AN EXPLORATION OF THE FACTORS THAT MODULATE SENSORY DOMINANCE

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ABSTRACT

Investigations of multisensory integration have demonstrated that under certain conditions, one modality is more likely to show dominance over the other, with strong evidence over the past few decades suggesting that the visual modality is more dominant. However, this visual prepotency effect can be reversed to show auditory dominance in certain tasks. The experimentation conducted within investigated two stimulus characteristics that have been hypothesized to potentially modulate sensory dominance using an oddball detection paradigm.

It was hypothesized that when manipulating stimulus transience (by changing the relative duration of either the auditory or visual stimulus in a bimodal stimulus stream), participants would show dominance for the modality with the shorter duration, as theoretically attention would be drawn to the more transient modality. Participants showed auditory dominance in the 1-button condition irrespective of manipulation to duration. In the 3-button condition participants showed auditory dominance when looking at their response times, but also simultaneously demonstrated visual dominance when using a more traditional measure of sensory dominance (i.e., making a higher proportion of visually based errors to bimodal trials). Furthermore duration did not modulate these errors.

The second experiment addressed the hypothesis that a stimulus that is presented earlier will be processed first and therefore contribute to sensory dominance. Stimulus order was manipulated such that the visual or auditory stimulus was presented prior to one another. It was hypothesized that dominance would be observed for the stimulus

(auditory or visual) that occurred first. Participants, in the 1-button and 3-button conditions, were more likely to show auditory dominance with simultaneous presentations, and under all conditions where the auditory stimulus preceded the visual stimulus, however auditory dominance was eliminated when the visual stimulus occurred slightly before the auditory stimulus, only demonstrating visual dominance when the visual stimulus preceded the auditory stimulus by 200 ms. Errors in the 3-button task provided evidence for visual dominance which was modulated when presenting auditory stimuli prior to visual stimuli. Overall these results affirm that auditory dominance effects are more pronounced early in processing, whereas visual dominance effects are more pronounced later in processing. Theoretical implications of these results are discussed.

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1. General Introduction

Understanding how the mind creates stable and complete percepts out of seemingly distinct sensory experiences is an important scientific undertaking. Typically, the discussion of this capability focuses on the relative timing and behavioral outcomes of both unisensory and multisensory processing, with the assumption being that unisensory processing is at first separate given the existence of modality specific sensory pathways responsible for the transduction of sensory information; after which unisensory information arriving from multiple modalities can be combined into a unitary percept (multisensory integration) via multisensory processing (Tang, Wu, & Shen, 2015). However, this simplistic view of sensory processing is wrought with difficulties as research has shown that, multisensory processing can occur fairly early in neurological systems seemingly dedicated to a particular sensory modality (Ghazanfar & Schroder, 2006), various factors influence whether sensory events belong to the same unitary percept (Shimojo & Shams, 2001; Tang et al., 2015), and that in some situations information arriving at separate senses can compete for resources leading to one event being processed/perceived at the expense of another not being perceived (Colavita, 1974; McGurk & MacDonald, 1976). The research conducted for this dissertation focuses on this final point and furthers our understanding of the underpinning mechanisms that lead to situations when one sense dominates another.

In order to fully understand the reasons why sensory dominance occurs, it is critical to explore what circumstances lead to certain sensations dominating processing, and as a result behavior. Although a multitude of investigations have attempted to disentangle these factors in several different multimodal situations, the vast majority of research has focused on audition and vision (although, see Hartcher-O'Brien, Gallace, Krings, Koppen, & Spence, 2008 and Hecht & Reiner, 2009 for visuotactile and auditory tactile examples, respectively). To preview the current state of the literature, overall, studies demonstrate that under some circumstances when a bimodal (auditory and visual) event occurs, vision tends to dominate processing and as a result dominates observable behavior as well (Spence, Parise, & Chen, 2012), however, in other situations audition appears to dominate vision (Robinson, Chandra, & Sinnett, 2016; Robinson & Sloutsky, 2013). The studies in this doctoral dissertation further examine auditory and visual dominance in adults to better understand what situations and stimuli characteristics lead to different sensory dominances (i.e., visual or auditory dominance). Given the quantity and breadth of research on sensory dominance, an introduction to important issues, theories, and findings is necessary in order to best understand the motivations for the research conducted in this dissertation. Importantly, this introduction will focus on multisensory integration first and then expand on key issues in sensory dominance.

1. 1. Multisensory Integration

Multisensory integration can be thought of as the joining of two or more unisensory events (which are, importantly, processed by different senses at first) that coincide in space and/or time, leading to some meaningful and integrated percept (Alais & Burr, 2004; Ernst & Banks, 2002; Körding, Beierholm, Ma, Quartz, Tenenbaum, & Shams, 2007; Rohe & Noppeney, 2015; Welch & Warren, 1980; for a review, see Spence, 2007). Outwardly, the idea of multisensory integration seems basic; however, multiple elements have been shown to influence the extent with which sensory events are combined, including stimulus features, locations, timing, attention, and more recently expectation (Gau & Noppeney, 2016; Spence, 2007; Tang et al., 2015). As a result, multisensory integration has been shown to have multiple effects on behavioral responses. For example, in some situations multisensory integration has been shown to improve a person's ability to do certain tasks (Raab, 1962) while at times multisensory integration "gone wrong" has been shown to influence responses by creating potent illusions (e.g., McGurk & MacDonald, 1976).

1. 2. Influences on Multisensory Integration

Typically, studies of multisensory integration support the *unity assumption* – which purports that to the extent that unimodal sensory events are consistent with one another, the more likely they are to be viewed as a single unit (Welch & Warren, 1980). For instance, when viewing a video or newscast where the video and audio tracks are not synchronous, the seemingly automatically integrated speech signal now appears as two separate signals (a similar example can be seen when watching a dubbed film). Spence (2007) expands on the unity assumption by specifying which factors can influence the "consistency" of sensory events. In particular, he identifies two primary classes of factors that guide multisensory integration (or the binding of two unisensory events, one auditory and the other visual in nature, into one audiovisual event). First are factors that are *stimulus-driven* or bottom-up factors. These bottom-up factors are numerous, but of particular importance are spatiotemporal correspondence (i.e., the extent with which an audiovisual event's timing and relative locations correspond with one another; Bermant & Welch, 1976; Hairston, Wallace, Vaughan, Stein, Norrris, & Schirillo, 2003; Jackson, 1953), temporal patterning (i.e., the correlation between an auditory and visual items' occurrence, this can also be thought of the extent with which the duration of the stimuli are similar; Jones & Jarick, 2006; Radeau & Bertelson, 1987), and stimulus motion (i.e., the extent to which auditory and visual signals appear to be moving in the same general direction; Soto-Faraco, Lyson, Gazzaniga, Spence, & Kingstone, 2002). Therefore, the more that an individual believes that multisensory stimuli have high spatiotemporal correspondence, consistent temporal patterning, and similar motion, the greater the likelihood that these events will be linked into a unitary percept.

In addition to these stimulus-driven factors, top-down or *cognitive factors* are also believed to be a crucial part of whether or not multiple unimodal sensory events are viewed as a singular sensory event. In particular, Spence (2007) identifies semantic congruency, or the extent with which an auditory and visual event are semantically consistent with one another, as one of these important factors. For example, a researcher could present a (semantically consistent) picture of a dog and an auditory file of a bark, or (a semantically inconsistent) picture of a dog and an auditory file of a meow. The semantically consistent pair will be more likely to be considered a whole, as demonstrated by more efficient responses to the congruent pair when compared to the incongruent pair (Molholm, Martinez, Ritter, Javitt, & Foxe, 2004).

An additional top-down factor that has been shown to influence multisensory integration is task instructions. Instructions have been shown to influence an observer's belief about an audiovisual event in such a way that they are either viewed or not viewed as a unitary sensory experience (Arnold, Johnston, & Nishida, 2005; Spence, 2007;

Windmann, 2004). For example, Arnold et al. (2005) investigated the possibility that some sort of perceptual compensation[1] must occur to address the fact that sound travels more slowly than light and thus hearing and seeing are inherently mistimed. The researchers employed the "bounce illusion" to test their theory (see also Berenthal, Banton, & Bradbury, 1993 and Sekuler, Sekuler, & Lau, 1997). In this illusion, two dots presented on a screen are shown to be moving towards one another until they are superimposed. If a tone is presented at the timing of superimposition, the dots appear to bounce; whereas in the absence of a tone the dots appear to move through one another. Arnold and colleagues were able to modulate how participants perceived the bounce illusion by asking the participants to imagine the tone originating from a different source.

Arnold et al. (2005) hypothesized that if perceptual compensation were occurring it would be evident in the timing of the perceived bounce. In particular, when the screen is far away and the sound is presented via headphones, participants should perceive the tone as occurring too early for the bounce illusion to manifest itself. Their experiment demonstrated that as viewing distance increased in the loudspeaker condition, the earlier the tone would have to occur for the bounce illusion to occur, suggesting that no perceptual compensation was occurring: in order for audiovisual events to be bound together they must enter sense receptors at approximately the same time. In regard to the question of whether task instructions can modulate this effect, in one experiment

[1] Perceptual compensation, in this context, can be thought of as processing that occurs to align an auditory and visual event even if they occur asynchronously.

(Experiment 3), participants were instructed to *imagine* that the origin of the sound was the visual display (rather than the headphones or loudspeakers that were being used to emit the sound). Under these instructions perceptual compensation occurred such that the earlier tones were no longer needed for the bounce illusion to be perceived, demonstrating that top-down factors such as task instructions can bias an observer to view perceptual events as whole.

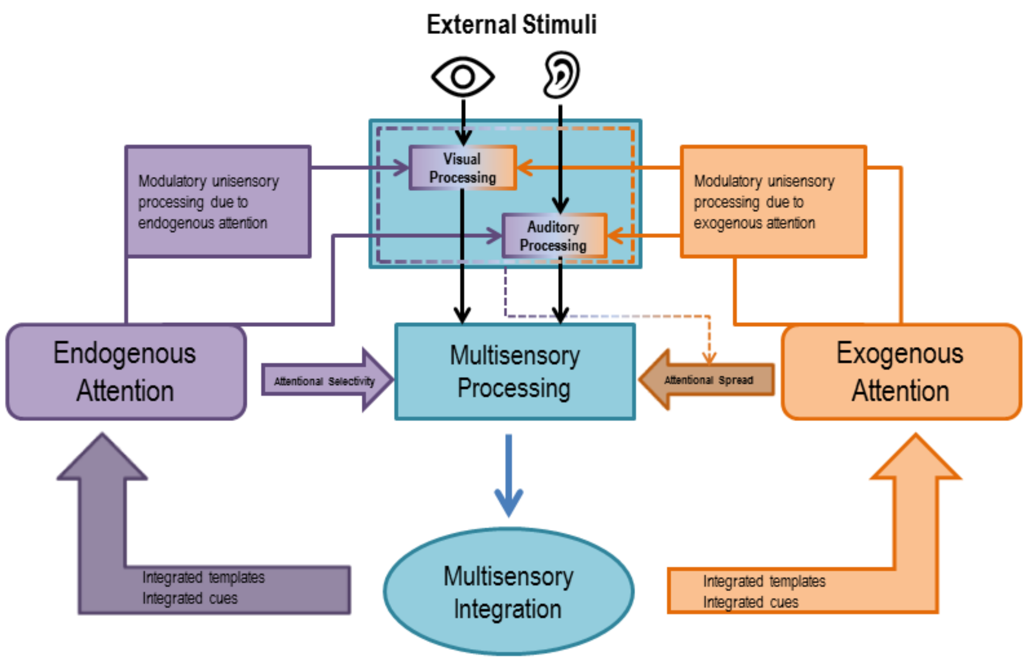

Figure 1-1. Conceptualization of Multisensory Integration. A depiction of how exogenous and endogenous attention are proposed to affect multisensory integration according to Tang, Wu, and Shen (2015).

In addition to task instructions, other aspects of attention[2] have also been shown to have an effect on multisensory integration. Tang et al. (2015) argue that multisensory integration is mediated by both exogenous (i.e., *stimulus-driven*; when the properties of a stimulus capture attention reflexively) and endogenous (i.e., *goal-driven*; or when an individual volitionally directs attention towards something) attention. These researchers, in their review, claim that the interplay between attention, multisensory processing, and subsequently multisensory integration is complex. As pictured in Figure 1-1, unimodal stimuli are first processed in parallel, after which endogenous attention affects multisensory processing via attentional selectivity. That is, for example, when participants are instructed to pay attention (i.e., their endogenous, goal-driven attention is engaged) to audiovisual stimuli at particular spatial locations on a display it has been observed that audiovisual processing is enhanced regardless of whether they are asked to selectively attend to one modality or attend to both modalities when compared to not cueing endogenous attention to a particular spatial location (Busse, Roberts, Crist, Weissman, & Woldorff, 2005; Santangelo, Fagioli, & Macaluso, 2010; Senkowski, Talsma, Herrmann, & Woldorff, 2005; Wu, Yang, Gao, & Kimura, 2012). Furthermore,

[2] Importantly, the model discussed herein focuses on the exploration of this issue as discussed by Tang et al. (2015). More contemporary research on sensory processing has demonstrated that an important and oft miscategorized contributor to multisensory integration is *expectation*. Expectation differs from attention in that it is a top-down factor embodied by prior knowledge about sensory events. Summerfield and Egner (2016) use the example of a familiar room to explain the effect of expectation on sensory experiences. In particular, one enters a familiar room with knowledge beforehand about the room, and as a result much information from that room is (a) processed less deeply because it is arguably redundant and (b) gives contextual clues about objects that may appear in the room, for vision in particular. For additional discussions on how expectation affects multisensory processing see also Gau & Noppeney (2016) and Ten Oever, Romei, van Atteveldt, Soto-Faraco, Murray, & Maustz (2016).

multisensory interactions are thought to affect exogenous attention by way of attentional capture: when participants are under heavy perceptual loads, multimodal cues capture attention involuntarily more often than unimodal cues (Santangelo et al., 2008; Santengelo & Spence, 2007) whereas under low cognitive loads, unimodal and multimodal cues can both capture attention involuntarily (Santangelo et al., 2008). In this model, after multisensory integration has occurred, multisensory integration in turn affects both endogenous and exogenous attention (see Figure 1-1) in a cyclical manner. Multisensory signals can then be stored as integrated templates[3] that can influence both kinds of attention in a top-down manner, and given that integrated cues have been theorized to be more salient (i.e., they capture attention more readily), this in turn affects both endogenous and exogenous attention. For example, Matusz and Eimer (2013) demonstrated the effect that integrated cues can have on attentional capture. These researchers found that when pairing a task-irrelevant tone with a target during a stimulus detection task, participants were able to locate targets more quickly in search arrays.

In sum, the model described by Tang et al. (2015) attempts to provide a complete picture of the nature of attention's effect on multisensory integration, the important point being that both kinds of attention (endogenous and exogenous) work to influence both multisensory processing and integration and, as can be expected, the interplay between these processes and attention is complicated, much more so than the simplistic unisensory

[3] Attentional templates are task-relevant representations stored in working memory that influence attention (Matusz & Eimer, 2013).

processing → multisensory processing → multisensory integration model discussed earlier. The model highlights that multisensory integration is an active and ongoing process that acts dynamically on multisensory stimuli.

1. 3. Multisensory Illusions

Interestingly, under some conditions multisensory integration can result in intriguing multisensory illusions, in which conflicting information from different modalities results in the perception of something that did not objectively occur. One of the most compelling examples of this is what is commonly termed the *McGurk effect* (McGurk & MacDonald, 1976). In this effect it is possible to create a speech illusion by presenting an individual with an auditory stream that has an incongruent visual speech signal. The most widely used example of this comes from when the auditory stream contains "ba" and the visual stream contains a face articulating "ga". Under these conditions an individual is very likely to misperceive "da", an item that is completely different than either of the unisensory signals that composed the integrated percept. The McGurk effect arguably demonstrates that auditory and visual information, at some point in processing, become conjunctively coded to create a single unitary audiovisual percept.

Multisensory illusions are not limited to the McGurk effect. Additional examples include the *ventriloquism effect* which occurs when the spatial location of a visual stimulus influences where an auditory stimulus is believed to be coming from (Bertelson, 1999; Bertelson, Vroomen, & De Gelder, 2000; Hairston, Wallace, Vaughn, Stein, Norris, & Schirillo, 2003; Howard & Templeton, 1966), the *sound induced flash illusion* whereupon presenting multiple auditory stimuli causes participants to misperceive one light flash as two (Shams, Kamitani, & Shimojo, 2000), and the *freezing effect* where, during a rapidly presented visual stream, the interjection of an auditory stimulus can cause the visual stream to appear to freeze momentarily (Vroomen & De Gelder, 2004). What each of these examples of audiovisual integration demonstrates is that once unisensory information is processed and multisensory processing occurs, the outcome of multisensory integration is at times not a "true" representation of what has occurred. As such, these illusions provide compelling evidence that the outcome of multisensory integration is a new sensory experience that could be disembodied from the unisensory events that created them.

1. 4. Multisensory Response Enhancement

Multisensory integration causes other interesting behavioral responses other than just those observed in multisensory illusions; the integration of multiple modalities has been shown to improve response performance in certain tasks. A particularly relevant example of this would be the redundant target effect (RTE), in which targets in detection tasks are more quickly identified (via reaction time measures) when the targets are bimodal (i.e., a corresponding image and sound[4]) than when targets are unimodal (Raab, 1962). This reaction time advantage for bimodal stimuli is greater than expected by the probability summation of the RT distributions of the responses to the unimodal signals (i.e., on the basis of the race model; see Colonius & Diederich, 2006; Miller, 1982). For

[4] RTE has been demonstrated in various modality combinations, including visual-tactile presentations (Forster, Cavina-Pratesi, Aglioti, & Berlucchi, 2002).

example, Van der Stoep, Spence, Nijboer, and Van de Stigchel (2015) were able to demonstrate that the high temporal consistency of an audiovisual event contributes to multisensory response enhancement via multisensory integration. Thus, the fate of multisensory information is variable, although at times multisensory integration can yield powerful illusions, it can help individuals more quickly perceive bimodal events. The third potential outcome of multisensory integration is of particular interest to the proposed set of studies and warrants a more detailed discussion.

2. Sensory Dominance

In some conditions, unisensory signals compete for processing resources, leading to one sensory modality dominating another. Arguably, some of the instances of multisensory illusions cited earlier are also examples of the phenomenon of sensory dominance. For example, Tiippana (2014) noted that in her work examining the unimodal streams in the McGurk effect, visual “ga” is often times mistaken for “da” in isolation of any auditory information. As a result, the visual articulation of “ga” may bias an individual to perceive “da” in the McGurk effect, therefore the McGurk effect may, in a few circumstances, be an example of visual dominance (although, note that there are several other stimulus combinations that lead to the McGurk effect). Overall, modality dominance has been an active area of investigation for a significant amount of time now and much is known about the situations that lead to one sense dominating over another in a number of modalities; however, for the purposes of this dissertation the focus will be on auditory and visual dominance in particular.

2. 1. Visual Dominance

Seminal research on visual dominance in humans comes from the work of Colavita (1974). In Colavita’s original work, participants were given a speeded task in which unimodal auditory, unimodal visual, or bimodal audiovisual targets were presented. Participants responded to each of the unimodal target types with different keys, and with both keys for bimodal trials. Interestingly, in bimodal trials, participants frequently failed to respond to the auditory stimulus, and in fact, nearly exclusively responded to only the visual component of the bimodal signals (e.g., 98% of responses to bimodal trials were visual only in Experiment 1). Accordingly, the failure to respond to a stimulus in a modality other than the visual modality during bimodal trials has been termed the *Colavita effect*. This visual prepotency occurs across a wide range of stimulus manipulations including differences in stimulus intensity (Colavita, 1974), various stimulus modalities including the tactile modality (Hartcher-O'Brien,et al., 2008; Hetcht & Reiner, 2009), simple and complex stimulus types (Sinnett, Soto-Faraco, & Spence, 2008; Sinnett, Spence, & Soto-Faraco, 2007), and when the spatial origin of the stimuli is varied (Colavita, 1974, 1982) amongst many others (for a detailed review of the factors that have been investigated to affect the Colavita effect, please see Spence et al., 2012). As can be clearly seen, explaining the Colavita effect and what aspects influence it has become a priority amongst perception researchers.

2. 1. 1. Stimulus Complexity and the Colavita Effect. Sinnett et al. (2007) provided evidence that visual dominance effects can occur even when utilizing more complex stimuli (i.e., in contrast to the simple stimuli typically used in the traditional Colavita effect). In these experiments, visual stimuli consisted of common objects from the Snodgrass and Vanderwart (1980) database (e.g., an airplane, glove, etc.) instead of light flashes, while auditory stimuli consisted of common sounds (e.g., a doorbell, phone ring, etc.) instead of simple tones. Participants were asked to monitor the screen for unimodal auditory, unimodal visual, and bimodal audiovisual stimuli and utilized different keys in response to each of these targets (Experiment 1). Overall, Sinnett et al. replicated the findings of Colavita (1974), observing the Colavita effect even with complex visual and auditory stimuli. In Experiment 2, participants were presented with an audiovisual stimulus stream and assigned specific unimodal targets to search for, or the bimodal presentation of both assigned unimodal targets. For example, participants may be asked to look for a picture of a stop sign and listen for the sound of a cat meowing. They were then asked to press a button if they heard the sound of the cat (unimodal auditory), a different button if they saw the stop sign (unimodal visual), and a third button if they both heard the cat and saw the stop sign (bimodal). Once again, Sinnett et al. observed the Colavita effect, with participants more frequently erroneously responding with the unimodal visual button to bimodal trials.

In this same work Sinnett et al. (2007) also explored situations where participants' attention was biased towards a particular modality. In Experiments 5 and 6 participants were given the same instructions as Experiment 2, however the proportion of trials was manipulated such that either unimodal auditory or unimodal visual trials were presented more frequently, thus biasing attention towards a particular sensory modality (Experiment 5). In the final condition (Experiment 6) the number of distracting stimuli was reduced in the auditory biased and visual biased conditions, allowing for more attentional resources to be directed at either the auditory or visual streams. The findings suggested that an attentional bias was capable of modulating the Colavita effect, such that a reduction in the visual dominance effect was observed when biasing attention towards the auditory modality (i.e., a reduction in the amount of erroneous visual only responses to bimodal trials), although they were unable to completely reverse the effects of the Colavita visual dominance effect to demonstrate auditory dominance.

