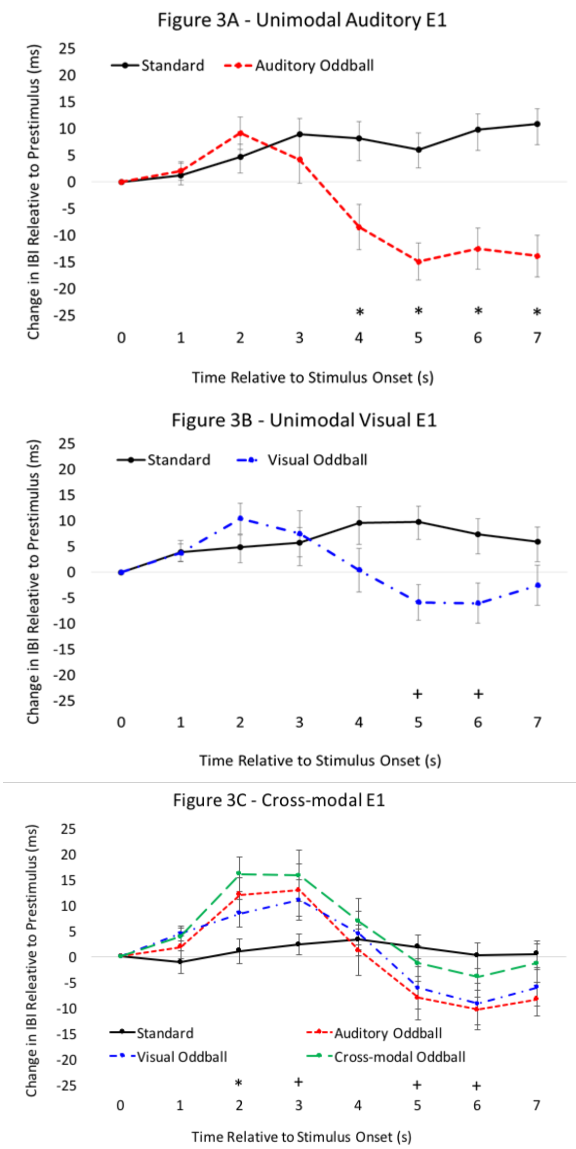

Figure 3. Cardiac responses across time. Error Bars denote *SE*s, and "+" and "*" denote auditory and visual oddballs differed from standard, *p*s < .05 and .007, respectively. Bonferonni corrections require a *p* value of .007 to reach significance.

Experiment 2

The primary goal of Experiment 2 was to further examine modality dominance effects, while using a task that is more similar in structure to the traditional visual dominance tasks (Colavita, 1974). It was hypothesized that requiring separate responses to auditory, visual, and cross-modal oddballs would result in visual dominance, with participants making more visual based errors when both modalities change (c.f., Robinson et al., 2016; Sinnett et al., 2007).

Method

Participants, Materials, and Procedure Twenty-seven new participants (15 Females, M = 23.97 years) from The Ohio State University Newark participated in Experiment 2. The stimuli and procedure was identical to Experiment 1 except that participants were instructed to press 1 on the number pad if the auditory component changed, 2 if the visual component changed, and 3 if both modalities changed (button assignment was counterbalanced across participants). Participants in the unimodal condition were only instructed to press one of the buttons.

Results and Discussion

Behavioral Analyses Accuracies in the current experiment were in the opposite direction compared to Experiment 1. While hit rates exceeded .99 when detecting visual oddballs, cross-modal presentation attenuated auditory hit rates, with auditory oddball detection in the unimodal auditory condition (M = .99) exceeding auditory hit rates in the cross-modal condition (M = .78), t (26) = 6.57, p < .001.

To examine Colavita visual dominance effects, we examined errors made on double oddballs. The overall error rate to double oddballs was 15%. Of the 66 errors made, there were 11 misses where participants failed to make any response. On the remaining trials, participants pressed only the visual button 41 times and only the auditory button 14 times, resulting in a visual modality bias, χ^2 (1, N = 27) = 12.30, p < .001.