2. 1. 2. Stimulus Timing and the Colavita Effect. Koppen and Spence (2007) investigated the idea that differences in stimulus onset times could modulate the Colavita visual dominance effect. The underlying motivation for their investigation was to explore the possibility that if auditory and visual events were presented further apart from one another, then at some point the Colavita visual dominance effect should be eliminated as the visual stimuli would be less likely to interfere with the auditory stimuli. Participants were given a temporal order judgement (TOJ) task with auditory and visual stimuli and a manipulation of the Colavita (1979) task in which stimulus onset asynchronies (SOAs) were manipulated. Once the results of each study were correlated, it was revealed that the Colavita visual dominance effect diminished at the point where participants were able to reliably judge that the auditory stimulus occurred prior to the visual stimulus, and vice versa. This test of the visual prepotency effect is important as it demonstrates the possibility that sensory dominance effects may be susceptible to the "law of prior entry" (Spence, Shore, & Klein, 2001; Titchner, 1908), which states that sensory experiences that are being attended to are perceived more rapidly. In the case of Koppen and Spence, visual stimuli in their task may have captured attention first, thus leading to the Colavita effect when both visual and auditory signals were presented at the same time. However, once it becomes clear that the visual stimuli are clearly presented after the auditory stimuli, a reduction in the Colavita effect can be observed. Importantly, the Colavita effect was not reversed in this case (i.e., auditory dominance is not observed), thereby demonstrating the robustness of the Colavita visual dominance effect. They go on to argue that the unity assumption, which states that when two unimodal events are consistent with one another they are assumed to be a unitary bimodal event, drives the Colavita visual dominance effect: once an individual can reliably separate the bimodal audiovisual event into two unimodal events the Colavita effect disappears.

2. 1. 3. Explanations of Visual Dominance. Various explanations have been offered to account for visual dominance effects. One such early and oft cited account of visual dominance was proposed by Posner, Nissen, and Klein (1976), who argued that what may be driving visual dominance in adults is the poor alerting ability of the visual modality. Posner et al. (1976) claimed that the visual modality requires more attentional resources because effort must be exuded to perpetually monitor a visual stream for important changes and occurrences. In contrast, the auditory modality can capture attention more readily; for example, if a person were to approach you from behind the auditory modality has the ability to alert you to that person's presence (i.e., one could hear their footsteps) more readily than the visual modality (i.e., one would have to check over their shoulder often to see if someone was behind them). Furthermore, Posner et al. (1976) argue that allocating resources to the visual modality inhibits processing in the auditory modality. Thus, within this framework there is a fundamental imbalance of attentional resources, which might lead to visual dominance, at least as measured in these tasks.

Another especially compelling argument for why visual dominance and the Colavita effect is observed in a diverse number of experimental manipulations of both visual and auditory stimuli comes from Spence et al. (2012), who draw inspiration from the work of Desimone and Duncan (1995; Duncan, 1996). They hypothesized that attention is an emergent phenomenon that occurs as a result of one stimulus modality winning the competition for the activation of neural representations. More specifically, in the case of the Colavita effect, visual representations could be more likely to be activated and consequently inhibit the influence of auditory representations, a standpoint which is shared by Posner et al. (1976), because the competition naturally favors visual information. Although evidence for this viewpoint may still yet be sparse, Spence et al. (2012) view the fact that a fairly large proportion of the cortex is dedicated to processing visual information (Serano, Dale, Reppas, Kwong, Belliveau, Brady, et al., 1995) represents a promising clue that such a theory may be validated. As such, the neural underpinnings of the Colavita effect represent an important area of open inquiry in the study of sensory dominance.

2. 2. Auditory Dominance

Given the breadth of research that demonstrates visual dominance in adults and the fact that it does not reverse to auditory dominance even when biasing attention towards auditory stimuli (e.g., Sinnett et al., 2007), the Colavita visual dominance effect seems fairly robust. Thus far one of the few situations discussed here where visual dominance was diminished required researchers to essentially make it appear as if there were two unimodal events, rather than one bimodal sensory event, by having the auditory event be clearly presented before the visual event (see Koppen & Spence, 2007). Therefore, it may seem that auditory dominance is simply not possible to demonstrate in adults unless precise and extreme experimental conditions are met.

However, Ngo, Cadieux, Sinnett, Soto-Faraco, and Spence (2011) incorporated a task manipulation that led to auditory dominance: an n-1 repetition detection task using a bimodal stimulus stream. In this work Ngo et al. first hypothesized that, although iconic and echoic memory are by definition transient, research shows that iconic memory has a shorter timespan than echoic memory (e.g., Cowan, 1984; Sperling, 1960); therefore, auditory dominance might arise in a situation where the auditory component of a bimodal target is still being held in the echoic memory buffer, while the visual component would not be accessible due to the limits of iconic memory (up to a second, see Cowan, 1984). Essentially, participants may be superior at recognizing n-1 auditory repetitions[5] because echoic memory will store the representation of the auditory stimulus longer. The results of their first experiment did in fact demonstrate this, but upon further investigation and subsequent testing, it appeared that the presence of an intervening stimulus between n-1 repetitions was really driving the reversal of the Colavita visual dominance effect. In the case of the auditory stream, the auditory stimulus presented between the n-1 repetitions had no effect on accuracy. In contrast, the visual stimulus that occurred between the n-1 repetitions did impact participant responses as the intervening stimulus served as a mask disrupting the memory for the n-1 item. Therefore, the auditory dominance observed in these experiments is more likely driven by the differential effect masking stimuli has on processing across sensory modalities. More specifically, the processing of visual stimuli

[5] Ngo, et al. (2010) modified the task to require participants to detect either auditory, visual, or bimodal repetitions in an attempt to assess the modality appropriateness hypothesis (Welch & Warren, 1980). Visual dominance was observed despite the inherent advantage audition should have in tasks that are reliant on temporal information.

is more susceptible to the interference of semantically relevant visual masks whereas auditory stimuli are not.

Robinson and Sloutsky (2013) have also observed auditory dominance in adults, albeit with a very different task than has traditionally been used in research exploring sensory dominance (see Colavita, 1974; Egeth & Sager, 1977; Ngo et al., 2010, 2011; Sinnett et al., 2007, 2008; Spence, 2007). Robinson and Sloutsky required adults to participate in unimodal and bimodal statistical learning tasks. Participants were presented with streams of spoken syllables and visually presented shapes presented in triplets (i.e., bimodal condition), spoken syllables in isolation (i.e., unimodal auditory), or shapes in isolation (i.e., unimodal visual), and asked to respond to repetitions in the stream. The streams could be either random (i.e., triplets may contain any 3 items) or the structured 3-item triplets seen in Figure 2-1. Furthermore, participants in the bimodal condition could have a correlated audiovisual stream where each modality had structured triplets, or non-correlated audiovisual streams where one modality had a stimulus stream that was random. Afterwards, participants were tested on their recall for triplets that occurred during the stream.

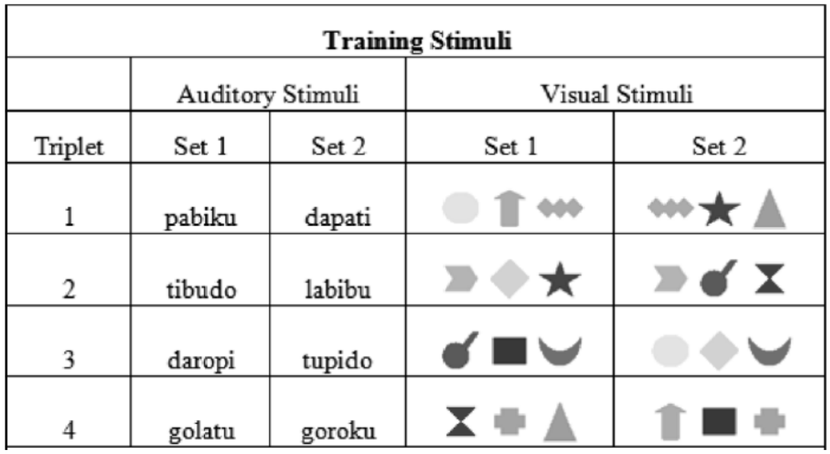

Figure 2-1. Training Stimuli. Examples of the structured triplets from Robinson and Sloutsky (2013).

The results of the study show that in each unimodal condition participants were able to identify the triplets that been previously presented at rates that were better than chance. However, the critical finding of this study was the differences observed in the correlated and non-correlated bimodal streams. In these streams participants were best at recalling the triplets that occurred in the correlated stream, and in the non-correlated stream random auditory triplets attenuated visual statistical learning, but random visual triplets had no effect on auditory statistical learning. The researchers concluded that the results of the study do not necessarily mean that the auditory modality is better able to engage in statistical learning, but that the auditory modality delays processing and thus attenuates the visual modality during multisensory processing. The reason that auditory dominance is observed here despite so much evidence suggesting that adults are visually dominant is still as of yet unknown, but the fact that auditory dominance is observed caused Robinson and Sloutsky (2013) to hypothesize that different processes may lay at the heart of visual and auditory dominance. For example, one possibility is that in implicit tasks auditory dominance may be more likely to be observed, since the vast majority of visual dominance tasks require participants to make explicit responses.

3. Contemporary Theorizing on Sensory Dominance and Current Directions

As discussed, studies of sensory dominance typically demonstrate that adults are visually dominant (Spence et al., 2012). However, findings with children tend to show the opposite. That is, in certain tasks children often demonstrate auditory dominance (Napalitano & Sloutsky, 2004; Nava & Pavani, 2013; Robinson & Sloutsky, 2004; Lewkowicz, 1988a, 1988b). Therefore, it is largely believed that sensory dominance shifts throughout an individual's lifespan from auditory to visual dominance (Robinson & Sloutsky, 2013; Sloutsky & Napolitano, 2003). Shifting from one sensory dominance type to another throughout development demonstrates that the processes that are involved in phenomena like the Colavita effect are not necessarily present or functioning in the same manner in childhood as they are in adulthood. The fact that auditory dominance in children has been demonstrated as robustly as visual dominance in adults provides an interesting clue about the development of sensory processing across modalities[6].

Robinson and Sloutsky (2010) have considered this special issue recently when they theorized about the nature of sensory dominance and the role that attention may play in it. In particular, they argue that two features of processing have an effect on sensory dominance: how quickly an individual orients attention to a particular modality, and the speed of processing within that modality, and that these two factors may undergo

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[6] The developmental underpinnings of multisensory processing across the lifespan is an important issue, but beyond the scope of this dissertation. For additional discussion about the development of multisensory processing in children see Ernst (2008) and Nardini, Jones, Bedford, and Braddick (2008). A recent example of work with children and older adults in this area by Parker and Robinson (in press) is especially interesting.

developmental changes. Furthermore, individual sensory modalities “race” to win a shared (and limited) pool of attentional resources early in processing, with the modality that engages attention quicker being the modality in which dominance will be observed. As a result, Robinson and Sloutsky (2010) believe that modality dominance effects will be more pronounced at earlier processing stages, because eventually attentional resources will be released to the non-winning modality for crossmodal processing to occur (see also Spence et al., 2012).

In regard to development, auditory dominance may occur because auditory stimuli are more transient than visual stimuli and thus require attentional resources early, otherwise the information may be lost (see Robinson & Sloutsky, 2013 and Sloutsky & Napolitano, 2003 for similar arguments). Furthermore, auditory stimuli are dynamic which may give auditory input an early advantage in processing since visual stimuli can be dynamic but are more often static. Finally, Robinson and Sloutsky (2010) argue that adults are quicker to process auditory stimuli than visual stimuli (see also Green & von Gierke, 1984), and as a result, in conjunction with the transient and dynamic nature of auditory stimuli, children may be further pushed to favor the auditory modality.

These insights from the developmental shift from auditory dominance to visual dominance from childhood to adulthood, wherein children 12 and younger tend to favor auditory stimuli (Nava & Pavani, 2013), inspired a recent investigation of sensory dominance that identified some conditions where auditory dominance is more likely to occur. Robinson, Chandra, and Sinnett (2016) investigated the Colavita effect in the context of an oddball identification task. This task was selected for this study because

Event Related Potential (ERP) evidence in a passive version of this same task demonstrated slower P300[7] components for visual oddballs and faster P300 components for auditory oddballs, a finding argued to be consistent with auditory dominance (Robinson, Ahmar, & Sloutsky, 2010). As such, investigating auditory dominance in the context of this passive task, and aligning it with other investigations for sensory dominance that require explicit responses from participants would be an important and logical next step in understanding the possibility of situational auditory dominance in adults.

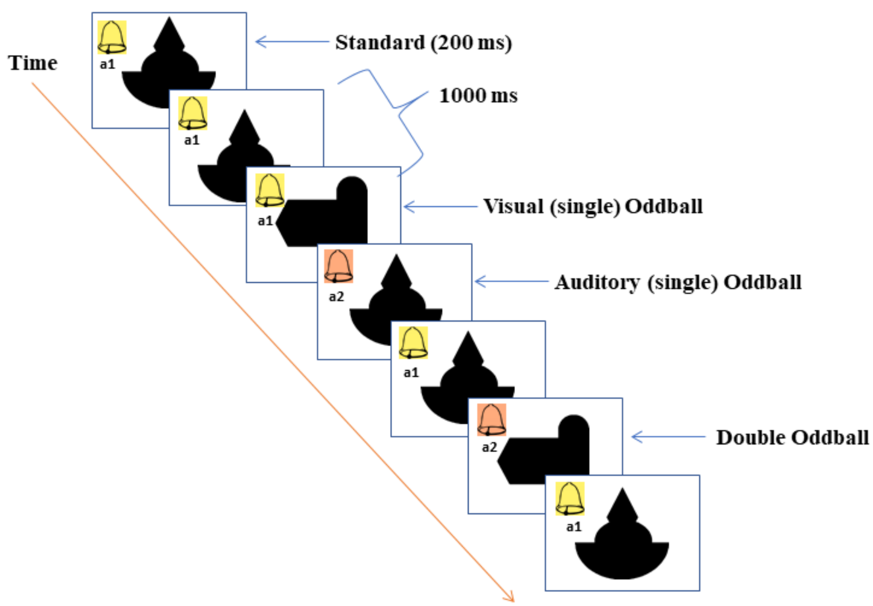

Figure 3-1. Stimuli Timing from Robinson et al. (2016). In the stimulus stream participants are presented with a standard bimodal stimulus and asked to press a key any time they see a visual oddball (i.e., only the image chages), an auditory oddball (i.e., only the sound changes), or a double oddball (i.e., both the sound and the image change).

[7] The P300 wave is indicative of oddity detection (Sutton, Braren, Zubin, & John, 1965).

In the study conducted by Robinson and colleagues (2016), participants were instructed to monitor a stimulus stream in which bimodal (auditory and visual) stimulus combinations were presented and participants were asked to press a key in response to any deviations from a standard (see Figure 3-1). Participants completed this basic oddball detection task under a variety of response manipulations. For example, in the 1-button task participants were asked to press a key if they detected a unimodal auditory oddball, unimodal visual oddball, or a bimodal oddball (Experiment 1). In the 3-button version of this task, participants were required to press separate keys for each oddball (Experiment 2), and in the final manipulation (Experiment 3) of the 1-button task participants were to press the same key in response to single oddballs (i.e., an auditory or a visual stimulus change in isolation) and refrain from responding to double oddballs (i.e., when the auditory and visual stimulus both changed). The 3-button version of the task (Experiment 2) was developed to align the study with other investigations of modality dominance: it afforded the researchers the ability to look at unimodal response errors (e.g., the proportion of times participants pressed the "visual" key to bimodal oddballs). The second 1-button task (Experiment 3) was done to test the hypothesis that response biases or cognitive load could modulate sensory dominance effects. It was hypothesized that asking participants to choose amongst multiple response buttons requires an individual to employ additional motor and decision-making processes that occur later in processing, where it is theorized that visual dominance effects are more profound because auditory processing may be disrupted by visual processing at this stage (Robinson et al., 2016).

Interestingly, clear evidence of auditory dominance was demonstrated in both versions of the 1-button task, while visual dominance was observed in the 3-button version of the task. Robinson et al. (2016) theorized that multiple factors could have led to the observed pattern of results. For one, they argue that what drives auditory and visual dominance may be two separate underlying mechanisms, further postulating that auditory dominance is more likely to occur earlier in processing during stimulus encoding, and that visual dominance arises later in stimulus processing, subsequently interrupting auditory processing leading to visual dominance effects becoming more pronounced when an individual is making a response and/or a decision.

3. 1. Aims of this dissertation

The reversal of dominance types in adults when participants perform the 1-button condition of the Robinson et al. (2016) and the 3-button task (from auditory to visual dominance), provides an ideal point from which to further investigate the factors thought to influence sensory dominance. Accordingly, the purpose of the research conducted for this dissertation was to further examine auditory and visual dominance within the context of the oddball paradigm utilized by Robinson et al. (2016) by systematically manipulating the auditory and visual stimuli in the crossmodal version of the experiment in order to assess three primary factors that seem to influence whether or not auditory or visual dominance occurs.

First, given that it has been hypothesized that transience is an inherent characteristic of auditory stimuli, auditory dominance might be observed in adults because the attentional system preferentially weights auditory processing in an attempt to capture an important stimulus that will quickly disappear (Shimojo & Shams, 2001). One way to assess the effect of transience on sensory dominance would be to systematically manipulate stimulus durations during the oddball task in order to see how differing exposure lengths between each modality potentially modulate sensory dominance. Accordingly, it was hypothesized that when stimuli are made to be more transient (by reducing their presentation lengths in relation to one another: for example, a 50 ms auditory stimulus presented concurrently with a 200 ms visual stimulus), the more transient (i.e., shorter) stimulus will be the one to show greater evidence of modality dominance.

Second, the literature on sensory dominance has also suggested that sensory modalities may "race" for attentional resources (Robinson et al., 2016). Therefore, the experiments conducted here also manipulate stimulus onset times for both auditory and visual stimuli. If auditory or visual stimuli are presented earlier than one another, then differences in behavioral responses may be observed (i.e., the stimuli may be subject to the effects of prior entry; see Spence and Parise, 2010 for a detailed review). Therefore, it was hypothesized that the stimulus (either auditory or visual) presented earlier would be more likely to demonstrate modality dominance.

Lastly, decision-making (or at least the complexity of the decision) seems to also have a mediating effect on whether or not auditory or visual dominance is observed (Robinson et al., 2016). Previously, researchers addressed this issue by providing either a 1-button or 3-button version of the oddball paradigm. Therefore, for this research, manipulations pertaining to transience and stimulus onsets will also be examined under the lens of decision making by employing both 1-button and 3-button version of this task. This final manipulation is important as the strict control of the number of responses keys, and thus the complexity of decision making, enables one to precisely look at the relative influence that stimulus transience and temporal asynchrony has on sensory dominance. For a detailed breakdown of the expected dominances based upon these factors for each of the Experiments in this research, see Table 3-1 below.

Table 3-1. A summary of all predicted dominances		
Experiment	**Condition**	**Dominance Prediction**
Experiment 1a (Single response)	Long Auditory/ Long Visual	Auditory Dominance, condition is identical to Robinson et al. 2016
	Short Auditory/ Short Visual	Control for unknown effects of shortening the stimuli
	Long Auditory/ Short Visual	Visual Dominance
	Short Auditory/ Long Visual	Auditory Dominance
Experiment 1b (Multiple responses)	Long Auditory/ Long Visual	Visual Dominance, condition is identical to Robinson et al. 2016
	Short Auditory/ Short Visual	Control for unknown effects of shortening the stimuli
	Long Auditory/ Short Visual	Visual Dominance if decision making overwrites the influence of transience
	Short Auditory/ Long Visual	Visual Dominance if decision making overwrites the influence of transience
Experiment 2a (Single response)	+200 ms Auditory	Auditory Dominance
	+100 ms Auditory	Auditory Dominance
	Simultaneous presentation	Auditory Dominance, condition is identical to Robinson et al. 2016
	+200 ms Visual	Visual Dominance
	+100 ms Visual	Visual Dominance
Experiment 2b (Multiple responses)	+200 ms Auditory	Visual Dominance if decision making overwrites the influence of early processing
	+100 ms Auditory	Visual Dominance if decision making overwrites the influence of early processing
	Simultaneous presentation	Visual Dominance, condition is identical to Robinson et al. 2016
	+200 ms Visual	Visual Dominance
	+100 ms Visual	Visual Dominance

4. Experiment 1: Stimulus Duration Manipulation

The primary aim of Experiment 1 was to address the effect that stimulus transience has on sensory dominance. Recall, that previous work has suggested that auditory stimuli are special in that they are argued to be more often transient in comparison to visual stimuli (Shimojo & Shams, 2001). Therefore, it was hypothesized that making manipulations to the relative durations of signals composing a bimodal stimulus would affect observed dominances. More specifically, it was expected that when the auditory stimulus has a shorter duration relative to the visual stimulus, auditory dominance should be observed as the attentional system should preferentially process the stimulus that was presented for a shorter time in order to accurately process the transient stimulus (i.e., an unavailable item). In contrast, it was expected that when the visual stimulus has a shorter duration than the auditory stimulus, visual dominance should be observed. When the stimuli for both modalities are the same length it is expected that in the 1-button condition auditory dominance should be observed and in the 3-button condition visual dominance should be observed (as was the case in the work of Robinson et al., 2016).

4. 1. Experiment 1a: Stimulus Duration Manipulation in the 1-Button Oddball Task

4. 1. 1. Participants. Twenty-Eight University of Hawaii at Manoa undergraduate students were recruited to participate in this experiment in exchange for course credit[8]. However, four participants were removed from the sample due to failure to consistently follow instructions throughout all 4 trial blocks, reflected by an overall accuracy of less than 60%. In theory, participants could achieve an accuracy of 77% by never making any responses to oddballs during the experiment, due to the fact that 77% of trials are standard trials in which participants make no responses. Therefore, a 60% overall accuracy is a conservative benchmark with which to assess whether participants accurately performed the task, or if instead were possibly pushing the response button more frequently in an attempt to shorten the experiment. The remaining participants (N = 24; N = 16 female participants; age: M = 22.41, SD = 5.44) were predominately right-handed and reported having normal or corrected-to-normal vision and hearing. All experimental procedures conformed with the guidelines set forth by the University of Hawaii at Manoa's Center on Human Studies (CHS), see Appendix A.

4. 1. 2. Stimuli. Stimuli for this experiment consisted of tones and pictures utilized previously in an oddball detection task by Robinson et al. (2016). The visual stimuli included 5 novel shapes, each of which were 400 x 400 pixel bitmap images (v1-v5) that

[8] While not representative of the general population, undergraduate students are typically used in this kind of research (Robinson et al., 2016). The age range used here is ideal as sensory dominance is thought to clearly manifest itself after the age of 12 (e.g., Nava & Pavani, 2013).

were monochromatic and created in Microsoft Word (see Figure 4-1). Auditory stimuli were 5 pure tones that ranged from 200 Hz to 1000 Hz (a1-a5) and were created in CoolEdit 2000 and presented as 200 ms wav files (see also Robinson et al., 2016). In order to manipulate stimulus durations, the pure tone files were further edited to create a second set of auditory stimuli with a duration of 50 ms. Crossmodal stimuli were created by overlapping the auditory and visual stimuli such that each possible stimulus duration combination was made: 200 ms auditory stimuli with 200 ms visual stimuli (Long Auditory/Long Visual), 50 ms auditory stimuli with 50 ms visual stimuli (Short Auditory/Short Visual), 200 ms auditory stimuli with 50 ms visual stimuli (Long Auditory/Short Visual), and 50 ms auditory stimuli with 200 ms visual stimuli (Short Auditory/Long Visual)). Note, the Long Auditory/Long Visual condition is essentially a replication of Robinson et al. (2016). From these auditory and visual items, a stimulus stream was constructed such that each stimulus had an interstimulus interval (ISI) of approximately 1000 ms. The ISI was computed using a 15% jitter with a range of +/- 150 ms (i.e., a jitter range of 850 ms to 1150 ms, see Wodka, Simmonds, Mahone, & Mostofsky, 2009 for a discussion of optimal jitter durations; see Figure 4-2 for additional information about stimuli presentation timing). Stimuli were presented to participants on an Apple iMac OSX desktop computer with a monitor refresh rate of 60 hz. Auditory stimuli were heard through Logitech USB H390 headsets at a participant-controlled volume (i.e., participants were asked to adjust the volume to one that is comfortable for them).

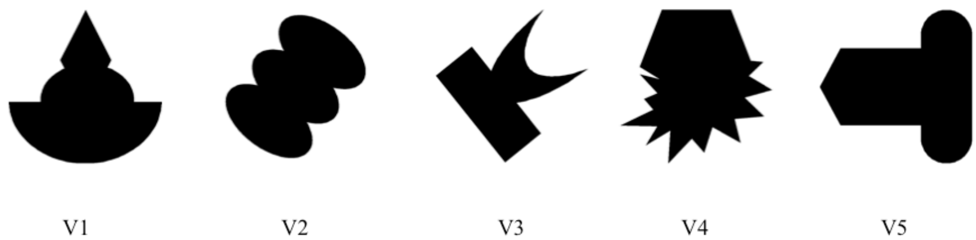

Figure 4-1. Visual stimuli used in all experiments. Images v1-v5 that were used, with one selected as the visual standard and the remaining utilized as visual oddballs.

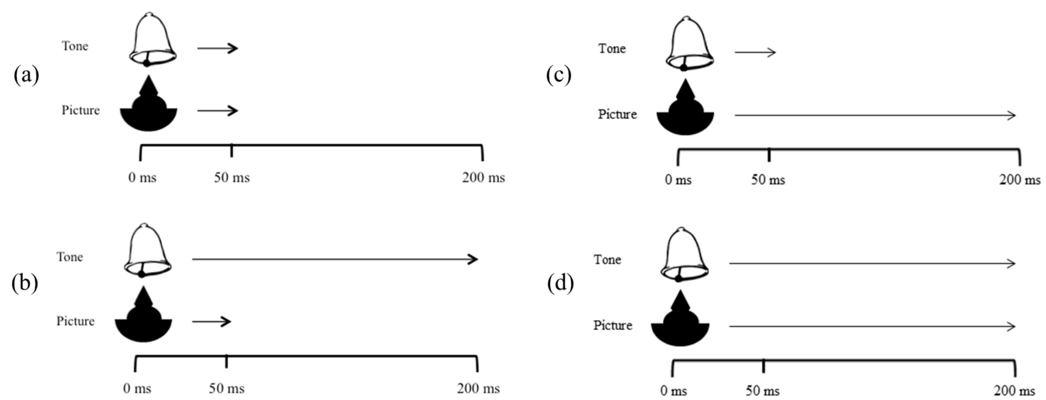

Figure 4-2. Stimulus timing for Experiment 1. Both auditory and visual stimuli begin together at the same time at 0 ms, however they differ in their duration of presentation: (a) Short Auditory/Short Visual, (b) Long Auditory/Short Visual, (c) Short Auditory/Long Visual, (d)Long Auditory/Long Visual.

For each participant one visual stimulus and one auditory stimulus was chosen as the standard (or target) for the oddball task. The experiment was created such that each tone and picture served as the standard at least once, while all other stimuli were utilized to create single oddballs (i.e., an auditory stimulus change from the standard or a visual stimulus change from the standard) and double oddball trials (i.e., both the auditory and visual stimulus change from the standard). The proportion of standard trials, single oddball trials, and double oddball trials were calculated in accordance with Robinson et al. (2016), such that standard trials consisted of approximately 77% of all trials, while single oddball trials consisted of approximately 19% of all trials, and double oddball trials approximately 4% of all trials. In sum, each participant was presented with an auditory and visual stimulus on every trial, with the vast majority including both standard stimuli, and a smaller proportion of trials including either a visual, auditory, or bimodal oddball. The four stimulus presentation duration combinations were presented in a blocked format, with the blocks being randomly presented. In different blocks the stimuli varied in their duration of presentation. The experiment lasted approximately 30 minutes.

4. 1. 3. Procedure. Stimuli pairings were pseudo-randomly selected and 5 versions of the experiment were made to ensure that each stimulus was used as the standard at least once (see Appendix B, Table B-1 for a complete list of stimulus pairings). Participants were randomly assigned to one of the 5 versions of the experiment. Each version of the experiment contained 4 blocks of trials, with each block of trials varying in their stimulus duration times. Therefore, each participant received 1 block of trials where the auditory stimuli lasted 200 ms and the visual stimuli lasted 200 ms, another block where the auditory stimuli lasted 50 ms and the visual stimuli lasted 200 ms, another where the auditory stimuli lasted 200 ms and the visual stimuli lasted 50 ms, and finally a block where the auditory stimuli lasted 50 ms and the visual stimuli lasted 50 ms. For each of these blocks a different standard was selected and the order of presentation of blocks was randomized for all participants. Blocking the experiment based on presentation length ensures that participants were not influenced by relative changes in the duration of the stimuli (i.e., to ensure that it is clear to the participants what the oddball is). Essentially, when deciding whether or not an auditory stimulus is the "same" or "different" from the standard the participant could interpret this in two ways: either looking for a duration change or a tone change. Therefore, telling participants to respond to a "change in sound" may be too ambiguous, and instructing participants to pay attention to the tone alone may complicate the task further, or inadvertently bias attention towards the auditory modality.

Participants were shown a standard pairing briefly on the screen and were instructed that the standard pair of auditory and visual stimuli would co-occur frequently throughout the experiment. In the *1-button* task participants were instructed to press the spacebar on the keyboard if they saw either the auditory or visual stimulus change, or to press the spacebar if both the auditory and visual stimuli change and to avoid responding when the standard is on the screen[9]. Each block lasted approximately 5 minutes and contained 188 trials (140 standard trials, 20 single (unimodal) auditory oddball trials, 20 single (unimodal) visual oddball trials, and 8 double (bimodal) oddball trials). After each block participants were prompted with a screen to allow them a brief rest and at the beginning of the next block new instructions appeared for the new standard pair.

4. 1. 4. Results. For all participants mean reaction times (for correct responses) were calculated for auditory (single) oddball trials and visual (single) oddball trials from the

[9] The 1-button task utilized in this experiment closely resembles that of Robinson et al.'s (2016) Experiment 3 rather than the 1-button task utilized in their first experiment. Overall, this version of the task was chosen for this study as it was the more stringent test for auditory dominance in the original research. In their first experiment participants only had to respond to oddballs (auditory, visual, or crossmodal) with the same button, therefore it was not certain if participants were really attending to each stimulus stream separately or not. The requirement for participants to withhold from responding for double oddballs ensures that participants actively monitor each stimulus stream for relevant changes.

time of stimulus onset in each of the four conditions. Due to the fact that participants withheld responses to bimodal (double) oddballs, reaction time data cannot be analyzed for double oddballs in the 1-button version of the experiment. Detection accuracy for each oddball type was calculated by dividing the number of hits (i.e., successful button presses in response to unimodal oddball trials) by the number of each respective trial type, yielding a hit rate for each oddball type (auditory or visual) across each of the four conditions. A summary of the mean reaction times and accuracies for all four conditions can be found in Table 4-1.

Table 4-1. One-Button Duration Manipulation Descriptive Statistics

	Auditory Oddball		*Visual Oddball*	
Condition	Mean RT	Mean Acc.	Mean RT	Mean Acc.
Long Auditory/Long Visual	610	.92	619	.95
Short Auditory/Short Visual	608	.91	605	.92
Long Auditory/Short Visual	611	.88	597	.91
Short Auditory/Long Visual	632	.89	616	.93

As previously discussed, it was hypothesized that the stimulus that is presented for a shorter duration should be preferred, and therefore sensory dominance should sway in the direction the more transient modality (see pages 26-28 and Table 3-1). To determine if this was the case, a 2 x 2 x 2 repeated measures ANOVA was conducted with Oddball type (Auditory or Visual), Auditory duration (Long or Short), and Visual duration (Long or Short) as factors on participant RTs. Insignificant main effects were observed for Oddball ($F(1, 23) = .44$, $p = .52$), Auditory duration ($F(1, 23) = .20$, $p = .66$), and Visual duration ($F(1, 23) = 1.86$, $p = .19$). Furthermore, insignificant interactions were observed for all two-way interactions; Oddball type and Auditory duration ($F(1, 23) = .82$, $p = .37$), Oddball type and Visual duration ($F(1, 23) = .21$, $p = .65$), and Auditory duration and Visual duration ($F(1, 23) = .04$, $p = .84$). Finally, the three-way interaction between Oddball type, Auditory duration, and Visual duration also failed to reach statistical significance ($F(1, 23) = 2.22$, $p = .15$), demonstrating overall that participants' RTs were not affected by manipulations to the duration of stimuli nor oddball type, see Figure 4-3.

In the case of accuracy, this same Oddball x Auditory duration x Visual duration ANOVA was conducted. The main effects of Oddball type ($F(1, 23) = 3.19$, $p = .09$), Auditory duration ($F(1, 23) = .007$, $p = .93$), and Visual duration ($F(1, 23) = .59$, $p = .45$) were insignificant. The two-way interactions between Oddball type and Auditory duration ($F(1, 23) = .15$, $p = .70$), Oddball type and Visual duration ($F(1, 23) = .66$, $p = .43$), and Auditory duration and Visual duration ($F(1, 23) = 1.93$, $p = .18$) also failed to reach significance. The three-way interaction between Oddball type, Auditory duration, and Visual duration was insignificant as well ($F(1,23) = .22$, $p = .64$), see Figure 4-4.

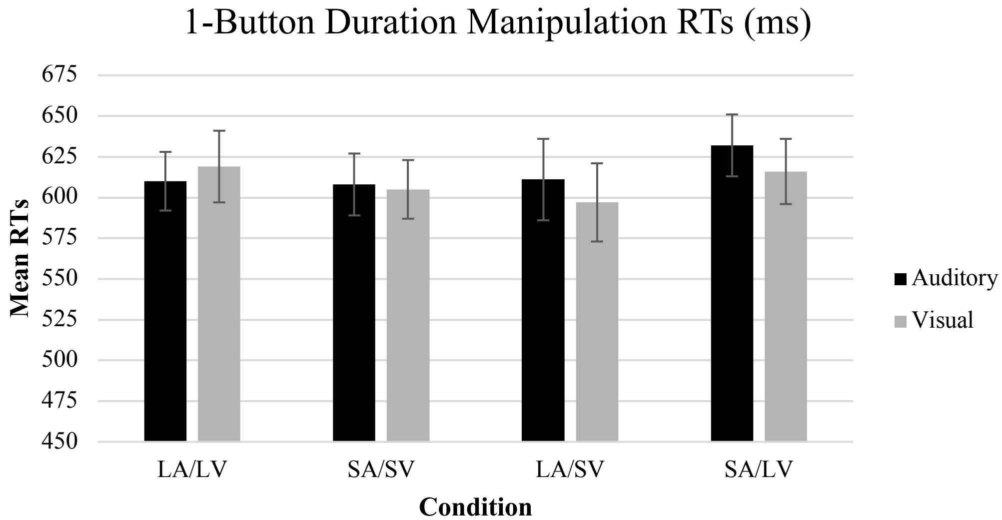

Figure 4-3. One-button Duration manipulation RTs (ms). Mean RTs for participants across all four conditions (LA/LV: Long Auditory/Long Visual condition, SA/SV: Short Auditory/Short Visual condition, LA/SV: Long Auditory/Short Visual condition, SA/LV: Short Auditory/Long Visual condition) in the duration manipulation grouped by oddball type (auditory or visual).

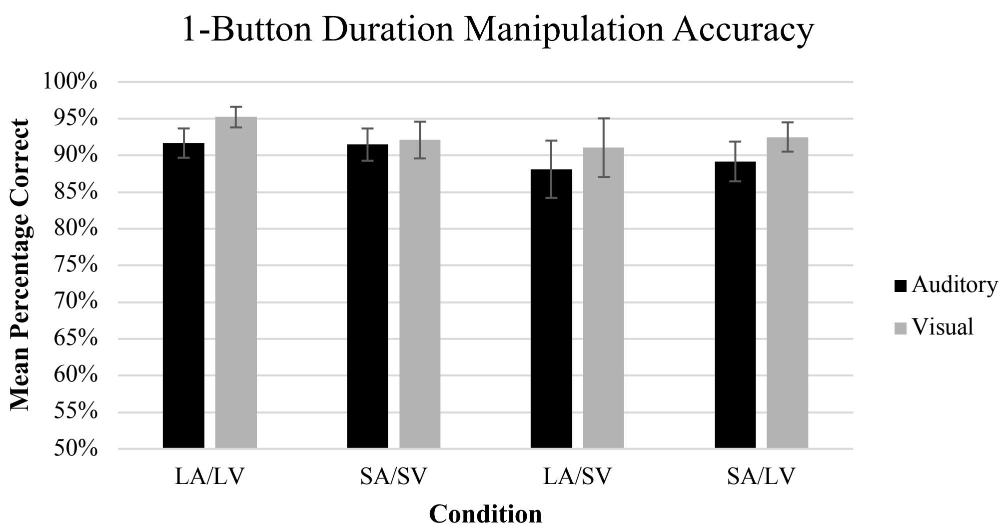

Figure 4-4. One-button Duration manipulation accuracy. Mean percentage correct for participants across all four conditions (LA/LV: Long Auditory//Long Visual condition, SA/SV: Short Auditory/Short Visual condition, LA/SV: Long Auditory/Short Visual condition, SA/LV: Short Auditory/Long Visual condition) in the duration manipulation grouped by oddball type (auditory or visual).

4. 1. 5. Discussion. The original hypothesis for the experiment was that sensory dominance would shift in accordance with changes to the duration of stimuli, such that when participants encountered a relatively shortened auditory or visual stimulus, dominance would be more likely to be observed in the that particular modality. This was expected as the transience of the stimuli should, at least based on previous literature, differentially affect how attention is distributed to each sensory signal (Shimojo & Shams, 2001). However, the findings thus far fail to indicate any support for this hypothesis.

The accuracy data in the 1-button duration manipulation cannot address the question of which dominance is being displayed, due to the fact that meaningful error data cannot be collected here (i.e., it is not possible to differentiate errors during bimodal oddballs as being an "auditory" or "visual" response, as can be done when using multiple response keys; notably, this is how dominance was assessed in Colavita's (1974) work). However, the accuracy data does at least demonstrate that participants were able to complete the task, despite the manipulation not having any effect. It should be noted that the main effect of oddball type did approach significance ($p = .09$) with a trend in these data for participants to make more errors to auditory oddballs (participants were incorrect on 10% of trials overall) when compared to visual oddballs (participants were incorrect on 7% of trials overall), perhaps suggestive of visual dominance.

While the findings thus far would seemingly indicate a lack of a shift in expected dominances, and furthermore, a failure to replicate the results of Robinson et al. (2016) (i.e., in the Long Auditory/Long Visual condition), a key aspect of how sensory dominance was previously measured has yet to be addressed. Previously, Robinson et al. operationalized sensory dominance as the modality that is affected *less* by the presence of the other modality in the bimodal stimulus stream. This was assessed by measuring how participants' reaction times to oddballs were differentially affected when responding to an oddball presented alone (unimodal), or in the presence of the standard from the other modality (bimodal). When this experiment was initially conceptualized the unimodal comparison condition was neglected because of experimental concerns that a particularly long experiment (i.e., completing all potential conditions would have resulted in an excessively long experiment) would result in participant fatigue.

Given this shortcoming, additional unimodal control data were collected with a new set of participants and a between-subjects analysis was conducted in order to better assess the effect of stimulus transience on dominance by establishing a baseline response time to unimodally presented auditory and visual oddballs (i.e., to be analogous with Robinson et al., 2016). It is important to note that conclusions from the following analysis should be considered carefully as this type of cross-experiment analysis is far from ideal, and that a fully within-subjects design would be optimal. Having said that, the decision to collect these control data was not a posteriori, and much of it was collected at the same time that Experiments 1a and 1b were conducted. This was due to the need to have unimodal controls for the variable stimulus durations. These unimodal control participants ($N = 84$) were assigned either to an auditory or visual unimodal oddball detection condition with either a short or long (i.e., 50 ms or 200 ms)[10] presentation duration and were required to respond with 1 button (i.e., analogous to the way unimodal data were collected in Robinson et al., 2016). For additional details on how the unimodal data utilized in the subsequent analysis were obtained, please see Appendix C.

4. 1. 6. Results: Dominance as assessed by relative processing slowdown rates.

The following analysis was conducted in order to examine the effect that the standard auditory or visual stimuli had on response times to visual or auditory oddballs, specifically comparing relative slowdowns in bimodal when compared to unimodal conditions. This allows for a clear measure of which dominances were present in each condition, and whether stimulus transience does indeed modulate sensory dominance. In short, evidence for auditory dominance would be reflected by a smaller difference between reaction times in the unimodal and bimodal presentation when detecting oddballs in the auditory modality when compared with the visual modality (i.e., the presentation of the visual standard affected processing for the auditory oddball to a lesser extent than the auditory standard had on the visual oddball). Whereas, visual dominance would be observed if the opposite were to be demonstrated, that is, a smaller difference between reaction times in the unimodal and bimodal presentation when detecting oddballs in the visual modality when compared with the auditory modality (i.e., the presentation of the auditory standard affected processing for the visual oddball to a lesser

[10] *N* = 22 participated in the Long Auditory condition, *N* = 24 participated in the Long Visual condition, *N* = 19 participated in the Short Auditory condition, and *N* = 19 participated in the Short Visual condition.

extent than the visual standard had on auditory oddballs). Accordingly, participants' relative slow down rates in reaction times were calculated by comparing the oddballs that were presented simultaneously with unimodal standards were compared to the response latencies to unimodal oddballs that were presented amongst unimodal standards. Additionally, to ensure the effects of stimulus duration (i.e., 50 ms and 200 ms stimuli durations) in Experiment 1a were controlled for, stimulus duration was the same for all comparisons (i.e., the relative slowdown for response times to oddballs in bimodal presentations when compared to unimodal presentations always compared the same oddball duration). The mean RTs[11] and accuracy for each unimodal condition can be found in Table 4-2, all means are calculated from stimulus onset.

Table 4-2. Unimodal Control Descriptive Statistics

Condition	Mean RT	Mean Acc.
Long Auditory	452	.98
Short Auditory	443	.98
Long Visual	407	.99
Short Visual	403	.98

[11] Interestingly, the Long Auditory (M = 452, SD = 65.22) and Short Auditory (M = 443, SD = 54.02 conditions did not statistically differ in their mean RTs ($t(37) = .45$, $p = .65$), this was also the case for the Long Visual (M = 407, SD = 74.62) and Short Visual (M = 403, SD = 37.70; $t(31) = .21$, $p = .84$) conditions. The auditory unimodal conditions (M = 448, SD = 59.70) and the visual unimodal conditions together (M = 406, SD = 59.76) were statistically different from one another ($t(76) = 1.67$, $p = .002$).

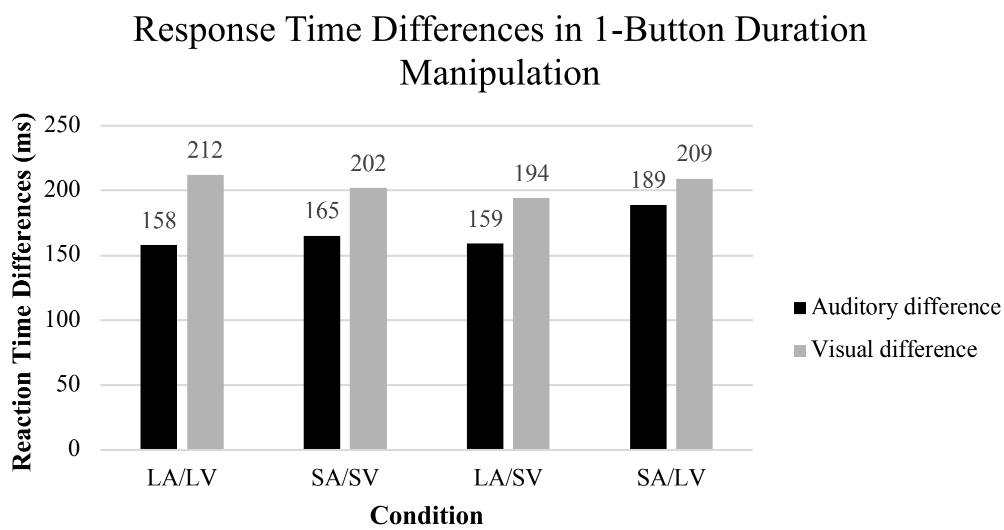

Figure 4-5. One-button Duration manipulation response time differences. Participants mean response differences between unimodal auditory and bimodal auditory conditions and mean response differences between unimodal visual and bimodal visual conditions in the 1-button duration manipulation.

To examine the effect of interference on participants responses to auditory and visual oddballs, difference scores were computed (e.g., bimodal – unimodal oddball RTs), essentially creating a measure of dominance that can be easily and directly compared across conditions. For example, the mean RT for auditory oddballs in the Long Auditory/Long Visual condition was 610 ms while the mean RT for visual oddballs in this condition was 619 ms; while respective means in the unimodal controls were 452 ms (auditory) and 407 ms (visual). These scores were used to calculate the relative slowdowns (i.e., 610-452 = 158 ms slowdown for auditory oddballs and 619-407 = 212 ms slowdown for visual oddballs) between the bimodal and unimodal condition so that the effect of Duration could be assessed, see Figure 4-5.