Additional analyses focused on response times. A 2 (Modality: Auditory vs. Visual) x 2 (Presentation Mode: Unimodal vs. Cross-modal) repeated measures ANOVA only revealed an effect of Presentation Mode, F (1,26) = 449.17, p < .001, which suggests that cross-modal presentation equally affected response times in both modalities.

To make direct comparisons across Experiments, we submitted accuracies and RTs to two 2 (Experiment: 1 vs. 2) x 2 (Modality: Auditory vs. Visual) x 2 (Presentation Mode: Unimodal vs. Cross-modal) mixed-factors ANOVAs. We focus only on the effects and interactions with Experiment. All main effects and interactions were significant for accuracy, Fs (1,63) > 11.52, ps < .001, but only a main effect of Experiment and an Experiment x Modality interaction were found for RT, Fs (1,63) > 178.96, ps < .001.

HRV Analyses As in Experiment 1, we collected resting heart rate, calculated RMSSD for each participant, and used a median split to classify each individual as low or high HRV. A 2 (HRV: Low vs. High) x 2 (Modality: Auditory vs. Visual) x 2 (Presentation Mode: Unimodal vs. Cross-modal) mixed-factors ANOVA revealed no significant effects or interactions with HRV, F's < 2.31, p's > .141, suggesting that both groups showed the same overall pattern (Figure 4).

We also examined if HRV could predict the type of errors made on double oddballs. The low HRV group made 18 visual-based errors and 4 auditory-based errors. The high HRV group made 23 visual-based errors and 10 auditory-based errors. A *Fisher's* exact test revealed no differences between the proportion of visual-based errors, p = .36.

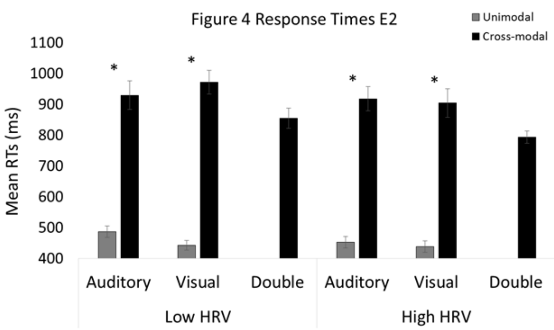

Figure 4. Mean response times across trial types, conditions, and HRV in Experiment 2. Error Bars denote Standard Errors and "*" denotes cross-modal RTs differ from unimodal RTs, ps < .001.

HR Analyses Time-locked cardiac responses to standards and oddballs are reported in Figure 5 and significant paired t tests are reported on the x axis. While discrimination was not as robust as in Experiment 1, the same pattern emerged with discrimination of auditory and visual oddballs being more robust and occurring earlier in the course of processing in the cross-modal condition than in the unimodal condition.

General Discussion

The Colavita visual dominance effect (Colavita, 1974) has been robustly replicated in the literature for the past several decades (see for example, Ngo et al., 2010; Sinnett et al., 2007; Spence et al., 2012 for a review). Indeed, while Ngo et al. (2011) did manage to reverse the effect (only under extreme conditions), it was not until recently (Robinson et al., 2016) that visual dominance has been consistently reversed. The first goal of this experiment was to extend these findings by using a slightly different procedure with more salient visual stimuli. In doing so, auditory dominance was again demonstrated when looking at both response latency and accuracy (Experiment 1). That is, responses to visual oddballs were slowed down when presented concomitantly with auditory standards, when compared to visual oddballs presented in silence. Additionally, more errors were made to visual oddballs when paired with an auditory standard than when presented in silence. This demonstration of auditory dominance dovetails with other research using a similar oddball/change detection paradigms (Robinson et al., 2016; Sloutsky & Napolitano, 2003).