These scores were then modeled in a 2 x 2 x 2 repeated measures ANOVA that compared Oddball type, Auditory duration, and Visual duration. This analysis revealed a significant main effect for Oddball type ($F(1, 23) = 15.71$, $p = .001$). However, the main effects for Auditory duration ($F(1, 23) = .59$, $p = .45$) and Visual duration were not significant ($F(1, 23) = 1.36$, $p = .25$). When examining the two-way interactions, there was no significant interaction between Oddball type and Visual duration ($F(1,23) = .02$, $p = .89$), nor was there an interaction between Auditory duration and Visual duration ($F(1, 23) = .04$, $p = .84$). However, a statistically significant interaction was observed between Oddball type and Auditory duration ($F(1, 23) = 4.52$, $p = .05$). Paired samples t-tests revealed that participants experienced greater slowdown to the detection of visual oddballs ($M = 203$, $SD = 100.43$) when compared to auditory oddballs ($M = 159$, $SD = 88.67$) when the auditory stimuli were 200 ms long ($t(23) = 5.11$, $p < .001$), and a greater slowdown to detecting visual oddballs ($M = 205$, $SD = 80.08$) compared to auditory oddballs ($M = 176$, $SD = 85.08$) when auditory stimuli were 50 ms long ($t(23) = 2.62$, $p = .02$). Finally, the three-way interaction between Oddball type, Auditory duration, and Visual duration was not statistically significant ($F(1, 23) = 2.22$, $p = .15$). This pattern of results is indicative of auditory dominance across all manipulations to duration in this experiment.

4. 1. 7. Discussion. It was hypothesized that the attentional system would prioritize the more transient stimulus, leading to dominance effects in that direction. For example, if the auditory stimulus was comparatively shorter than the visual stimulus in the bimodal presentation, then auditory dominance should be observed while, if the visual stimulus was comparatively shorter to the auditory stimulus, then visual dominance should be observed.

Utilizing the work of Robinson et al. (2016) as a reference, analyses of the relative slowdown related to the addition of the standard when detecting auditory and visual oddballs were conducted. It was expected that Auditory and Visual Slowdown scores may add additional insight into what dominances were being observed and how they might vary as a result of stimulus transience. When considering the effect discovered in the unimodal comparison (i.e., that participants are affected by the presence of stimuli in a separate modality when detecting an oddball in the other modality), it was found that after collapsing these data across all four manipulations to duration, participants overall showed strong auditory dominance, as evidenced by the main effect for Oddball type in this analysis. That is, participants were slowed down to a greater degree when responding to visual oddballs, suggesting that the auditory standard interfered with processing to a greater extent than the visual standard (i.e., auditory dominance, as defined by Robinson et al., 2016).

The findings from this experiment do not support the hypothesis that manipulating the duration of stimuli such that one is more transient than another should affect observed dominances. While clearly a deeper exploration into the question is needed, it is possible that the auditory dominance observed in the 1-button oddball detection task is robust to these types of manipulations. This could be taken as evidence that auditory dominance arises earlier in processing and is impervious to attentional manipulation. Regardless of the underpinning mechanism, it is important to note that the auditory dominance observed here replicates the findings of Robinson et al. (2016) and provides corroborating evidence of auditory dominance with the previous studies conducted with this paradigm (see also Robinson et al., 2010).

4. 2. Experiment 1b: Stimulus Duration Manipulation in the 3-Button Oddball Task

In order to address what effect decision making (if any) has on the manipulations to the relative duration of stimuli, a 3-button version of the task in which participants are asking to identify auditory, visual, and double oddballs with unique keys was conducted. This manipulation also allows for the ability to analyze error data in a meaningful way; recall that in previous examples of dominance (e.g., Colavita, 1974), dominance was assessed by the number of errors a participant made during bimodal trials (i.e., how often a "visual" response during a bimodal trial is given relative to "auditory" only responses). The following is an attempt to look at sensory dominance in this manner while also considering the effect that decision making has on modulating the effect of duration.

4. 2. 1. Participants. Twenty-Eight University of Hawaii at Manoa undergraduate students were recruited to participate in this experiment in the same manner as Experiment 1a. Three participants were, again, removed from the sample due to failure to consistently follow instructions using the same criteria discussed in Experiment 1a. The remaining sample consisted of $N = 25$ participants; $N = 16$ female participants; age: $M = 20.36$, $SD = 3.21$.

4. 2. 2. Stimuli and Procedure. The same stimulus configurations discussed for Experiment 1a were utilized for this experiment. The key procedural difference between Experiment 1a and Experiment 1b was the response buttons participants were instructed to use during the task. Rather than only a single response button, participants were instructed to press a different key in response to single (unimodal) visual oddballs, single (unimodal) auditory oddballs, and double (bimodal) oddballs. Response keys (the '1', '2', or '3' key on the keyboard number pad) were randomly assigned to each oddball type, but stayed consistent across blocks. That is, someone who was randomly assigned '1' for double oddballs, '2' for single auditory oddballs, and '3' for single visual oddballs continued to press those keys for those oddball types for the duration of the experiment.

4. 2. 3. Results. Similarly to Experiment 1a, mean reaction times (calculated from stimulus onset and only for trials where participants made correct responses) and accuracies were calculated for each oddball type (auditory and visual) in the manner described above (see Table 4-3 for these descriptive statistics). Again, 2 x 2 x 2 repeated measures ANOVAs were conducted to assess the effect of Oddball type (Auditory or Visual), Auditory duration (Short or Long), and Visual duration (Short or Long) on both RTs and accuracy. With regard to RTs, the main effects for Oddball type ($F(1, 24) = .40$, $p = .53$), Auditory duration ($F(1, 24) = 1.04$, $p = .32$), and Visual duration ($F(1, 24) = .49$, $p = .49$) were all insignificant. There was also no significant interaction between Oddball type and Auditory duration ($F(1, 24) = .07$, $p = .79$), or Auditory duration and Visual duration ($F(1, 24) = 1.38$, $p = .25$). However, a significant two-way interaction was observed between Oddball type and Visual duration ($F(1, 24) = 4.39$, $p = .05$). Paired samples t-tests were conducted to reveal the relationship in this interaction. Overall, participants had faster RTs for detecting auditory oddballs ($M = 740$, $SD = 126.68$) than visual oddballs ($M = 786$, $SD = 109.59$) when the visual stimuli were long, although this failed to reach statistical significance: $t(24) = 1.95$, $p = .06$. In contrast, participants were faster to detect visual oddballs ($M = 738$, $SD = 147.03$) than auditory oddballs ($M = 762$, $SD = 91.60$) when the visual stimuli were short, although once again this failed to reach statistical significance: $t(24) = .95$, $p = .35$. Finally, the three-way interaction between Oddball type, Auditory duration, and Visual duration also failed to reach statistical significance ($F(1, 24) = .65$, $p = .43$), see Figure 4-6.

Table 4-3. Three-Button Duration Manipulation Descriptive Statistics

	Auditory Oddball		*Visual Oddball*	
Condition	Mean RT	Mean Acc.	Mean RT	Mean Acc.
Long Auditory/Long Visual	755	.76	797	.72
Short Auditory/Short Visual	766	.77	733	.73
Long Auditory/Short Visual	757	.84	743	.76
Short Auditory/Long Visual	725	.76	775	.76

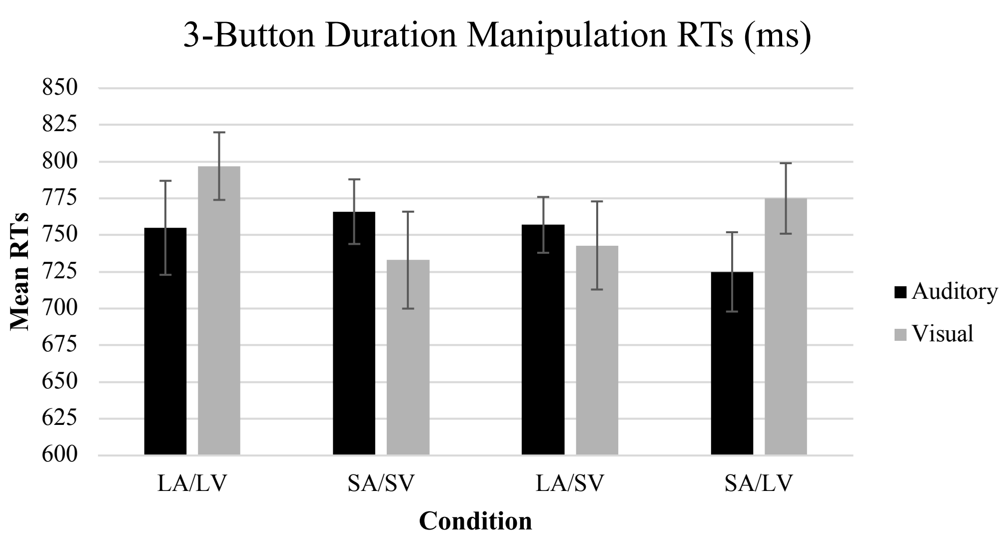

Figure 4-6. Three-button Duration mainpulation RTs (ms). Mean RTs for participants across all four conditions in the duration manipulation grouped by oddball type (auditory or visual).

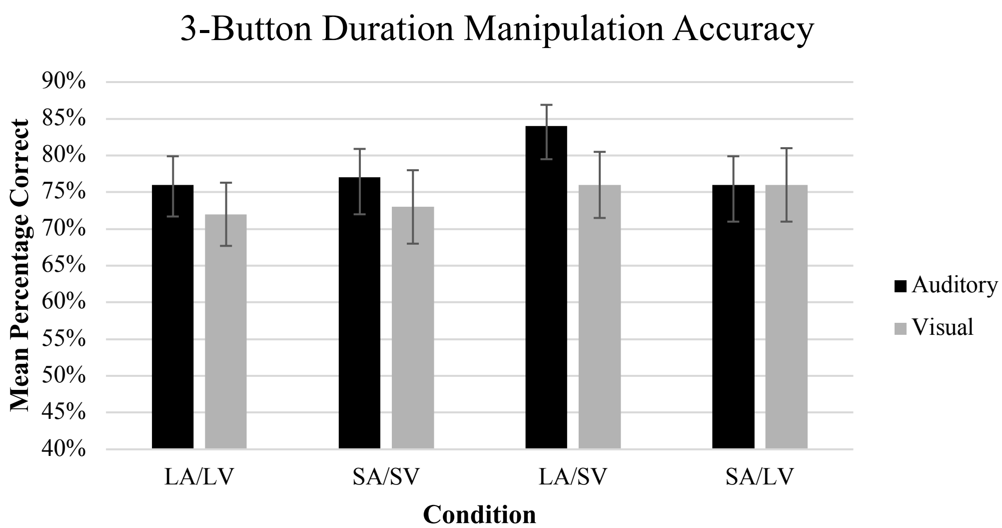

Figure 4-7. Three-button Duration manipualtion accuracy. Mean percentage correct for participants across all four conditions in the duration manipulation grouped by oddball type (auditory or visual).

The 2x2x2 ANOVA on participant accuracies did not reveal any significant main effects for Oddball type ($F(1, 24) = 1.27$, $p = .27$), Auditory duration ($F(1, 24) = .25$, $p = .62$), or Visual Duration ($F(1, 24) = .55$, $p = .47$). Additionally, no significant two-way interactions were observed for Oddball type and Auditory duration ($F(1, 24) = 1.87$, $p = .18$), Oddball type and Visual duration ($F(1, 24) = 3.01$, $p = .10$), or Auditory duration and Visual Duration $F(1, 24) = 1.10$, $p = .31$). Finally, the three-way interaction between Oddball type, Auditory duration, and Visual duration failed to reach statistical significance ($F(1, 24) = .00$, $p = 1$), see Figure 4-7.

In the 3-button manipulation it is possible to analyze errors in a more detailed fashion because participants were required to respond to each type of oddball (auditory, visual, or bimodal, “double”). Therefore, the proportion of visual only and auditory only errors made to double oddball trials was calculated for each unimodal response type (auditory or visual) by dividing the total number of auditory responses to double oddball trials by the total number of errors made for each participant across all oddball trials (i.e., yielding the proportion of errors that were auditory) and dividing the total number of visual responses by the total number of errors made (to get the proportion of errors that were visual), see Table 4-4 for a breakdown of the mean proportion of these errors across all participants by oddball type in each condition.

Table 4-4. Three-Button Duration Manipulation Errors

Condition	Auditory Errors	Visual Errors
Long Auditory/Long Visual	.33	.51
Short Auditory/Short Visual	.33	.47
Long Auditory/Short Visual	.18	.62
Short Auditory/Long Visual	.27	.57

An Error type (Auditory or Visual) by Auditory duration (Short or Long) by Visual duration (Short or Long) repeated measures ANOVA was conducted on the proportion of errors made. A significant main effect for Error type was observed ($F(1, 24) = 13.51$ $p = .001$). However, main effects for Auditory ($F(1, 24) = .00, p = 1$) or Visual duration ($F(1, 24) = .32, p = .57$) were not observed. None of the two-way interactions reached significance; Error type and Auditory duration ($F(1, 24) = .51, p = .48$), Error type and Visual duration ($F(1, 24) = .05$, p = . 82), and Auditory duration and Visual duration ($F(1, 24) = .00, p = 1$). Finally, the three-way interaction between these factors also failed to reach statistical significance ($F(1, 24) = 2.33, p = . 14$). In response to the significant main effect for Error type, paired samples t-test were conducted on the pooled average of participants' auditory and visual errors across all four conditions, to determine if during bimodal trials auditory or visual errors were more likely. There was a significant difference between the proportion of error types ($t(24) = 3.68$, $p = .001$) for auditory ($M = .28$, $SD = .18$) and visual ($M = .54$, $SD = .25$) errors. Overall, visual errors occurred more than auditory errors, indicative of evidence for visual dominance.

It is important to assess the effect that decision making has on the accuracy and RTs of participants when identifying oddballs. Therefore, an Oddball type by Auditory duration by Visual duration repeated measures ANOVA with response type (either 1 or 3 buttons) as a between-subjects factor was conducted for both RTs and accuracy. A significant between-subjects main effect of response type on both RTs ($F(1, 47) = 48.67$, $p < .001$) and accuracy ($F(1, 47) = 12.27$, $p = .001$) was observed, while no other main effects or interactions were significant. Independent sample t-tests showed that RTs were faster in the 1 button condition ($M = 614$, $SD = 75.8$) than in the 3 button condition ($M = 774$ $SD = 85.5$; $t(47) = 6.976$, $p < .001$) and that participants were more accurate in the 1 button condition ($M = .89$, $SD = .12$) than in the 3 button condition ($M = .78$, $SD = .10$; $t(47) = 3.503$, $p = .001$).

4. 2. 4. Discussion. Experiment 1b was conducted in order to address a number of critical issues that were directly relevant to the hypotheses of this dissertation. In particular, it was important to address what differences in sensory dominance might arise when duration and number of responses (i.e., 1- vs. 3-keys) are manipulated. Although Experiment 1a (i.e., the 1-button manipulation) failed to show an effect for manipulations to duration, it is possible that when processing was taxed further by the fact that participants had to make a decision (i.e., Experiment 1b), the effect of duration may have emerged. It was hypothesized, again, that duration would modulate observed dominances and that overall visual dominance would be observed in the 3-button task.

The initial results of this study showed that there were no main effects for the duration of the auditory stimulus, the visual stimulus, or Oddball type, however an interaction was observed between Visual duration and Oddball type. In an attempt to assess this interaction simple main effects were analyzed. When comparing participants RTs for auditory oddballs and visual oddballs when the visual stimuli were relatively short or long, participants were faster at responding to the auditory oddball when the visual stimulus was long, and faster at responding to the visual oddball when the visual stimulus was short (although this difference was not statistically significant when directly compared, $p = .06$ and $p = .35$, respectively). These results provide some evidence that manipulation to duration may influence dominance types, however as overall interactions failed to reach conventional levels of significance, this interpretation should be considered carefully.

Another important feature of the 3-button manipulation, is the ability to assess the kinds of errors made to bimodal trials. Importantly, the main effect for Oddball type was significant with respect to the proportion of errors made by participants, suggesting that across all four manipulations to duration, participants were more likely to make a visual error (i.e., make a 'visual' keypress when a double oddball was being displayed) than an auditory error, when they should have in fact responded with the bimodal response key.

These findings align well with seminal work in the field by Colavita (1974), who also found that participants made more visually based errors than auditory based errors when responding to bimodal trials (see also Koppen & Spence, 2007; Ngo et al., 2010, 2011; Sinnett et al., 2007, 2008).

Finally, another key aim of this study was to consider what effect manipulating the number of required responses would have on sensory dominance. Interestingly, participants were quicker and more accurate at identifying oddballs in the 1-button condition. This expected effect would presumably be due to the added challenge of deciding between multiple response options in the 3-button response task. However, when directly analyzing the type of observed dominance, there were no difference between conditions.

Contrary to the hypothesized outcome, manipulating the relative length of the auditory or visual stimulus did not modulate the type of sensory dominance that was observed. That is, although visual dominance was observed when looking at errors, varying the relative length of the auditory or visual stimulus in the bimodal stimulus stream failed to modulate sensory dominance in any significant direction. Although, a marginally significant interaction was present suggesting that varying dominance types only seemed to occur clearly in two small cases and only when comparing oddballs within one modality.

As previously discussed, the error rate in this paradigm is one way to assess dominance types, with another way being to gauge the extent to which response times to visual and auditory oddballs are slowed by the presence of the irrelevant standard in bimodal trials when compared with responses times to these same oddballs when they are presented alone. For Experiment 1a unimodal control data were utilized to make this assessment, similarly, the same unimodal baselines were then utilized in the following analysis (see Appendix C for information on how this unimodal control was conducted).

4. 2. 5. Results: Dominance as assessed by relative processing slowdown rates. A similar set of analyses was conducted using the unimodal controls for the reaction times of participants in the bimodal 3-button duration manipulation (see Table 4-2. for unimodal control mean RTs). In order to clarify which dominance may be present during the 3-button condition, and to better assess the effect of manipulations to duration, as in Experiment 1a, slowdown rates for auditory and visual oddballs were calculated using the means of the unimodal controls' RTs for auditory oddballs and visual oddballs by computing a difference score for each participant (i.e., the bimodal condition's auditory oddball detection RT - the unimodal controls' mean RT for auditory oddballs; the bimodal condition's visual oddball detection RT - the unimodal controls' mean RT for visual oddballs). This yields a difference score for both auditory and visual oddballs for each participant such that an Auditory Slowdown score and Visual Slowdown score can be calculated. These scores were then used in a 2 x 2 x 2 repeated measures ANOVA with Oddball type (Auditory or Visual), Auditory duration (Short or Long), and Visual duration (Short or Long) as within-subjects factors. The ANOVA revealed a significant main effect for Oddball type ($F(1, 24) = 9.35$, $p = .005$), but no significant main effect for Auditory duration ($F(1, 24) = .48$, $p = .50$) or Visual duration ($F(1, 24) = .35$, $p = .56$). Overall, participants experienced less slow down for the auditory oddballs ($M = 303$, *SD*

= 98.34) than for the visual oddballs (*M* = 356, *SD* = 108.10; $t(24) = 3.06$, $p = .005$), indicative of overall auditory dominance. The two-way interactions for Oddball type and Auditory duration ($F(1, 24) = .45$, $p = .51$), Oddball type and Visual duration ($F(1, 24) = 3.89$, $p = .06$), and Auditory duration and Visual duration ($F(1, 24) = 1.38$, $p = .25$) were all statistically insignificant. With respect to the three-way interaction between these factors, statistical significance was also not observed ($F(1, 24) = .65$, $p = .43$).

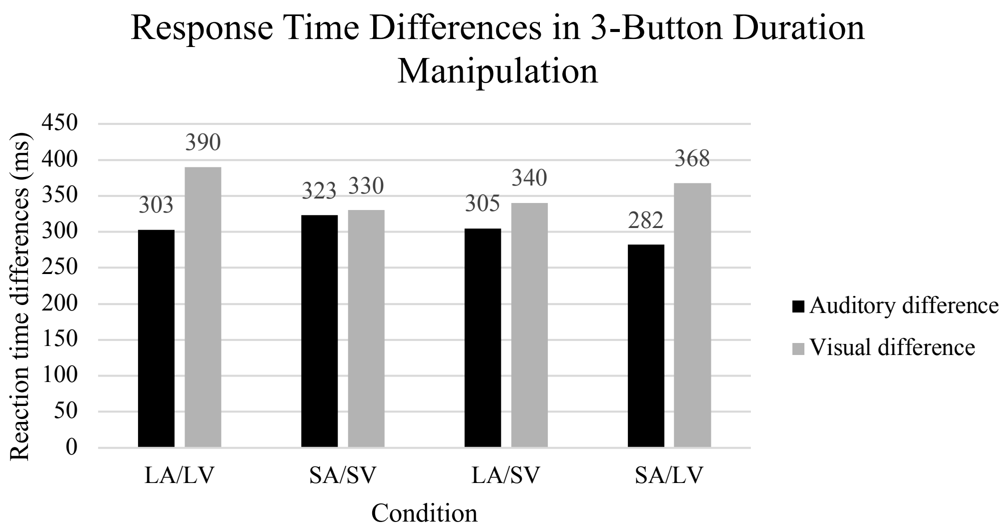

Figure 4-8. Response time differences in the 3-button Duration manipulation. Participants mean response differences between unimodal auditory and bimodal auditory conditions and mean response differences between unimodal visual and bimodal visual conditions in the 3-button duration manipulation.

In order to statistically compare whether modulations in dominance were occurring in the 3-button duration manipulation, a 1-way repeated measures ANOVA was conducted on the difference scores (i.e., the overall difference between the Auditory Slowdown score and the Visual Slowdown score) across the four manipulations to duration. The ANOVA was not significant ($F(3, 72) = 2.47$, $p =.07$). Lastly, the effect of number of responses can be analyzed in a similar fashion with these Auditory dominance difference scores. Accordingly, a one-way repeated measures ANOVA on Duration (Short Auditory/Short Visual, Long Auditory/Long Visual, Long Auditory/Short Visual, Short Visual/ Long Auditory), with Response type (1- or 3-buttons) being a between-subjects factor was conducted. The main effect for Duration was not significant ($F(3,141) = 2.32$, $p = .09$). and the main effect for Condition also failed to reach significance ($F(1, 47) = .73$, $p = .40$). Additionally, the interaction between Duration and Condition also failed to reach conventional levels of significance ($F(3, 141) = 2.20$, $p = .10$). Therefore, participants' Auditory dominance scores were not affected by the duration of the stimuli nor the number of responses (either the 1-button or 3-button condition).

4. 2. 6. Discussion.

In the analysis of the Auditory and Visual Slowdown scores in the 3-button task, a pattern of auditory dominance was observed. Participants showed auditory dominance (as evidenced by the auditory standard having a stronger influence when responding to visual oddballs when compared with the influence the visual standard had on auditory oddball responses) across all conditions. This aligns with the findings of Robinson et al. (2016), given that the longer duration times in the Long Auditory/Long Visual condition represent a replication of their earlier work.

The tendency for participants to demonstrate auditory dominance overall in the 3-button condition is puzzling, in part because previous research conducted by Robinson et al. (2016) showed a pattern of visual dominance in a nearly identical task. However, it is important to note that several methodological differences exist between this replication of the previous work and the work conducted by Robinson and colleagues that may have potentially contributed to these findings. In particular, Robinson et al. (2016) had four times as many trials as those given to participants in the Long Auditory/Long Visual condition conducted for this experiment (756 and 188 trials, respectively). Furthermore, unimodal control data were collected for this experiment with participants making a keypress with the spacebar, however Robinson et al. (2016) collected their unimodal control data within-subjects and as a result participants used either the '1', '2', or '3' key to respond to oddballs in the unimodal condition (i.e., depending on key assignment). Additionally, another key methodological difference was that participants' unimodal data were collected within-subjects, whereas they were collected between-subjects for this experiment. Importantly, if the number of trials and which keys are being used to respond to oddballs affects the observed sensory dominance, then the visual dominance observed in the 3-button condition conducted by Robinson and colleagues warrant additional scrutiny.

When reflecting on the error data in the 3-button condition, participants overall showed clear signs of visual dominance regardless of the manipulation to duration: participants were far more likely to make a visual than an auditory error (i.e., responding with the visual oddball key only rather than the bimodal key. Indeed, the propensity to make visual errors was not modulated by stimulus duration. Taken together with the pattern of results observed when looking at the effects that the standards had on slowing down responses to bimodal oddballs, a mix of dominance types was demonstrated. With regard to Slowdowns, participants show overall auditory dominance, whereas visual dominance was observed when looking at participant error data.

5. Experiment 2: Stimulus Onset Asynchrony (SOA) Manipulation

Recall that Robinson et al. (2016) suggested that modalities must compete for processing resources, and those who engage attention (and thus processing) earlier are more likely to show modality dominance, and as a result modality dominance should be more prominent earlier in processing. In order to address this question, stimulus onsets were manipulated such that either the auditory or the visual stimulus was presented prior to the other. This experiment also addresses another important goal of this dissertation by addressing the question of the effect of decision making by testing what effect 1- and 3-button responses has on modality dominances.

5. 1. Experiment 2a. SOA Manipulation in the 1-Button Oddball Task

5. 1. 1. Participants. Twenty-Seven University of Hawaii at Manoa undergraduate students participated in exchange for course credit. One participant was omitted from the analysis due to their failure to achieve 60% in overall accuracy (i.e., the same criteria as Experiment 1) resulting in final sample size twenty-six participants (N = 18 female participants; age: M = 20.3, SD = 3.31). The experiment was conducted in accordance with the procedures specified by CHS (See Appendix A).

5. 1. 2. Stimuli. The same auditory and visual stimuli used in Experiment 1a and 1b were utilized in this experiment. The primary difference in stimulus preparation was in the stimulus streams. In this experiment, the auditory or visual stimulus occurred either 100 ms or 200 ms before the other in each trial, or at the same time (i.e., the control condition). Therefore, in some circumstances the auditory stimulus was presented 100 ms before the visual stimulus (for a total of 300 ms of stimulus presentation during a trial), the auditory stimulus 200 ms before the visual stimulus (for a total of 400 ms of stimulus presentation during a trial), the visual stimulus 100 ms before the audio stimulus (for a total of 300 ms of stimulus presentation during a trial), or the visual stimulus presented 200 ms before the audition stimulus (for a total of 400 ms of stimulus presentation during a trial), see Figure 5-1 for depiction of the stimulus onset times in each condition and Appendix B, Table B-2 for stimulus configurations.

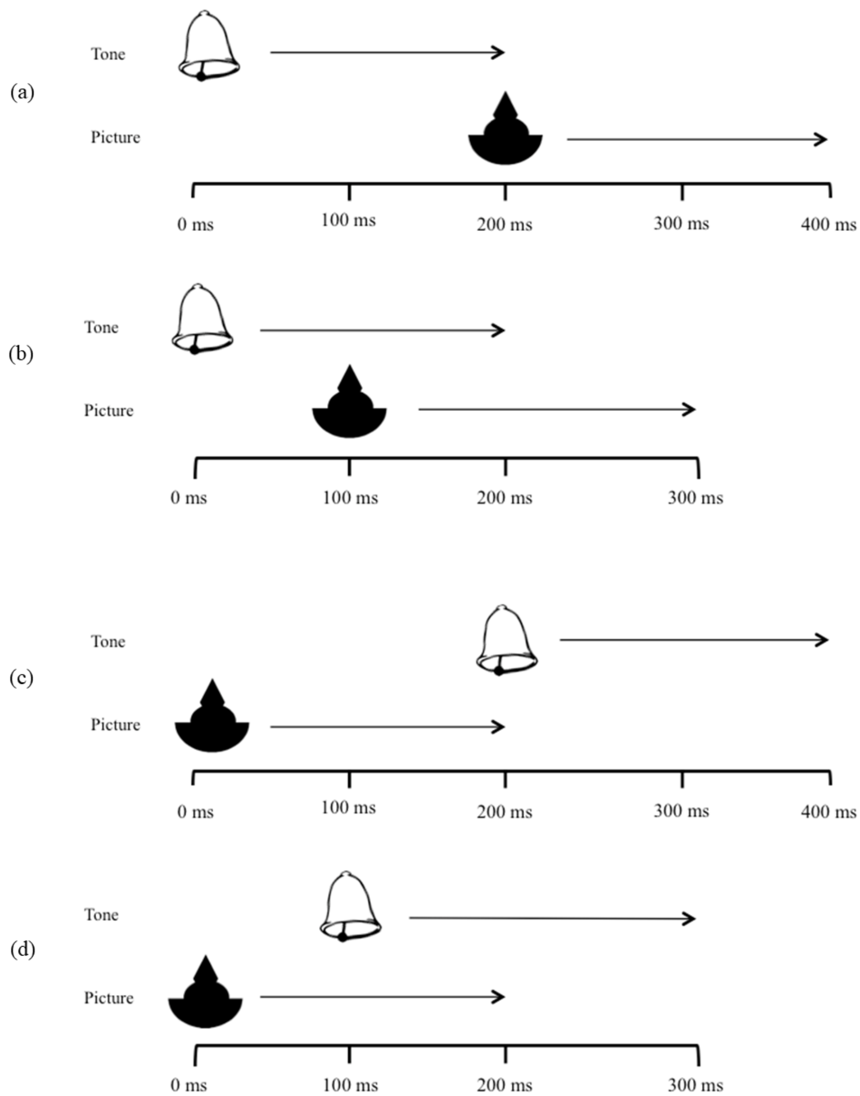

Figure 5-1. Stimulus timing for Experiment 2. Stimulus presentation timing for stimulus onset manipulation experiments, in some circumstances the auditory stimulus preceded the visual stimulus and in others the visual stimulus preceded the auditory stimulus: (a) +200 Auditory condition, (b)+100 Auditory condition, (c) +200 Visual condition, (d) +100 Visual condition.

5. 1. 3. Procedure. Stimulus presentation mirrored Experiments 1a and 1b. Participants were given a standard to compare each trial, which dictated what button they pressed in response to the stimulus. In this case, participants were instructed to press the spacebar on the computer keyboard every time they detected a change in either the visual or the auditory stream. However, in the case that they detected a change in both streams they were asked not to respond. Each condition was presented to every research participant across 5 blocks: +100 ms Visual, +200 ms Visual, +100 Auditory, +200 Auditory, and a control condition in which no there was no stimulus onset asynchrony (i.e., simultaneous presentation). Block order was randomized for each participant and each block featured a different standard[12].

5. 1. 4. Results. In a similar manner to that of Experiment 1, mean reaction times (for correct responses) were calculated for auditory (single) oddball trials and visual (single) oddball trials in each of the five conditions. Due to the fact that bimodal (double) oddballs were identified by a non-response, reaction time data cannot be analyzed for the 1-button version of this experiment. Additionally, detection accuracy for each oddball type was calculated by dividing the number of hits (i.e., successful button presses in response to unimodal trials) by the number of each respective trial type, yielding a proportion correct for each oddball type (auditory or visual) across each of the five

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[12] Once again, this was done to control for the possibility that participants may misinterpret instructions since a change in sound could either mean a change in a sound's duration or tone.

conditions. A summary of the mean reaction times and accuracies for all five conditions can be found in Table 5-1 RTs were computed from the onset of the first stimulus.

Table 5-1. One-Button SOA Manipulation Descriptive Statistics

	Auditory Oddball		*Visual Oddball*	
Condition	Mean RT	Mean Acc.	Mean RT	Mean Acc.
+200 Auditory	712	.94	824	.93
+100 Auditory	652	.96	722	.95
Simultaneous	622	.93	637	.94
+100 Visual	686	.92	654	.97
+200 Visual	825	.95	698	.90

In order to assess the effect that Stimulus Onset Asynchrony (SOA) (simultaneous presentation, +100 Auditory, +200 Auditory, +100 Visual, +200 Visual) and Oddball type (either auditory or visual) had on RTs and accuracy, separate two-way repeated measures ANOVAs were conducted. For the reaction time data, this analysis revealed a significant main effect for SOA ($F(4, 100) = 22.59$, $p < .001$) and an insignificant main effect for Oddball type ($F(1, 100) = .98$, $p = .33$). For response latencies, there was a significant interaction between SOA and Oddball type ($F(4, 100) = 55.06$, $p < .001$). Paired sample t-tests showed that participants were faster to detect the auditory oddball ($M = 652$, $SD = 83.50$) than the visual oddball ($M = 722$, $SD = 75.57$) in the +100 Auditory condition; $t(25) = 5.73$, p < .001, while this was not statistically significant when the visual stimulus preceded the auditory stimulus by 100 ms (i.e., +100 Visual condition) ($M = 654$, $SD = 128.12$ for the visual oddball and $M = 686$, $SD = 117.01$ for the auditory oddball; $t(25) = 2.011$, $p = .06$. When the auditory stimuli preceded the visual stimuli by 200 ms (i.e., +200 Visual condition), participants were faster to detect the auditory oddball ($M = 712$, $SD = 96.68$) when compared with the visual oddball ($M =$

824, *SD* = 97.98; *t*(25) = 9.228, *p* < .001). The reverse was true when the visual stimuli preceded the auditory stimuli by 200 ms (i.e., +200 Visual condition) (*M* = 698, *SD* = 118.12 vs. *M* = 825, *SD* = 72.80, respectively; *t*(25) = 8.35, *p* < .001). There was no statistical difference in response time in the control condition (i.e., simultaneous presentation), with visual oddball responses not being different from auditory oddball responses (*M* = 637, *SD* = 102.07 vs. *M* = 622, *SD* = 94.73, respectively; *t*(25) = 1.16, *p* = .26), see Figure 5-2.

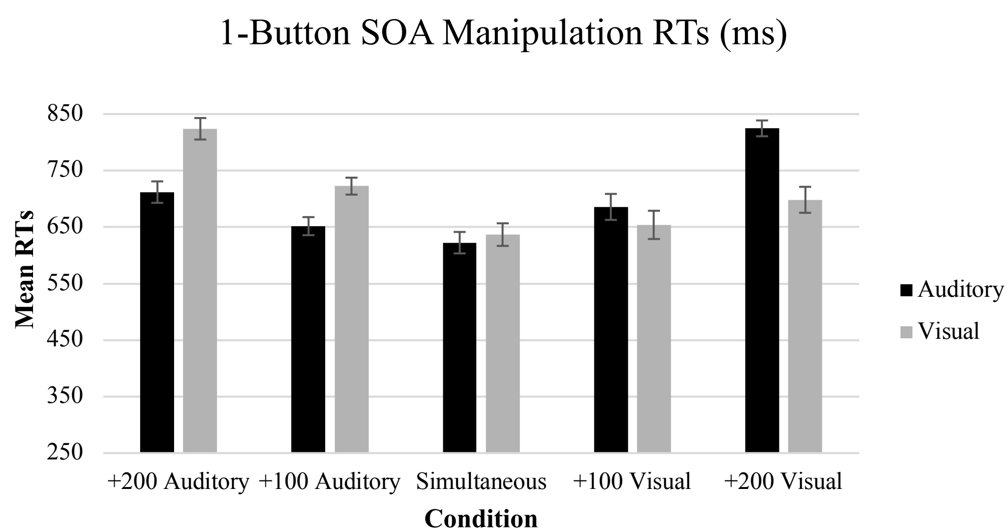

Figure 5-2. One-button SOA manipulation RTs (ms). Mean reaction time of participants in the 1-Button SOA manipulation across all 5 SOA manipulations by oddball type (auditory or visual).

With respect to accuracy between the five conditions, a two-way repeated measures ANOVA revealed no significant main effects for Oddball type (*F*(1, 100) = .05, *p* = .83) or SOA (*F*(4, 100) = .68, *p* = .61), nor was a significant interaction observed (*F*(4, 100) = 2.41, *p* = .10), see Figure 5-3.

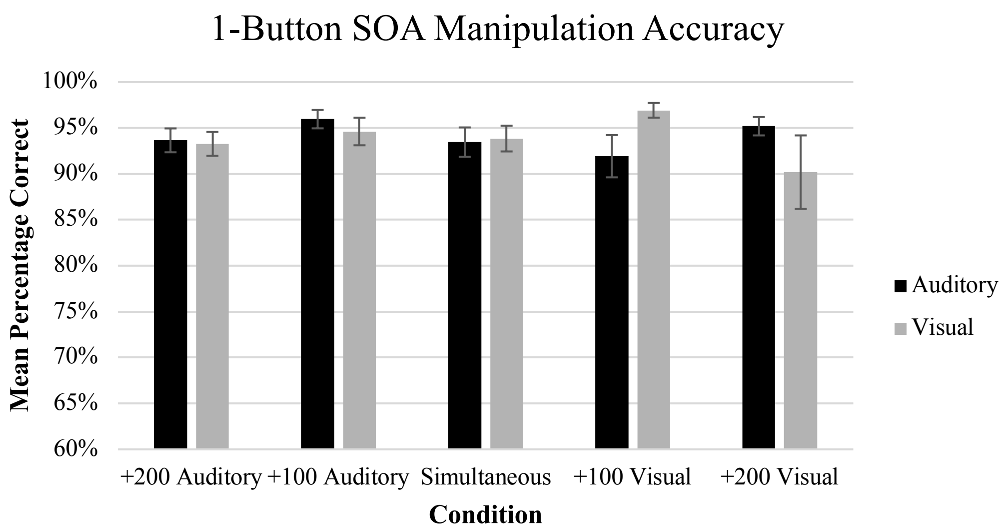

Figure 5-3. 1-button SOA manipulation accuracy. Mean percentage correct for participants in the 1-Button SOA manipulation across all 5 manipulations, by oddball type (auditory or visual)

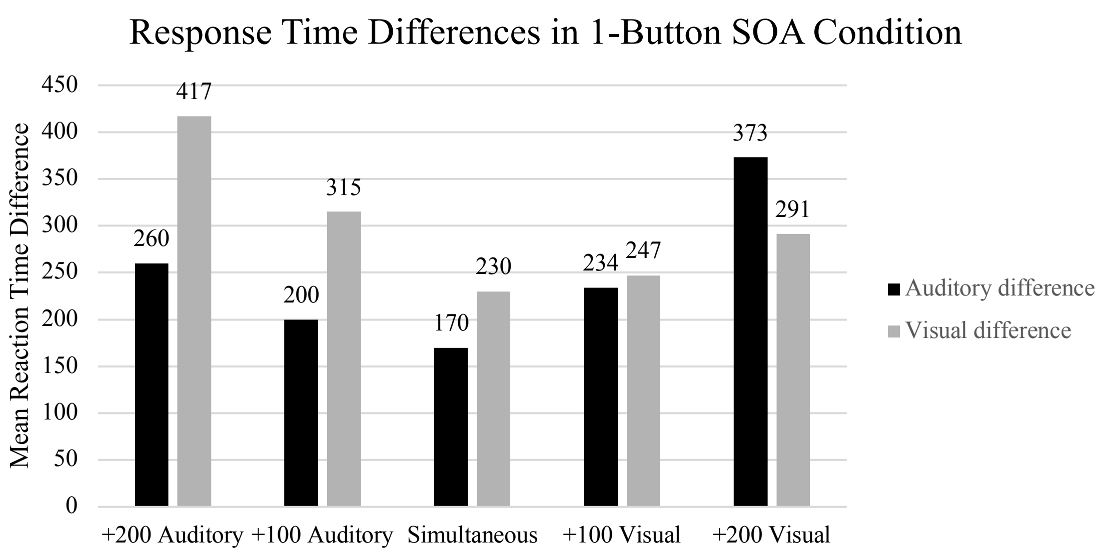

Figure 5-4. One-button SOA manipulation response time differences. Participants mean response differences between unimodal auditory and bimodal auditory conditions and mean response differences between unimodal visual and bimodal visual condition.

In order to further follow up on the effect that SOA had on the varying dominance types observed, participants' Auditory and Visual Slowdown scores were calculated by subtracting the mean of the unimodal auditory and visual response latencies to oddballs (452 ms and 407 ms, respectively) from their reaction times to auditory and visual oddballs that were accompanied by the standard (bimodal presentations) in each of the 5 bimodal SOA manipulations (simultaneous presentation, +100 Auditory, +100 Visual, +200 Auditory, +200 Visual), yielding a slowdown score by oddball type for each condition. A two-way (SOA x Oddball type) repeated measures ANOVA was then conducted on these scores, which demonstrated a main effect for SOA ($F(4, 100) = 22.59$, $p < .001$) as well as a main effect for Oddball type ($F(1, 100) = 45.09$, $p < .001$). Additionally, a significant interaction was observed ($F(4, 100) = 55.06$, $p <.001$). Paired t-tests revealed auditory dominance in the simultaneous presentation condition, reflected by a greater slowdown when responding to visual oddballs that were presented simultaneously with the auditory standard ($M = 230$, $SD = 102.07$), when compared to auditory oddball response times, ($M = 170$, $SD = 94.72$; $t(26) = 4.79$, $p < .001$). When presenting the auditory stimulus 100 ms before the visual stimulus, participants were slowed to a greater degree when detecting the visual oddball ($M = 315$, $SD = 75.57$) than the auditory oddball ($M = 200$, $SD = 83.50$; $t(26) = 9.34$, p < .001), thereby reflecting auditory dominance. In the +100 Visual condition no difference was observed in relative slowdown rates for the auditory ($M = 234$, $SD = 117.02$) and visual ($M = 247$, $SD = 128.12$) oddballs ($t(26) = .82$, $p = .42$). Lastly, in the +200 auditory SOA condition, participants experienced a greater slowdown when detecting the visual oddball ($M = 417$, *SD* = 97.98) than when detecting the auditory oddball (*M* = 260, *SD* = 96.68), indicating auditory dominance, while the reverse was the case in the +200 visual SOA condition (*t*(26) = 12.92, p < .001), as participants experienced a greater slowdown when detecting auditory oddballs (*M* = 373, *SD* = 72.80) than visual oddballs (*M* = 291, *SD* = 118.12; *t*(26) = 5.39, *p* <.001).

A difference score was then calculated by subtracting the visual slowdowns in each condition from the auditory slowdown. In this case smaller (and more negative values) are indicative of greater Auditory dominance. A one-way repeated measures ANOVA was conducted to determine if dominance types were significantly different from one another at different SOAs. This ANOVA was strongly significant (*F*(4, 100) = 55.06, *p* < .001), see Figure 5-4. Pairwise comparisons revealed that, when compared to the control condition (i.e., simultaneous presentation, *M* = -59, *SD* = 62.92), increased auditory dominance was observed in the +100 auditory SOA condition (*M* = -116, *SD* = 63.10; *t*(25) = 3.33, *p* = .003), while auditory dominance was decreased in the +100 visual SOA condition (*M* = -13, *SD* = 80.72; *t*(25) = 2.35, *p* = .03), and in fact could be considered to have been eliminated as this -13 ms effect was not significant. An increased amount of auditory dominance was observed in the +200 auditory SOA condition when compared with the simultaneous control condition (*M* = -157, *SD* = 61.95; *t*(25) = 5.62, *p* < .001), with dominance being reversed in the in the +200 visual SOA condition (*M* = 82, *SD* = 77.23; *t*(25) = 6.73, *p* < .001). Furthermore, when examining the relationship between earlier auditory SOAs, in the +100 auditory SOA condition, participants showed an increased amount of Auditory dominance when compared to the +100 visual SOA condition ($t(25) = 6.42$, $p < .001$) and the +200 visual SOA condition ($t(25) = 9.27$, $p < .001$), but less auditory dominance when compared to the +200 auditory SOA condition ($t(25) = 3.64$, $p = .001$). When the visual stimuli preceded the auditory stimuli by 100 ms (i.e., the +100 visual SOA condition) participants showed more auditory dominance when compared to the +200 visual SOA condition ($t(25) = 5.53$, $p < .001$) and less Auditory dominance when compared to the +200 auditory SOA condition ($t(25) = 10.00$, $p < .001$). Finally, the most drastic difference in Auditory dominance is observed when comparing the +200 visual SOA condition with the +200 auditory SOA condition ($t(25) = 12.26$, $p < .001$).

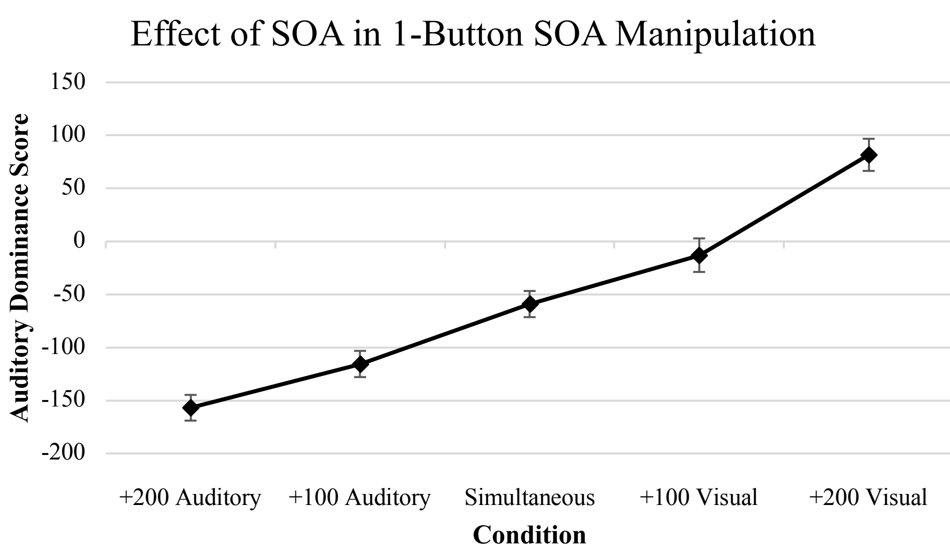

Figure 5-5. Effect of SOA in the one-button SOA manipulation. Mean Auditory Dominance Scores across the four manipulations to SOA. Values that are negative reflect greater amounts of auditory dominance, whereas values that are more positive reflect greater amounts of visual dominance.