In Experiment 2, auditory dominance reverted to visual dominance when participants were required to use multiple response keys. Opposite to Experiment 1, participants made more errors to auditory oddballs when paired with the visual

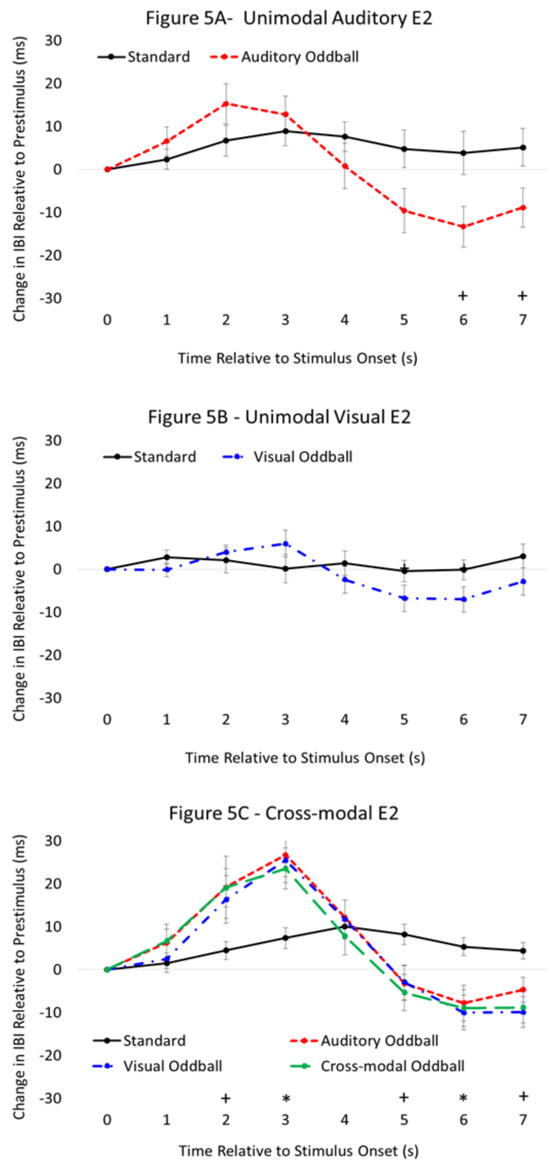

Figure 5. Cardiac responses across time. Error Bars denote SEs, and "+" and "*" denote auditory and visual oddballs differed from standard, ps < .05 and .007, respectively.

standard when compared with auditory oddballs presented without images. Visual dominance was further reflected in the percentage of visually-based errors (responding with the visual response button only) to double oddballs.

The second goal of the current study was to explore whether auditory or visual dominance effects can be modulated by top-down attentional control. To address this, we used HRV as a proxy for top-down attentional control, as previous research (Hansen, Johnson, & Thayer, 2003; Thayer & Lane, 2000) has demonstrated that high HRV is correlated with increased performance on tests of executive functioning. Interestingly, when performing a median split on our participants (see Figures 2 and 4), HRV did not seem to modulate dominance type. These findings are consistent with previous research showing that attentional manipulations do not reverse modality dominance (Napolitano & Sloutsky, 2004; Ngo et al., 2010; Sinnett et al., 2007), and suggest that factors other than endogenous attention may modulate dominance effects.

The third goal of this project was to examine real-time psychophysiological responses to changing auditory and visual information to possibly gain insight into the time course of cross-modal interference effects. While both studies report slower behavioral responses in the cross-modal conditions, cardiac responses to auditory and visual oddballs were actually faster than the cross-modal condition. Interestingly, these early cardiac responses in the cross-modal condition were decelerations, not accelerations. While future research is needed, it is possible that both auditory and visual dominance reflect competition while participants are making a decision and/or initiating a response, and that early cardiac decelerations reflect more robust or possibly even faster encoding in the cross-modal conditions.

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