The general pattern that emerges from this relationship is that greater auditory dominance is observed when the auditory stimulus precedes the visual stimulus or when both stimuli are presented at the same time, with less auditory dominance being observed when the visual stimulus precedes the auditory stimulus. When presenting the visual stimulus clearly before the auditory (i.e., the +200 ms visual condition), auditory dominance was reversed and visual dominance was instead observed (although, no evidence for dominance in either direction was observed when the visual stimulus preceded the auditory stimulus by 100 ms).

5. 1. 5. Discussion. Thus far, it has been hypothesized that sensory modalities, with respect to multisensory processing, compete for available, and limited, processing resources. Therefore, it was expected that when manipulating stimulus onset asynchronies (SOAs), dominance for whichever stimulus enters processing earlier should be observed. When analyzing response times, a pattern begins to emerge with regard to auditory and visual dominance. That is, faster response times are observed for the stimulus (either auditory or visual) that is presented first. More specifically, in the +100 Auditory and +200 Auditory conditions participants had faster reaction times to auditory oddballs when compared to the +100 Visual and +200 Visual conditions, where participants had faster response times to the visual oddballs. Overall, this seems to demonstrate support for the hypothesis that early entry into processing may cause processing resources to preferentially be allocated to the stimulus that occurs first (see Spence & Parise, 2010). At the very least, it demonstrates that the manipulation did lead to preferential processing for the stimulus that was present first. However, it is important to consider the different effects that may occur due to baseline differences in unimodal auditory and unimodal visual processing.

Previously, Robinson et al. (2016) defined dominance as the modality that experiences less of a slowdown during bimodal processing when compared with unimodal processing. When analyzing these data in the present experiment in accordance with this definition, the analysis showed that participants experienced greater slowdown in the +100 Auditory and +200 Auditory condition to the visual oddballs and a greater slowdown in the +200 Visual condition to the auditory oddballs. Furthermore, no difference in slowdown scores was observed in the +100 Visual condition. As such, it would appear that auditory dominance is present when the auditory modality precedes the visual modality, and also for the simultaneous presentation, with a reversal in dominance only being observed when presenting the visual stimulus clearly in front of the auditory stimulus. As indicated previously, it is important to note that the simultaneous condition lead to auditory dominance, which replicates the findings of Robinson et al. (2016).

Another important result from these analyses is the lack of a demonstrable dominance in the +100 Visual condition even when looking at Auditory and Visual slowdown scores. This pattern of results could occur due to the possibility that, when considering the effects of SOA, the visual modality may need increased lead time to show a reversal of auditory to visual dominance in the 1-button version of this task, given that previous work has demonstrated that the auditory modality is favored in this task (i.e., Robinson et al., 2016; Robinson et al., 2010). That said, auditory dominance washes away in the +100 Visual condition, suggesting that presenting the visual stimulus 100 ms in advance did have an effect, although not strong enough to completely reverse dominance type.

Finally, when combining the Auditory and Visual Slowdown scores into a singular Auditory Dominance score, it is possible to statistically compare these qualitatively described dominance changes. The findings showed that with respect to the control condition, more auditory dominance was observed in the situations where the auditory stimulus precedes the visual stimulus (i.e., the +100 Auditory and +200 Auditory condition) and that less Auditory dominance was observed when the visual stimulus precedes the auditory stimulus (i.e., the +100 Visual and +200 Visual conditions), where visual dominance was instead observed. The relative amount of dominance appeared to increase when presenting auditory stimuli progressively more in front of the visual stimulus, with +200 Auditory condition leading to greater amounts of auditory dominance when compared with the +100 Auditory condition, the +100 Visual condition, and the +200 Visual condition. This can be compared to the +200 Visual condition, where more auditory dominance was observed in the +100 Visual condition, but less than the +200 Auditory and +100 Auditory conditions. Again, reinforcing the patterns observed thus far, that dominance shifts as a result of manipulation to SOA overall.

In sum, in addition to the replication of Robinson et al. (2016), this experiment addressed the second aim of this dissertation, which was to explore how presentation order could modulate sensory dominance. The findings largely align with the hypothesized result and demonstrate a strong effect of presentation order. In general, when participants were faced with situations where the auditory or visual stimuli were presented earlier, oddball detection showed that dominance shifted towards the modality that was presented first. Combined, these patterns of results support the hypotheses set forth by Robinson and colleagues (Robinson et al., 2016; Robinson & Sloutsky, 2013), that sensory dominance is more pronounced earlier in processing, and further supports the idea that sensory dominance effects may be a result of a race for processing resources, therefore giving a particular modality access to those resources first appear to allow for a greater chance for dominance for that modality to occur.

5. 2. Experiment 2b. SOA Manipulation in the 3-Button Oddball Task

In keeping with the particular aims of this dissertation, an investigation of the effects of decision making on sensory dominance was done for the SOA manipulation as well. It has been hypothesized that decision making and later processing appears to favor the visual modality, thus making visual dominance more likely. Previously, Robinson et al. (2016) demonstrated that when participants made separate keypresses to identify each of the three potential oddball types, modality dominance shifted from auditory dominance in the one button condition to visual dominance in the three-button condition. Therefore, the purpose of this manipulation was to see what modulating effects SOA has on the observed dominances, and how the use of multiple response keys would affect the pattern of observed sensory dominance. It was hypothesized that if decision making and later processing affect observed dominance greater, than the three-button manipulation should be accompanied with a shift back towards visual dominance, whereas if early processing has the greater effect on dominance, then auditory dominance should still be observed in this manipulation.

5. 2. 1. Participants. University of Hawaii at Manoa undergraduates ($N = 29$) were recruited to participate in this experiment. However, five participants were omitted, in accordance to the standards discussed earlier, from the final data analysis due to failure to follow instructions across all 5 blocks of the experiment resulting in a final sample of $N = 24$ participants ($N = 15$ female participants, age: $M = 20.7$, $SD = 3.34$).

5. 2. 2. Stimuli and Procedure. Participants were randomly assigned to one of 5 versions of the experiment (see Appendix B for stimulus pairings for all experiments) and blocks within each experiment version were randomized. The key difference between this and the previous stimulus onset manipulation (Experiment 2a), was that participants were instructed to press either the '1', '2', or '3' key on the keyboard number pad in response to changes in the stimulus stream. For example, the '1' key may have been pressed for an auditory (single) oddball, the '2' key may have been pressed for a visual (single) oddball, and the '3' key may have been pressed for an auditory/visual (double) oddball stimulus pair. Key assignments were counterbalanced across participants.

5. 2. 3. Results. Once again, mean reaction times and accuracies were calculated the same way as described in the previous experiment, with participants' RTs (calculated from the onset of the first stimulus and only for correct responses to the auditory or visual oddball) and accuracies being broken down by oddball type, see Table 5-2 for a summary of these means.

Table 5-2. Three-Button SOA Manipulation Descriptive Statistics				
	Auditory Oddball		*Visual Oddball*	
Condition	Mean RT	Mean Acc.	Mean RT	Mean Acc.
+200 Auditory	847	.80	930	.80
+100 Auditory	776	.85	826	.81
Simultaneous	725	.77	766	.76
+100 Visual	822	.83	799	.82
+200 Visual	971	.82	837	.89

Similar to the 1-Button SOA condition, of particular interest is the effect that SOA (simultaneous presentation, + 100 Auditory, +200 Auditory, +100 Visual, and +200 Visual) and Oddball type (Auditory or Visual) have on both RTs and accuracy. A two-way repeated measures ANOVA conducted with the within participants factors of SOA and Oddball type and revealed a significant interaction ($F(4, 92) = 22.87$, $p < .001$) for reaction times. Paired sample t-tests showed that participants were faster to detect auditory oddballs ($M = 725$, $SD = 77.98$) in the control condition (visual oddball: $M = 766$, $SD = 88.79$; $t(23) = 2.86$, $p = .001$), faster to detect auditory oddballs ($M = 847$, $SD = 101.85$) in the +200 auditory condition (visual oddball: $M = 930$, $SD = 86.82$; $t(23) = 3.994$, $p < .001$), and faster to detect visual oddballs (M = 837, SD = 98.99) in the +200 visual condition (auditory oddball: $M = 971$, $SD = 112.13$; $t(23) = 5.63$, $p < .001$). However, no significant difference in RTs between auditory and visual oddballs was observed in the +100 visual condition (auditory oddball: $M = 822$, $SD = 80.42$; visual oddball: $M = 799$, $SD = 80.57$; $t(23) = 1.37$, $p = .18$), additionally the difference between response latencies to auditory oddballs ($M = 776$, $SD = 80.74$) and visual oddballs ($M = 826$, $SD = 145$) in the +100 auditory condition was also insignificant ($t(23) = 1.92$, $p =$

.07), see Figure 5-6. With regard to participants' accuracies for identifying the auditory and visual oddballs the two-way repeated measures ANOVA revealed no main effect for SOA ($F(4, 92) = 1.53$, $p = .20$), or Oddball type ($F(1, 92) = .001$, $p = .97$), and no interaction between SOA and Oddball type ($F(4, 92) = 1.93$, $p = .11$), see Figure 5-7.

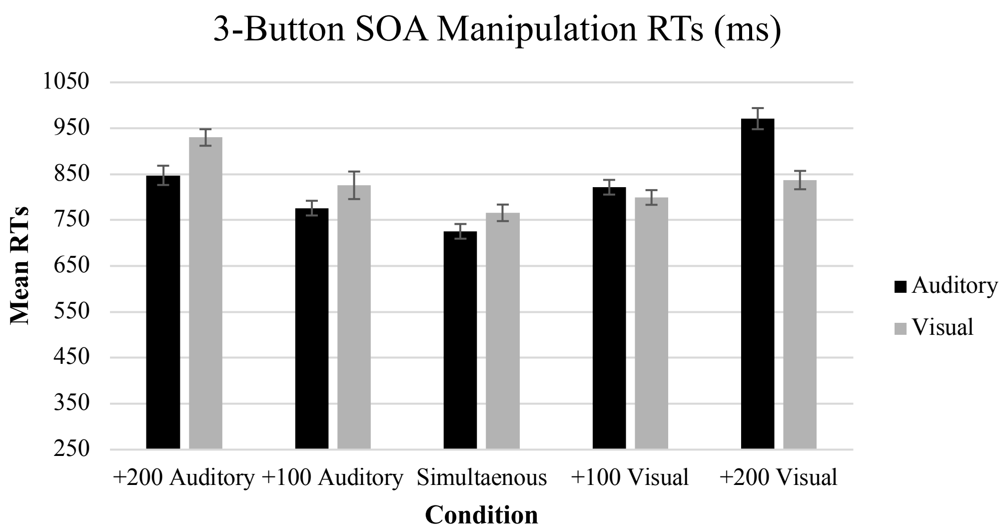

Figure 5-6. Three-button SOA manipulation RTs (ms). Mean reaction time of participants in the 3-Button SOA manipulation across all 5 SOA manipulations by oddball type (auditory or visual).

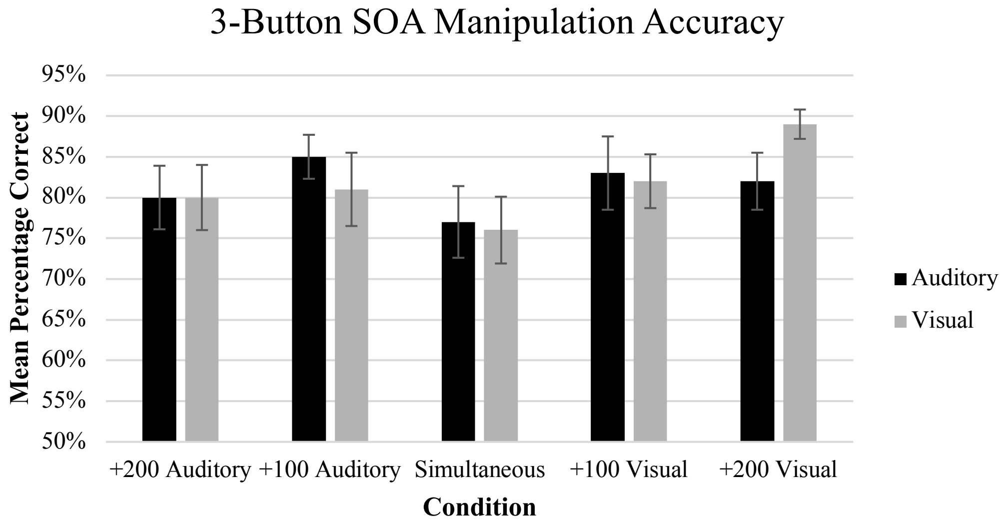

Figure 5-7. Three-button SOA manipulation accuracy. Mean accuracies of participants in the 3-Button SOA manipulation across all 5 SOA manipulations by oddball type (auditory or visual).

The 3-button paradigm allows for an in-depth analysis of participants' errors. Once again, error proportions during bimodal trials were calculated by dividing the number of auditory and visual errors (i.e., the number of times a person pressed the "auditory" button during double oddball trials and the "visual" button during double oddball trials) made by the total number of errors a participant committed during bimodal double oddball trials. These values were used to conduct a two-way repeated measures ANOVA with Oddball Error type (Auditory or Visual) and SOA as IVs and the proportion of errors as the DV. The main effects of Oddball Error type ($F(1, 92) = 28.71$, $p < .001$) and SOA ($F(4, 92) = 2.76$, $p = .03$) were both significant. Additionally, a statistically significant interaction was observed ($F(4, 92) = 4.36$, $p = .003$). Paired sample t-tests were then conducted to see if the there were differences in the number of auditory or visual errors, see Table 5-3. Overall, participants were just as likely to make visual errors during double oddball trials in the +100 (M = .52, SD = .41) and +200 (M = .34, SD = .42) auditory conditions when compared to the auditory errors for the +100 (M = .35, SD = .39) and the +200 (M = .41, SD = .44) auditory conditions respectively ($t(25)$ = 1.13, p =.28; $t(25)$ = .47, p = .65, respectively). However, in the +100 visual ($t(25)$ = 4.03, p < .001; visual M = .53, SD = .46; auditory M = .10, SD = .21), +200 visual ($t(25)$ = 4.16, p < .001; visual M = .63, SD = .45; auditory M = .12, SD = .27), and control conditions ($t(25)$ = 4.70, p < 001; visual M = .77, SD = .34; auditory M = .18, SD = .30) participants were more likely to make visual errors in comparison to auditory errors.

Table 5-3. Three-Button SOA Manipulation Errors

Condition	Auditory Errors	Visual Errors
+200 Auditory	.41	.34
+100 Auditory	.35	.52
Simultaneous	.18	.77
+100 Visual	.10	.53
+200 Visual	.12	.63

In order to fully address the significant interaction and better understand the effect that SOA had on these errors, difference scores were calculated by subtracting the proportion of visual errors made from the number of auditory errors made. In this case, lower scores would be indicative of more visual errors, whereas higher scores would be indicative of more auditory errors. These scores were then used in a one-way repeated measures ANOVA, as expected (due to the significant main effect of SOA already presented), this ANOVA was statistically significant ($F(4, 92)$ = 4.36, p = .003).

Pairwise comparisons on the difference scores with respect to the simultaneous presentation condition (M = -.59, SD = .61), revealed that participants made proportionally more visual errors in the control condition compared to the +100 Auditory condition (*M* = -.17, *SD* = .72; *t*(23) = 2.51, *p* =.02) and the +200 Auditory condition (*M* = .07, *SD* = .73l, *t*(23) = 3.11, *p* = .005). In contrast, participants made just as many visual errors in the simultaneous presentation condition when compared to the +100 Visual (*M* = -.43, *SD* = .53; *t*(23) = .47, p = .64) and the +200 Visual (*M* = -.51, *SD* = .60; *t*(23) = .97, *p* = .34) conditions. With regard to the +100 Auditory condition, participants made approximately the same proportion of visual errors when compared to the +200 Auditory condition (*t*(23) = 1.05, *p* =.30). When compared to the +200 Visual condition, participants did not make more visual errors in the +200 Visual condition compared to the +100 Auditory condition (*t*(23) = 1.96, *p* = .06), similarly for the comparison of the +100 Auditory condition and the +100 Visual condition, *t*(23) = 1.72, *p* = .10. When comparing the +200 Auditory condition with the +200 Visual condition, participants made proportionally more visual errors in the +200 Visual condition (*t*(23) = 2.84, *p* =.009), and more visual errors when compared to the +100 Visual condition (*t*(23) = 2.41, *p* = .02). Finally, participants were no different in the proportion of visual errors made when comparing the +200 Visual condition with +100 Visual condition (*t*(23) = .53, *p* = .60), see Figure 5-8.

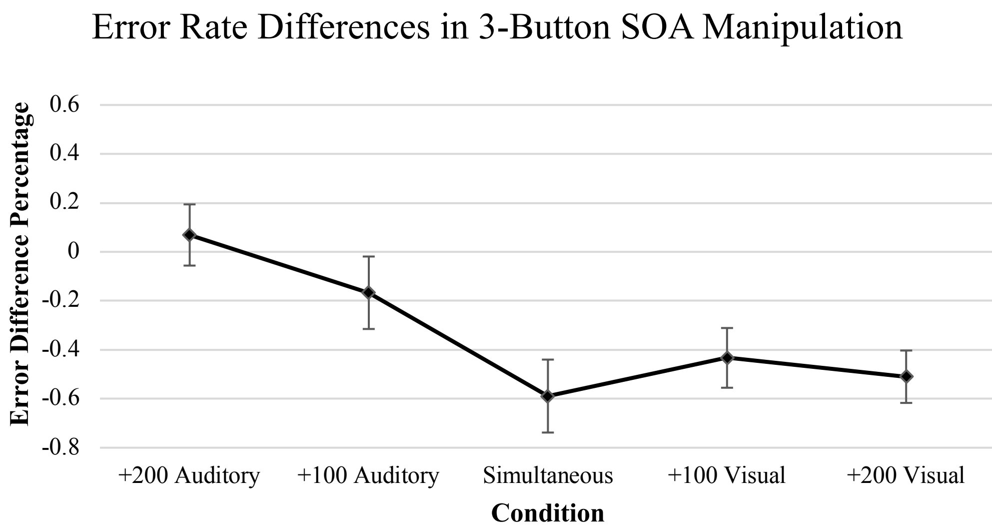

Figure 5-8. Error rate differences in the three-button SOA manipulation. Error rate differences calculated by subtracting the percentage of visually based errors from auditorially based errors, therefore values that are more negative are indicative of proportionally more visually-based errors.

In summary, the error data seems to suggest that when stimuli are presented simultaneously, visual dominance is observed, as more visually based errors are made when compared with auditory based errors to bimodal trials. When presenting the visual stimulus before the auditory stimulus (by either 100 or 200 ms), visual dominance continues to be observed. However, when presenting the auditory stimulus first, the visual dominance that was previously observed disappeared, with a statistically equal amount of visually or auditorily based errors to bimodal oddballs being made (at both SOAs). This was confirmed when directly comparing difference scores (i.e., measures of dominance) between the conditions when the auditory stimuli were presented prior to the visual stimuli with all other conditions (i.e., simultaneous and visual first conditions)

5. 2. 4. Discussion. As previously discussed, it has been hypothesized that dominance may shift in accordance with whichever stimulus (either auditory or visual) engages attention and thus processing first. In order to assess this, SOAs were manipulated in this experiment such that at times the visual stimulus occurred before the auditory stimulus, and vice versa, in a bimodal stimulus stream. Participants were required to use separate response buttons for each type of oddball (i.e., single auditory, single visual, or double oddball. It could be expected that, as previously found in Robinson et al. (2016) participants would show a greater inclination towards visual dominance due to the effects of later processing. Therefore, two potential patterns could be predicted: if the effects of early processing were weighted more heavily in regard to dominance, SOA should modulate sensory dominance irrespective of the number responses, conversely, if later processing (i.e., decision-making) affects participants' demonstrated dominance to a greater degree, visual dominance should be observed throughout.

Participants demonstrated faster RTs for the stimulus that occurred first in all conditions except the +100 Visual SOA condition, in which no difference was observed. Participants in the simultaneous presentation condition showed faster reaction times for the auditory oddball. Overall, this would seem to suggest that dominances may vary as a result of manipulation to SOA, warranting additional analysis (see the comparison to unimodal controls below). Furthermore, when considering the results of the accuracy data, no differences in overall accuracy were observed. This finding is important, because it demonstrates that although the task was more difficult than the one button task (as evidenced by the generally lower accuracies), participants did not find identifying oddballs more difficult when the visual or auditory stimuli preceded the other modality.

Finally, the error data presented an intriguing and important pattern of results. Despite faster response times for auditory oddballs in the +200 Auditory and +100 Auditory SOA conditions, there were no differences between the type of errors made to double oddball trials (i.e., participants were equally likely to make an auditory or visually based error). Additionally, when the visual stimulus preceded the auditory stimulus in the +200 Visual and +100 Visual SOA conditions, participants were much more likely to make visual based errors. This was also the case in the simultaneous presentation condition. These findings are important for several reasons. First, this shows that dominance, as conceptualized by Colavita (1974) in his work, shifted, depending on whether one stimulus was presented prior to another. That is, when the auditory stimulus occurred before the visual stimulus, visual dominance was eliminated. Surprisingly, the control condition shows evidence of two kinds of potential dominances, with visual dominance being evident in participants responses and auditory dominance being potentially demonstrated by the RT data.

Thus far, the analysis herein seems to suggest fairly clearly that, when using error data as a proxy for visual dominance, a prepotency for visual stimuli is observed in the simultaneous (+0 SOA) and visual first (+100/+200 Visual SOA) conditions. However, visual dominance disappears when presenting the auditory stimulus first, although it should be noted that auditory dominance never emerges, arguably demonstrating the robustness of visual dominance in this case. With respect to the reaction time data discussed, participants appeared to be faster at detecting auditory oddballs when the auditory stimuli preceded the visual stimuli and faster at detecting visual oddballs when the visual stimuli preceded the auditory stimuli, suggesting that some shifts in dominance types may be occurring.

In order to further address the question of what dominance types are being observed across the SOA conditions the unimodal control data (see Appendix C) was used to make direct comparisons to the work of Robinson et al. (2016) and make stronger claims about the way that stimulus order can modulate sensory dominance. While the error data clearly indicates that visual dominance can be eliminated by presenting the auditory stimuli first, it is important to also look at how response latencies can be modulated. Recall that Robinson et al. (2016) theorized that in the oddball paradigm used here, modality dominance can be measured by determining which modality is affected less by the presence of the standards in the other modality, which would ultimately be reflected in the differences in reaction times for auditory and visual oddballs in the unimodal and bimodal stimulus streams.

5. 2. 5. Results: Dominance as assessed by relative processing slowdown rates. For Experiment 2b, in order to clarify which dominance type was observed and to better assess the effect of SOA on dominance, a difference score was calculated by subtracting the means observed in the unimodal control conditions from the respective RTs for the auditory and visual oddballs in each of the five SOA conditions, resulting in Auditory and Visual Slowdown scores. These Slowdown scores were then used to conduct a two-way repeated measures ANOVA with Oddball type and SOA as factors on Slowdown scores. The main effect for SOA was significant ($F(4, 92) = 287.68$, $p < .001$) as was the main effect for Oddball type ($F(1, 92) = 13.61$, $p = .001$). Additionally, a statistically significant interaction was observed between SOA and Oddball type ($F(4, 92) = 22.87$, $p < .001$). Paired-samples t-tests revealed that participants experienced a greater slowdown for visual oddballs ($M = 359$, $SD = 88.79$) than for auditory oddballs ($M = 273$, $SD = 77.98$) demonstrating auditory dominance in the simultaneous bimodal manipulation ($t(23) = 6.03$, $p < .001$). In the +100 Auditory condition, participants experienced a greater slowdown for visual oddballs ($M = 419$, $SD = 114.97$) than for auditory oddballs ($M = 327$, $SD = 80.74$; $t(23) = 3.65$, $p = .001$). The slowdown was equitable for auditory ($M = 370$, $SD = 80.42$) and visual oddballs ($M = 392$, $SD = 80.47$) in the +100 Visual condition ($t(23) = 1.38$, $p = .18$). In the +200 Auditory SOA condition participants experienced, again, a greater slowdown to the detection of visual oddballs ($M = 523$, $SD = 86.82$) compared to auditory oddballs ($M = 395$, $SD = 101.85$; $t(23) = 6.16$, $p < .001$) and conversely, a significant difference was observed in the +200 Visual SOA condition, with a greater slowdown to the detection of auditory oddballs ($M = 519$, $SD = 112.13$) compared to that of visual oddballs ($M = 430$, $SD = 98.99$; $t(23) = 3.75$, $p =.001$), see Figure 5-9.

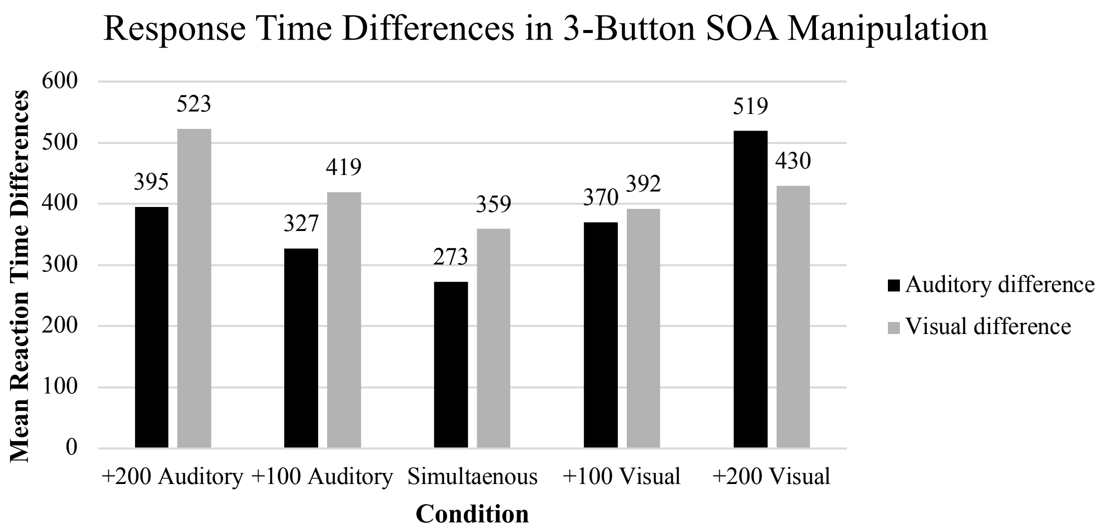

Figure 5-9. Response time differences in the 3-button SOA manipulation. Mean reaction time differences in the 3-Button SOA manipulation when compared to unimodal controls.

Table 5-4. Significance Tests for Pairwise Comparisons

	+200 Auditory	*+100 Auditory*	*Simultaneous*	*+100 Visual*
+100 Auditory	1.2			
Simultaneous	1.96	0.32		
+100 Visual	5.07***	2.33*	3.49**	
+200 Visual	8.39***	5.76***	9.23***	4.65***

* Denotes significance at the .05 level, ** significance at the .01 level, and *** significance at the .001 level, values are t-values, significance assessed with a df of 23.

Finally, in order to clarify which dominance type was observed and how SOA, in particular, modulated dominance across the five conditions, a difference score reflecting dominance type was calculated to determine if presentation timing would affect sensory dominance. This was done by subtracting the Slowdown score for the Visual oddballs from the Slowdown score of the Auditory oddballs yielding a single score for dominance, such that smaller and more negative values represent greater degrees of auditory dominance. These scores were used in a one-way repeated measures ANOVA; this ANOVA was statistically significant ($F(4, 92) = 22.87$, $p < .001$). Pairwise comparisons revealed, that with respect to the simultaneous bimodal condition ($M = -85$, $SD = 69.13$), participants were no different in their Auditory dominance scores when compared to the +100 Auditory condition ($M = -94$, $SD = 126.98$; $t(23) = .32$, $p = .75$). When compared to the +100 Visual condition ($M = -22$, $SD = 79.70$), participants exhibited greater Auditory dominance in the simultaneous presentation condition ($t(23) = 3.49$, $p = .002$). The difference between the simultaneous presentation condition and the +200 Auditory condition was also significant ($M = -127$, $SD = 101.18$; $t(23) = 1.96$, $p = .06$). Participants exhibited greater Auditory dominance in the control condition when compared to the +200 Visual condition ($M = 89$, $SD = 116.56$; $t(23) = 9.23$, $p < .001$). When comparing the +100 Auditory condition to the +100 Visual condition, participants were significantly different, with participants exhibiting greater auditory dominance in the +100 Auditory condition ($t(23) = 2.33$, $p = .03$). However, participants' Auditory dominance scores in the +100 Auditory condition were no different than their scores in the +200 Auditory condition ($t(23) = 1.20$, $p = .24$). Finally, participants' Auditory dominance scores in the +200 Visual condition were different from the +100 Auditory condition ($t(23) = 5.76$, $p < .001$); Auditory dominance was greater in the +100 Auditory condition. When focusing on the +100 Visual condition, participants' Auditory dominance scores were greater in the +200 Auditory condition ($t(23) = 5.07$, $p < .001$) and less Auditory dominance was observed when compared to the +200 Visual condition ($t(23) = 4.65$, $p <.001$). When considering the two most extreme comparisons, the +200 Visual condition and the +200

Auditory condition, participants were more Auditorily dominant in the +200 Auditory condition ($t(23) = 8.39$, $p < .001$), see Table 5-4 for a summary of these pairwise comparisons; see Figure 5-10 for a graphical representation of the shift of dominances across experimental conditions.

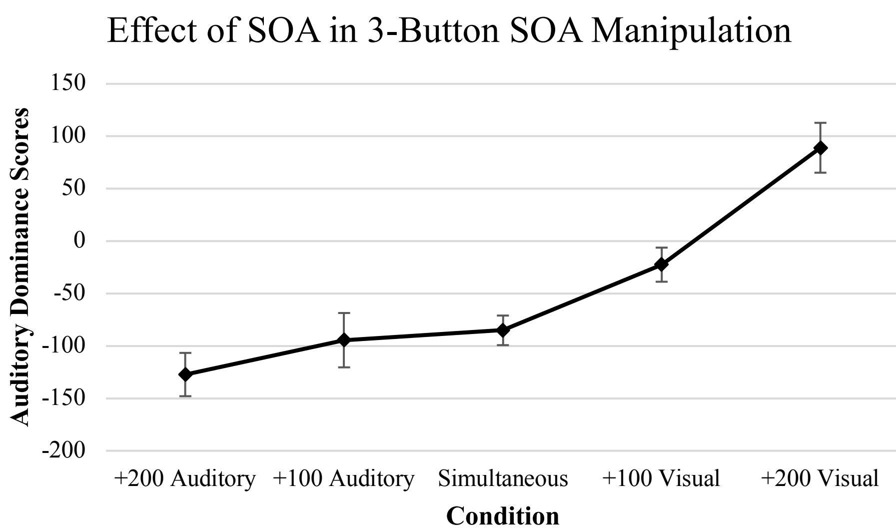

Figure 5-10. Effect of SOA in the three-button SOA manipulation. Mean Auditory Dominance Scores across the four manipulations to SOA. Values that are negative reflect greater amounts of auditory dominance, whereas values that are more positive reflect greater amounts of visual dominance.

The final comparison that was made was to examine the effects of the 1-button and 3-button manipulations with these Auditory dominance scores (i.e., the difference between the Auditory Slowdown and the Visual Slowdown with respect to the observed response to unimodal auditory and unimodal visual oddballs). It has been shown that decision making appears to have an effect on dominance, with participants showing greater amounts of Auditory dominance in the 1-button condition in comparison to the 3-button condition. Therefore, a one-way repeated measures ANOVA on Auditory dominance scores with Condition (1 or 3 buttons) as a between-subjects factor was conducted. The main effect for Condition was not significant ($F(1, 48) = .09$, $p = .76$), however the main effect for SOA was significant ($F(4, 192) = 67.49$, $p < .001$), which would be expected given that both the 1- and 3-button manipulations showed a similar pattern of results across manipulations to SOA. Finaly, the interaction with Condition and SOA was not significant ($F(4, 192) = 1.10$, $p = .36$).

5. 2. 6. Discussion. Similar to the analyses for previous experiments, unimodal control data were utilized to further explore the effects of the experimental manipulation (in this case, SOA) on demonstrated dominances. Participants in the simultaneous presentation condition showed auditory dominance, that is when the auditory stimuli preceded the visual stimuli in both the +100 auditory and +200 Auditory conditions, participants showed evidence of auditory dominance. Finally, visual dominance only clearly occurred in the +200 Visual condition, while the +100 Visual condition showed no evidence of dominance at all.

Importantly, when examining the effect that SOA had on dominance more closely with pairwise comparisons, dominances shifted, with participants' level of auditory dominance seemingly holding steady across the simultaneous presentation, +100 Auditory condition, and +200 Auditory condition. Participants' dominance shifted more drastically in the +100 Visual condition and +200 Visual condition, with less and less auditory dominance being observed (as evidenced by the only positive Auditory Dominance scores in the +200 Visual condition, i.e., visual dominance). Therefore, the amount of Auditory dominance observed when the auditory stimuli occurred first did not change with respect to the amount of lead time given to the auditory stimulus, however presenting the visual stimuli ahead of the auditory stimuli in the bimodal stimulus stream allowed for greater amounts of visual dominance to occur. This finding is critical, as it demonstrates that auditory stimuli may not benefit in a noticeable way from additional lead time into processing, this is especially important given that it provides some support for theoretical claims that audition may dominate early processing in general, and as a result it could be expected that differences in the amount of auditory dominance occurring would happen irrespective to manipulation to SOA, at least in the situation where participants responded to stimuli with three buttons and processing resources were additionally taxed. Therefore, it is possible to conclude that allowing visual stimuli early access to processing resources creates opportunities for visual dominance to occur and that those processing resources are relinquished by the auditory modality if the lead time before an auditory stimulus is available is sufficient.

Finally, another aim of this dissertation was to assess the effect that multiple responses had on sensory dominance compared to a single response. Surprisingly, the exact same pattern of dominances observed in the 1-button condition were also present in the 3-button condition, unlike what was predicted from the results of Robinson et al. (2016). In their experiment, visual dominance was observed in an experiment that was functionally equivalent to the simultaneous presentation condition in this experiment. More specifically, in the 3-button version of the oddball detection paradigm, as administered by Robinson et al., participants demonstrated greater slowdown to the *auditory* oddballs when processing the bimodal stimulus stream, whereas here a greater slowdown to the visual oddballs was observed. Again, this finding of a general trend towards auditory dominance as reflected by response latencies across Experiments 2a and 2b was unexpected, but could be due to a number of issues previously discussed including sampling error and key methodological differences between the simultaneous presentation condition and the bimodal condition in Robinson et al. (2016). More specifically differences in exposure (i.e., the number of trials participants experienced), differences in the responses participants were asked to provide (i.e., utilizing the spacebar in unimodal controls vs. the ‘1’, ‘2’, and ‘3’ keys), and the within rather than between-subjects design for unimodal controls.

Auditory dominance appeared to occur in the 1-button version of the experiment (i.e., Experiment 2a) in the simultaneous condition as well. Furthermore, the amount of auditory dominance appeared to be similar across the manipulations to SOA, given that the between-subjects comparison of the 1- and 3-button conditions failed to reach significance. But note, there was a main effect for SOA across both Experiments 2a and 2b, with participants being more likely to show auditory dominance when the auditory stimuli occurred before the visual stimuli, whereas participants were more likely to show visual dominance when the visual stimuli preceded the auditory stimuli by 200 ms in the 3-button condition.

When considering the error data presented for Experiment 2a, a mix of dominance types does appear to be occurring. With decision making errors (i.e., the selection of incorrect oddball types) showing clear signs of visual dominance in the simultaneous presentation, +100 Visual, and +200 Visual conditions. More specifically, participants were more likely to make visual errors than auditory errors in these conditions. However, in the +100 Auditory and +200 Auditory conditions, participants were just as likely to make auditory and visual errors. This pattern of results is indicative of an elimination of visual dominance. Therefore, the results of Experiment 2b complement one another, with the RT data showing auditory dominance holding steady when the auditory stimuli occur before the visual stimuli and the error data showing an elimination of sensory dominance in these conditions. In contrast, when visual stimuli precede auditory stimuli, RT data show clear signs of visual dominance in the +200 Visual condition, whereas no dominance was observed in the +100 Visual condition. However, when looking at the types of errors that participants made when responding to bimodal oddballs, visual dominance was observed in the simultaneous, +100 Visual, and +200 Visual conditions. These results reveal that manipulating SOA in the 3-button condition modulates sensory dominance at both a processing and decision-making level.

6. General Discussion

Colavita's (1974) finding that participants, when faced with a bimodal audiovisual stimulus, are more likely to respond to only the visual item while being seemingly unaware of the presence of the auditory stimulus, has inspired much research investigating sensory dominance in general. The typical findings amongst the subsequent studies were that visual dominance is robustly demonstrated, with very few studies showing an elimination of visual dominance, and even fewer showing a reversal of visual dominance to auditory dominance (Spence et al., 2012; Sinnett et al., 2007, 2008). The purpose of the studies herein were to take a paradigm known to demonstrate differential dominance types in adults (i.e., Robinson et al., 2016) and assess what stimulus factors contribute to shifts in dominance. In particular, it has been hypothesized that the auditory modality is special in that auditory stimuli in the environment are transient, and this fleeting nature drives early processing to prioritize this modality (Robinson & Sloutsky, 2013; Sloutsky & Napolitano, 2003). Furthermore, dominance effects are thought to be more pronounced earlier in processing, and since processing resources are arguably shared amongst the modalities, this race for processing resources favors the modality who engages processing first (Robinson & Sloutsky, 2010).

In this dissertation, participants completed a series of manipulations to attempt to better understand if these two factors (i.e., stimulus transience and early entry into processing) could in fact affect sensory dominance as evidenced by reaction times (in both the 1- and 3-button versions of each task) and by errors during bimodal "oddball" trials (in only the 3-button version of these task). Overall, the results of these studies showed that stimulus transience had little effect on dominance in either the 1- or 3-button version of the task and that in the manipulation of early entry into processing variable dominance types were observed. In order to better discuss the results of the experiments presented thus far, a short summary of the primary hypotheses and key findings will be presented for each experiment. Afterwards, the important experimental considerations and limitations of the research conducted for this dissertation will be discussed as well as potential recommendations for future investigations.

6. 1. Experiment 1a: Purpose and key findings

Experiment 1a attempted to address the hypothesis that stimulus transience, thought to be in part a feature more frequently observed in auditory stimuli (Robinson & Sloutsky, 2013), can affect sensory dominance. More specifically, the more transient the stimulus is, the more likely one should be able to observe dominance for that modality. Experiment 1a attempted to address this issue by manipulating the relative lengths of the stimuli, such that one item in the bimodal stream would be long and the other would be short, the hope being that the presence of the shorter stimulus with the longer stimulus would push processing resources to favor the modality of the more transient item. A 1-button version of an oddball detection task that has previously demonstrated overall auditory dominance when stimulus durations were the same was utilized (i.e., Robinson et al., 2016). Therefore, it was expected that if observed sensory dominance could be manipulated by stimulus transience in this way, in situations where the visual stimulus was comparatively shorter (i.e., the Long Auditory/Short Visual condition), visual dominance should be observed, while auditory dominance would be expected to be preserved throughout the other manipulations.

The findings of this experiment showed that participants' auditory dominance was fairly robust throughout Experiment 1a (i.e., overall participants were slowed down to a greater degree for visually presented oddballs during the bimodal stimulus streams) and that the manipulation to the relative durations of the stimuli had no effect on participants' auditory dominance. It is important to reiterate though, that these results are somewhat expected given the 1-button task's demonstrated ability to show auditory dominance in previous studies (Robinson et al., 2016; Robinson et al., 2010). A summary of these results can be found in Table 6-1.

Table 6-1. A summary of demonstrated dominances for Experiments 1a

	Dominance Observed by Category	
Condition	*Slowdown Scores*[13]	*Error Data*
Long Auditory/ Long Visual	Auditory Dominance	N/A
Short Auditory/ Short Visual	Auditory Dominance	N/A
Long Auditory/ Short Visual	Auditory Dominance	N/A
Short Auditory/ Long Visual	Auditory Dominance	N/A

[13] The evidence of auditory dominance comes from the significant main effect for Oddball type in the Auditory and Visual Slowdown score analysis (see pages 44-45), and not for the individual analyses within each condition.

6. 2. Experiment 1b: Purpose and key findings

In Experiment 1b, the effect of stimulus transience was further investigated within the realm of the 3-button version of the oddball detection task. Previous research with this task has shown that participants tend to show visual dominance (i.e., participants show greater slowdown to processing in the auditory modality during the identification of auditory oddballs during the bimodal stimulus stream, whereas they experience less slow down to processing when identifying visual oddballs during the bimodal stimulus stream). Therefore, it was expected that participants should exhibit predominantly visual dominance with more evidence of auditory dominance in the Short Auditory/Long visual condition and more visual dominance in the Long Auditory/Short Visual condition, in particular. Surprisingly, when looking at response latencies, auditory dominance was once again demonstrated throughout this paradigm, in clear contrast to the expected findings based upon previous research with this task (Robinson et al., 2016). Some marginal differences were observed in specific pairwise comparisons as well. That is, participants showed slightly more auditory dominance in the Long Auditory/Long Visual condition and slightly more auditory dominance in the Short Auditory/Long Visual condition. However, as stated, with respect to dominance, overall auditory dominance was demonstrated throughout.

Interestingly, error data a different pattern of sensory dominance. When analyzing the proportions of visually based errors made (i.e., the proportion of times a participant incorrectly pressed the “visual” key in the 3-button paradigm to a bimodal “double” oddball), participants demonstrated clear evidence of visual dominance. Regardless of manipulation to duration (i.e., stimulus transience), participants were far more likely to make visually based errors. Notably, this result does replicate the error data finding in Robinson et al. (2016), where participants also made more visually based errors to double oddballs in the 3-button condition. A summary of these results can be found in Table 6-2.

Table 6-2. A summary of demonstrated dominances for Experiments 1b

	Dominance Observed by Category	
Condition	*Slowdown Scores*[14]	*Error Data*
Long Auditory/ Long Visual	Auditory Dominance	Visual Dominance
Short Auditory/ Short Visual	Auditory Dominance	Visual Dominance
Long Auditory/ Short Visual	Auditory Dominance	Visual Dominance
Short Auditory/ Long Visual	Auditory Dominance	Visual Dominance

6. 3. Experiment 1: General Discussion and Theoretical Implications

Finally, Experiments 1a and 1b together were used to assess the effect that decision-making (as measured by the number of responses: single response or multiple responses) might have on these manipulations to duration. However, the number of response keys did not modulate observed dominances. Across both conditions, auditory dominance was robustly demonstrated, the only key difference observed from the analysis of the differences between the 1- and 3-button versions of the task were that participants were overall less accurate and slower in the 3-button version of the task. This pattern of results is likely due to the increased task difficulty (i.e., asking participants to

[14] The evidence of auditory dominance comes from the significant main effect for Oddball type in the Auditory and Visual Slowdown score analysis (see pages 57-58), and not for the individual analyses within each condition.

identify each individual oddball type with a particular key on the keyboard was observably more difficult than responding to the auditory and visual oddball with the same key).

When considering Experiment 1 together as a whole, participants in the 1-button manipulation showed an overall trend towards auditory dominance with respect to their response latencies. However, participants did not identify auditory or visual oddballs with multiple keypresses, therefore making it impossible to look at any kind of systematic error type. The 3-button manipulation allows for this, and signs of differing dominance types began to emerge, however the reaction time data demonstrated more auditory dominance. Nonetheless, when considering the error data, participants were in general much more likely to make a visual error (i.e., pressing the "visual" key in response to a double oddball) than an auditory error. As discussed, this pattern of results is important because it demonstrates that, depending on how one defines and measures dominance, functionally different dominance types can be demonstrated in the same task. The implication of this finding is important for future research on sensory dominance in particular because it demonstrates that care must be taken when designing experiments, in order to ensure that it is clear at what timepoint in processing an experiment is meant to examine, as there is some evidence here that early processing may still favor the auditory modality while later processing (i.e., decision-making) may favor the visual modality.

Despite the fact that the effects of stimulus transience were not clearly observed in Experiment 1, one must not hastily remove stimulus transience from consideration when evaluating key stimulus features that may affect sensory dominance. For example, it is possible that in this manipulation stimulus transience is not pushed far enough to see an effect. Importantly, participants were presented with some combination of 50 ms and 200 ms auditory and visual stimuli and asked to respond as quickly and accurately as possible. Typical characterizations of echoic and iconic memory estimate their memory store to last approximately 2000 ms and 1000 ms respectively (Cowan, 1984; Sperling, 1960), therefore both the auditory and visual stimuli are arguably still represented in echoic and iconic memory, potentially confounding the results. In order to better address this issue, the variable lengths to the stimuli could be manipulated as they are here (or arguably could be shortened to a greater degree), with the addition of a delay between presentation and response such that neither the auditory nor visual stimulus are accessible by sensory memory.

6. 4. Experiment 2a: Purpose and key findings

Experiment 2a was designed to investigate the claim that the effects of sensory dominance are more pronounced in early processing (Shimojo & Shams, 2001) and that, due to limited processing resources, sensory dominance may shift in accordance to whichever modality engages those processing resources first (Robinson & Sloutsky, 2010). In this experiment the 1-button version of the oddball detection task, which has been used to show auditory dominance was utilized. In each of the conditions stimulus onsets were manipulated, such that the auditory stimulus might appear before the visual stimulus (i.e., the +100 Auditory and +200 Auditory conditions) or that the visual stimulus might appear before auditory stimulus (i.e., the +100 Visual and +200 Visual conditions). It was expected that sensory dominance would shift in accordance to whichever stimulus was presented first, therefore it was hypothesized that auditory dominance would be observed in the +100 Auditory condition and +200 Auditory condition, that auditory dominance should be observed in the simultaneous presentation condition, and that visual dominance should be observed in the +100 Visual and +200 Visual conditions.

Overall, the hypothesized effect of presentation order was supported. In Experiment 2a, participants showed evidence of Auditory dominance in the simultaneous presentation, +100 Auditory, and +200 Auditory conditions, whereas no dominance was observed in the +100 Visual condition, and visual dominance was observed in the +200 Visual condition. Furthermore, the effect of presentation order resulted in greater amounts of auditory dominance the earlier the lead time of the auditory stimuli, while the visual modality only clearly demonstrated dominance when given a 200 ms lead on the auditory stimuli. Again, a key finding of this study is that auditory dominance was essentially eliminated in the +100 Visual condition. This result is especially important because it shows the strength of auditory dominance in this case, with its elimination only occurring when presenting the visual stimulus 100 ms prior, and its reversal to visual dominance only when presenting the visual stimulus well in advance (i.e., + 200 ms Visual). A summary of the results of Experiment 2a can be found in Table 6-3.

Table 6-3. A summary of demonstrated dominances for Experiments 2a		
	Dominance Observed by Category	
Condition	*Slowdown Scores*	*Error Data*
+200 Auditory	Auditory Dominance	N/A
+100 Auditory	Auditory Dominance	N/A
Simultaneous presentation	Auditory Dominance	N/A
+100 Visual	No Dominance	N/A
+200 Visual	Visual Dominance	N/A

6. 5. Experiment 2b: Purpose and key findings

In Experiment 2b, the effect of presentation order was further assessed in the 3-button version of the oddball detection task. It was hypothesized, in this case, that participants would again, demonstrate auditory dominance when the auditory stimuli preceded the visual stimuli (i.e., +100 Auditory and +200 Auditory conditions), however, *visual* dominance would be observed in the simultaneous presentation condition (as was predicted based upon the results of the 3-button manipulation in Robinson et al., 2016), and visual dominance in the case where the visual stimuli preceded the auditory stimuli (i.e., +100 Visual and +200 Visual conditions).

The general pattern of results partially supported these predictions. Indeed, when the auditory stimulus preceded the visual stimulus, when comparing the relative slowdowns, participants were affected to a lesser degree by the presence of the visual stimulus in the +200 Auditory and +100 Auditory conditions. Surprisingly, and in contrast to the results of previous experiments that have utilized this paradigm, auditory dominance in the simultaneous presentation condition was observed. Furthermore, no observable dominance was demonstrated in the +100 Visual condition, and finally visual dominance was clearly demonstrated in the +200 Visual condition. Further analysis revealed that the relative amount of auditory dominance observed in the +200 Auditory, +100 Auditory, and simultaneous presentation conditions were the same, whereas the +100 Visual condition showed no dominance and +200 visual condition showed clear evidence of visual dominance. These findings, as previously discussed are important in that they demonstrate that, at least in the 3-button condition, an equivalent amount of auditory dominance was observed between the simultaneous condition and the two conditions where the auditory stimulus preceded the visual stimulus. Thus, the amount of lead time afforded to the auditory stimuli does not appear to affect the amount of auditory dominance observed, which could potentially be a result of processing resources being further taxed by the necessity of participants to identify their oddballs with a particular key.

Finally, Experiment 2b allows for an assessment of the errors made by participants during double oddball trials (i.e., by looking at the proportion of visual and auditory only responses made to double oddballs). When the auditory stimuli preceded the visual stimuli, there was no difference in the proportion of auditory or visual only based errors, indicative of an elimination of visual dominance. Furthermore, when the visual stimulus preceded the auditory stimulus and during the simultaneous presentation, visual dominance was observed. These findings are interesting in that they, to a certain degree, are analogous to the difference scores for response latencies in this experiment, when auditory stimuli preceded visual stimuli. That is, when measuring response times, auditory dominance was observed when auditory stimuli preceded visual stimuli, and for simultaneous presentations, and then eliminated when visual stimuli preceded auditory stimuli, whereas an identical trend was observed when looking at the types of errors, with visual dominance being observed when visual stimuli preceded auditory stimuli, and for simultaneous presentations, and then eliminated when auditory stimuli preceded visual stimuli. However, interpreting the results of the simultaneous presentation condition becomes somewhat trickier in Experiment 2b, as participants actively demonstrate differing dominance types based upon how dominance is being measured. See Table 6-4 for a summary of these results.

Table 6-4. A summary of demonstrated dominances for Experiments 2b

	Dominance Observed by Category	
Condition	*Slowdown Scores*	*Error Data*
+200 Auditory	Auditory Dominance	No Dominance
+100 Auditory	Auditory Dominance	No Dominance
Simultaneous presentation	Auditory Dominance	Visual Dominance
+100 Visual	No Dominance	Visual Dominance
+200 Visual	Visual Dominance	Visual Dominance

6. 6. Experiment 2: General Discussion and Theoretical Implications

The final goal of Experiment 2 was to compare the results of Experiment 2a and 2b and make an assessment of the effect of number of responses (i.e., single response or multiple responses) had on patterns of sensory dominance when manipulating stimulus timing. Importantly, this analysis showed no difference between the 1-button and 3-button versions of the task. The same observed patterns of dominance, as assessed by relative slowdown to the auditory and visual modality during the bimodal stimulus streams, were preserved across both versions of this experiment.

The results of Experiment 2 (in contrast to those of Experiment 1) demonstrate a pattern that supports the hypothesized effect that early entry into processing might modulate sensory dominance, namely that whichever modality enters processing first is the de facto winner of the race for processing resources, and as a result modulating sensory dominance. More specifically, in both the 1-button and 3-button versions of the SOA manipulation, participants modality dominance demonstrated a pattern where auditory dominance was robustly demonstrated in the RT data in the +200 Auditory, +100 Auditory, and simultaneous presentation condition, with no dominance type being demonstrated in the +100 Visual condition, and visual dominance being demonstrated in the +200 Visual condition.

As discussed earlier, these patterns of results are interesting in part because the degree to which auditory dominance was demonstrated did not vary as a function of greater lead times for the auditory modality in the 3-button condition. That is, there was no demonstrable difference in the amount of auditory dominance observed in the +200 Auditory, +100 Auditory, and simultaneous presentation conditions, in contrast the amount of lead time needed for the visual stimuli to begin to show patterns of visual dominance did matter. However, this was not the case in the 1-button condition. In that condition, the greater the lead on the auditory stimuli greater amounts of auditory dominance were observed. With respect to the +100 Visual condition participants saw no dominance in particular being demonstrated in either version of the experiment. It is possible to take this result as meaning that the prepotency of auditory dominance in this experiment and in this paradigm necessitates a 100 ms lead on the visual stimulus before processing resources are equally distributed to both modalities, this would support the general characterization of auditory stimuli having special prioritization in early processing, to such a degree that this lead is necessary to negate these inherent processing biases. However, when given the lead time of 200 ms visual dominance becomes more apparent in both versions of this experiment.

Although this pattern of results seems to clearly paint a picture of shifting dominances during both the 1-button and 3-button SOA manipulations, it is again important to highlight the results of the error data in the 3-button condition (i.e., Experiment 2b), which demonstrates clear evidence of visual dominance in the +100 Visual and simultaneous presentation conditions. As discussed previously with respect to Experiment 1, this pattern of results is unique and interesting in that it again demonstrates that participants are potentially affected differentially by auditory and visual dominances. In effect, it can be interpreted in two meaningful ways: that early processing favors the auditory modality and later processing favors the visual modality; or that there is a behavioral pre-potency to make motor responses to visually presented stimuli over auditorily presented stimuli. In either case, additional research with this paradigm is needed to disentangle which of these two interpretations is more likely.

Finally, it has been argued in this dissertation that processing resources are actively shared across both the auditory and visual modality, and as a result this finite resource is taxed such that allowing a modality to engage those resources first results in dominance for that modality. One could argue that multisensory processing resources are not engaged until both modalities have received sensory information with which to process. One key assumption of this argument would be that in order for multisensory processing resources to be engaged, the unisensory components of the bimodal signal must be presented simultaneously, and to a degree, researchers have argued that this is an important feature of multisensory integration (i.e., whether or not two unisensory events are associated with one another for them to be integrated). From a strict perspective under this account, it would be difficult for manipulations to SOA to lead to insights about stimulus features in multisensory processing. However, research on the window of multisensory integration conservatively sets the timing offset with which MSI still occurs at around 300 ms (Dixon & Spitz, 1980; Fujisaki, Shimojo, Kashino, & Nishida, 2004) – 100 ms longer than any of the SOA manipulations made here – and some research shows this window can be as long as 1000 ms (Navarra, Vatakis, Zampini, Soto-Faraco, Humphreys, & Spence, 2005). However, there is still some concern that perhaps participants were not truly integrating the stimuli when presentation offsets occurred.

Perhaps one way to ensure that participants are in fact treating the bimodal stimulus stream as consisting of distinct bimodal events consisting of one auditory stimulus and one visual stimulus rather as two separate unimodal streams (one auditory and one visual), would be survey participants after their final block to see if they noticed anything in particular about the stimulus block they just experienced. If participants are able to verbally report that they noticed a difference in the presentation order in the streams, that may be indicative of participants not truly engaging in multisensory processing during the SOA experiment.

6. 7. Theoretical Implications of Experiments 1 and 2

When examining the results of Experiments 1 and 2 overall, the strong likelihood of participants responding auditorily in the 3-button condition is an important issue. This failure to replicate the results of Robinson et al. (2016) across two distinct attempts at replication calls into question the proposed finding that visual dominance, as evidenced by the amount of interference caused by presenting stimulus streams bimodally, occurs as a result of decision making. It is difficult to determine whether these diverging findings are a result of sampling error, or instead due to methodological differences described earlier (e.g., the greater number of trials, key assignments, or the between-subjects/within subjects way in which the experiments were conducted).

When considering the results of Experiments 1 and 2, it is also important to consider the 3-button condition in greater detail, especially since a replication of Robinson et al. (2016) was not demonstrated. Two methodological issues occur that warrant potential future intervention. First, is that in Robinson et al. (2016) participants in the 3-button condition completed unimodal control trials where they only made 1 response but made multiple responses to the bimodal stimulus stream. Whereas, the 1-button condition compares single response unimodal controls to single responses during the bimodal stimulus streams. It is possible that this inequality may influence observed dominance types if dominance types are measured by relative slowdowns between unimodal and bimodal reaction times. Therefore, better controls for the 3-button oddball detection task should be considered. Secondly, as was discussed briefly, it is important that participants view the bimodal stimulus streams as a single unitary percept if we are to say that sensory dominance is being examined, and as of now the paradigm does not have a check to ensure that this is occurring. This issue may be exacerbated in the 3-button condition, in that participants are monitoring each stimulus stream and making a different response for the oddballs in the auditory and visual streams. Therefore, it is possible that multisensory integration may not be occurring as deeply as it does in the 1-button condition.

6. 8. Limitations of the current work

Looking critically at the way these experiments were conducted is important for guiding future research on sensory dominance. In particular, one possible weakness of this research is the fact that unimodal controls were obtained between-subjects rather than within-subjects (as had been the case with Robinson et al., 2016). This design choice was made due to concerns about the length of the study and participant fatigue, however, it became clear that such unimodal controls are a necessary component in that it allows for additional ways to look at sensory dominance (i.e., via relative slowdown rates for the bimodally presented auditory and visual stimuli). Therefore, a fully within-subjects designs with participants partaking in unimodal controls is an important future step in this research. This will allow for the claims made about the differences in processing times much more strongly than the ones discussed in this dissertation, and importantly is presently being done to strengthen the arguments made herein.

Another important issue that warrants further discussion is the timing of when data were collected for the various manipulations. In this case, participants from Experiment 1a and 1b were collected sequentially in one academic semester, whereas participants form Experiments 2a and 2b were collected sequentially during the subsequent academic semester. However, statistical comparisons were made across 1a and 1b as well as 2a and 2b. Therefore, participants were not randomly assigned to the 1- or 3- button conditions. Although these results were null in this analysis (i.e., no differences were observed in the 1- and 3- button data other than overall increased reaction times and decreased accuracy, with regard to the 3-button condition), improvement could be made by fully randomizing experimental order. This is presently being controlled for by random assignment in these data that are being collected presently, again to strengthen the claims made in this dissertation.

6. 9. Suggestions for future research and concluding remarks

The results of the experiments presented raise additional questions about the nature of sensory dominance that warrant continued investigation. First, although duration of stimuli did not seem to affect sensory dominance in any kind of systematic way, future research should still consider the effect of stimulus transience on sensory dominance, as suggested earlier by potentially make additional modifications: this could include further shortening the relative duration of stimuli or by making participants wait for short periods of time such that auditory and visual stimuli are no longer represented in echoic and iconic memory.

Next, with regard to the robust auditory dominance demonstrated in every control version of the task, additional research must be done to (a) verify the findings of the 3-button oddball detection task and (b) to potentially investigate what variables may have affected the results of these data collected for this dissertation such that auditory dominance was demonstrated in the 3-button manipulation. Therefore, it is recommended that a simple replication of Robinson et al. (2016) be conducted with additional demographic variables collected to potentially parse out where the strong bias towards the auditory modality in the 3-button version of the task originates from.

Overall, the aim of this dissertation was to assess the effect that stimulus transience and early entry into processing has on sensory dominance. It was found that while stimulus transience did not reveal any strong effects on sensory dominance, further research that pushes the limit of stimulus transience could still show some support for the idea that this is an important stimulus feature that can drive sensory dominance. In contrast, manipulations to SOA indicative of early entry into processing did show a strong effect. Participants were overall very likely to show shifts in dominance in accordance to which stimulus occurred first, however the visual stimuli needed to occur earlier for the effects to manifest itself. The findings of this dissertation verify the claims made by others that early entry into processing affects sensory dominance, and that the auditory modality may be favored especially during these early stages. While no effect on stimulus transience were observed, much follow up is necessary to completely rule it out as important factor that affects sensory dominance.

Appendix A: IRB Approval and Consent Form

THE UNIVERSITY OF HAWAII AT MANOA

Department of Psychology
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Phone: 808.956.6272

Consent Form
Sensory interactions

Principal Investigator: Dr. Scott Sinnett, Department of Psychology, University of Hawaii at Manoa. Phone: (808) 956-6272, Email: ssinnett@hawaii.edu.

Introduction and Purpose
This study aims to gain a deeper understanding of how humans direct attention and perceive auditory and visual stimuli in our environments. One of the goals of this project is to assess how our ability to attend to and perceive stimuli is altered through the combination of two or more sensory experiences of various stimuli when compared to experiencing those stimuli with just one of our senses. We hope to develop broader knowledge of the factors that influence the perception of auditory and visual stimuli in an effort to contribute to an area of science that has many open questions. Developing our knowledge of how our attention and perception changes under certain circumstances can help us better understand how we perceive the environment.

Consent
Your participation in this study is entirely voluntary and you may refuse to participate or withdraw from the study at any time without prejudice or loss of compensation. Please feel free to ask the experimenter any additional questions you may have about the study.

Study Procedures
If you agree to participate, the experiment will take about 30-60 minutes of your time. You will spend most of this time seated in front of a computer monitor. You will be presented with a visual stream of objects originating from the screen and/or auditory sounds or spoken words originating from the speakers placed beside the screen or a pair of headphones. You will be able to adjust the volume of the auditory sounds to a level of your comfort. You will be required to respond to specific targets that occur in the auditory or visual stream by pressing different keys on the keyboard, or a button box. Before beginning the experiment, you will receive ample instruction and training on the task. If you are not sure about any instructions, or wish to have more practice, do not hesitate to ask. Throughout the experiment, you will be given ample opportunity to take breaks, should you wish, and may discontinue your participation at any time without loss of compensation of penalty.

Risks
This study presents minimum risk to you as a participant. The minimum risk includes feelings of mild exhaustion, dizziness or disorientation from viewing the images presented to you on the screen. To minimize these risks we will give you ample opportunity to take breaks throughout your participation for the amount of time you feel it is necessary to be able to continue. You will be continuously monitored during your participation and if at any time you begin to exhibit any signs of discomfort we will discontinue the experiment immediately. Termination of the experiment as a result of any discomfort you might experience will in no way effect your compensation.

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Benefits
There are no direct benefits to you, however your participation will contribute to the enhancement of our understanding of human cognition. The information gathered form this research may be used to enhance our knowledge of how we perceive auditory and visual stimuli in the environment.

Pre-existing conditions
If you suffer form any pre-existing conditions or risk factors (epilepsy for example) that you feel would prevent you from safely participating in this study, please do not participate. You non-participation as a result of a pre-existing condition or risk factor will in no way effect your compensation.

Confidentiality
Your identity will be kept strictly confidential. All documents will be identified only by a subject code number and kept in a locked filing cabinet. You will not be identified by name in any reports of the completed study. Data that will be kept on a computer hard disk will also be identified only by your subject code number and will be password protected so that only the principle investigator, Dr. Scott Sinnett, his graduate students, and research assistants will have access to it. Following the completion of the study, the data will be transferred to a CD and stored in a locked filing cabinet. Note, the results of this study will be used to write a scientific report.

Contact for information about the study
This study is being conducted by Dr. Sinnett, the principal investigator. Please call him if you have any questions about this study. Dr. Sinnett may be reached at (808) 956-6272 or ssinnett@hawaii.edu.

Contact for concerns about the rights of research subjects
If you have any concerns about your treatment or rights as a research subject, you may contact the IRB Committee on Human Studies at (808) 956-5007.

UNIVERSITY of HAWAIʻI® SYSTEM

Office of Research Compliance
Human Studies Program

TO:	Sinnett, Scott, PhD, University of Hawaii at Manoa, Psychology
	Ciraolo, Margeaux, ma, University of Hawaii at Manoa, Psychology
FROM:	Lin-deshetler, Denise, Dir, Hum Stds Prog, Social & Behavioral
PROTOCOL TITLE:	Sensory interactions
FUNDING SOURCE:	NONE
PROTOCOL NUMBER:	2016-30820

NOTICE OF APPROVAL FOR HUMAN RESEARCH

This letter is your record of the Human Studies Program approval of this study as exempt.

On November 14, 2016, the University of Hawai#i (UH) Human Studies Program approved this study as exempt from federal regulations pertaining to the protection of human research participants. The authority for the exemption applicable to your study is documented in the Code of Federal Regulations at 45 CFR 46.101(b) 2.

Exempt studies are subject to the ethical principles articulated in The Belmont Report, found at the OHRP Website www.hhs.gov/ohrp/humansubjects/guidance/belmont.html.

Exempt studies do not require regular continuing review by the Human Studies Program. However, if you propose to modify your study, you must receive approval from the Human Studies Program prior to implementing any changes. You can submit your proposed changes via email at uhirb@hawaii.edu. (The subject line should read: Exempt Study Modification.) The Human Studies Program may review the exempt status at that time and request an application for approval as non-exempt research.

In order to protect the confidentiality of research participants, we encourage you to destroy private information which can be linked to the identities of individuals as soon as it is reasonable to do so. Signed consent forms, as applicable to your study, should be maintained for at least the duration of your project.

This approval does not expire. However, please notify the Human Studies Program when your study is complete. Upon notification, we will close our files pertaining to your study.

If you have any questions relating to the protection of human research participants, please contact the Human Studies Program by phone at 956-5007 or email uhirb@hawaii.edu. We wish you success in carrying out your research project.

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Appendix B: Stimulus Configurations Experiments 1-4

Table B-1. Stimulus Configuration in the Duration Manipulation

		Targets by Block			
		Long Audio/Short Visual	Short Audio/Short Visual	Short Audio/Long Visual	Long Audio/Long Visual (Control)
Program Version	Version 1	a1, v1	a3, v4	a4, v2	a5, v3
	Version 2	a2, v5	a1, v1	a3, v4	a4, v2
	Version 3	a5, v3	a2, v5	a1, v1	a3, v4
	Version 4	a4, v2	a5, v3	a2, v5	a1, v1
	Version 5	a3, v4	a4, v2	a5, v3	a2, v5

Table B-2. Stimulus Configuration in the SOA Manipulation

		Targets by Block				
		+100 ms Audio	+200 ms Audio	+100 ms Visual	+200 ms Visual	Control
Program Version	Version 1	a1, v1	a3, v4	a4, v2	a5, v3	a2, v5
	Version 2	a2, v5	a1, v1	a3, v4	a4, v2	a5, v3
	Version 3	a5, v3	a2, v5	a1, v1	a3, v4	a4, v2
	Version 4	a4, v2	a5, v3	a2, v5	a1, v1	a3, v4
	Version 5	a3, v4	a4, v2	a5, v3	a2, v5	a1, v1

Appendix C: Unimodal Control Methodology

Recall that Robinson et al. (2016) theorized that modality dominance is demonstrated in these oddball tasks by whichever modality is affected less by the presence of the other in the bimodal stimulus stream, and this would ultimately be reflected in the differences in reaction times for auditory and visual oddballs in the unimodal and bimodal stimulus streams. As a result, instead of re-running Experiments 1 and 2 in their entirety, a sample of participants were assigned to various unimodal control conditions and their reaction times were utilized as a baseline for calculating dominance scores in each experiment. Herein is a description of the methodology utilized to conduct these unimodal controls.

Participants

Participants consisted of 84 University of Hawaii at Manoa undergraduate students recruited in exchange for course credit. The sample was predominantly female (N = 53) with a mean age of 20.5 years old. All participants reported normal or corrected to normal vision and hearing and were collected in adherence to the procedures outlined by CHS.

Stimuli and Procedure

Stimuli consisted of the same. 5 visual stimuli and 5 auditory stimuli used in Experiments 1 and 2. Participants were assigned to one of four possible conditions, a short auditory condition, a long auditory condition, a short visual condition, and a long visual condition. Each of the streams were unimodal, such that a participant only saw images or listened to audio. Participants were randomly assigned a standard (one of the five auditory stimuli if they were in an auditory condition or one of the five visual stimuli if they were in a visual condition). The stimuli streams consisted of 360 trials in total, and of which 80 (20%) were unimodal oddballs (i.e., 20 of each non-standard visual stimulus). Participants were instructed to press the spacebar on the computer every time the either saw an image or heard a sound that was different from their standard. Participants reaction times and responses were recorded.

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