The impact of response modality in an audiovisual Stroop task

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A Thesis submitted to the Faculty of Graduate Studies of
The University of Manitoba
in partial fulfillment of the requirements of the degree of

MASTER OF SCIENCE

Faculty of Kinesiology and Recreation Management
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Winnipeg

Acknowledgments

The path toward this thesis has been circuitous. Its completion is thanks in large part to the special people who encouraged, challenged, and stuck with me along the way. First, I would like to express my deepest thanks to my advisor Dr. Cheryl Glazebrook, of whom has provided continuous patient advice and guidance throughout the research process. I am sincerely grateful to learn under such an intelligent and passionate researcher. I would especially like to thank her for always having the solution to the problem I thought, in that moment, would end my career as a graduate student. Trust me, there were many. I would also like to thank my committee members Dr. Steven Passmore and Dr. Jonathan Marotta for their knowledge and insight that was essential in shaping this thesis.

Next, I would like to thank my parents for the countless opportunities they have provided me with that have led me to this milestone. Their unwavering love and support throughout this journey is the reason for my success. I would also like to thank all of my friends for being my biggest cheerleaders. Thank you for believing in me.

I would like to thank to all of the students in the Perceptual Motor Integration lab for their help and feedback. Especially the students involved in the initial programming and pilot testing of my project. Lastly, thank you to the handful of people who provided countless hours of technical support with MATLAB, excel, and remote desktop connection. I truly could not have done it if it were not for their expertise.

Thank you all for your various roles in my academic accomplishments.

Table of Contents

List of Tables and Figures

Abstract

What we see, hear, and remember depends largely on the information we receive from our senses. Given that our attentional resources are limited, coupled with the abundance of incoming sensory information, we must learn how to focus on task-relevant information while ignoring irrelevant stimuli. Humans use multisensory integration to help combine sensory information from different modalities so that it can be processed and perceived as a single percept. It is consistently reported that multimodal stimuli are responded to more quickly and accurately as compared to unimodal stimuli. The concept of attention supports the central nervous system with this process by directing attention to specific parameters based on task instructions. To determine how competing and/or supporting sensory information are processed, movement trajectories were recorded using three-dimensional motion capture while participants completed a two-choice goal-directed reaching task in response to audiovisual Stroop stimuli, in either both a respond-visual and respond-auditory conditions. In contrast to the predictions, response modality did not influence reaction time (RT), or movement time (MT). However, auditory-neutral trials led to significantly longer RTs. Consistent with the hypotheses, the respond-visual condition led to earlier trajectory deviations, especially when the written word was congruent with the auditory stimulus. Results are discussed in light of current models of goal-directed reaching by assessing how multisensory integration and attention impact voluntary movement. Ultimately these models can help to inform the design of new technology interfaces.

Introduction

The study of attention can be traced back to William James: What we see, hear, and remember depends mostly on the information we receive from our senses, but also upon which pieces of this information we choose to attend (James, 1890 in Driver, 2001). While there has been tremendous advancement in the fields of experimental psychology and motor behaviour research, there is still debate on what attention really means. In its most basic form, we can think of attention as a resource or a level of arousal. We expend a certain level of mental effort when performing attention-demanding tasks, such as reading a book or playing in a game of soccer. Berlyne (1960) suggested that the intensity of attention is related to the level of arousal that is revealed in various physiological measures and is largely controlled by the properties (i.e., intensity, modality, location) of the stimuli we are exposed to (Kahneman, 1973). Specifically, Berlyne (1960) suggested that novelty, complexity, and incongruity are three principal factors that cause some stimuli to be more arousing than others (Kahneman, 1973). The present thesis examined attentional processes as they unfold during voluntary goal-directed movements using a modified Stroop task. Novelty, complexity, and incongruity were utilized and manipulated to examine how competing sensory information may be reflected in the subsequent movement trajectories.

Attention can also be thought of as a limited capacity or resource (Schmidt, Lee, Winstein, Wulf, & Zelaznik, 2019). This is an important feature of the information-processing concepts and will be discussed in more detail below. Briefly, this view suggests that there is a limit in the capacity of information from the environment that humans are able to process. It also assumes that this limited capacity can be allocated among concurrent activities (Kahneman, 1973). The notion for the concept of a limited capacity of attention is illustrated in our ability to perform two different tasks simultaneously. If activity A requires attention, then some of our attention from our limited capacity pool of attention will be allocated to that task. Since our attention is limited in capacity, activity B that we are simultaneously engaging in will compete for attentional resources. For example, when driving with a passenger who is engaging in conversation, driving your vehicle will not receive 100% of your attention. Unfortunately, whether you mean to or not, your attention will be divided between the road and the story your passenger is recounting to you. This leads to the question of whether attention is unitary or dividable.

It is plausible to assume that attention can be divided for two common observations (Kahneman, 1973). The first one being that humans often perform several activities at the same time and seem to divide their attention between both activities, such as talking and driving. It is reasonable to refute the idea of the possibility of divided attention when we examine what happens when two stimuli are presented at once; quite frequently only one of them is perceived while the other is ignored (Kahneman, 1973). This phenomenon suggests the likelihood of a bottleneck, a stage of internal processing can only operate on one stimulus or one response at a time; and will be discussed in further detail later in the literature. An attentional bottleneck in response programming would explain our ability or inability to attend and respond to multiple stimuli at once.

With the increase in multisensory environments and the amount of sensory input humans receive on a daily basis, integration from different sensory modalities is paramount to successfully interact in complex environments. Multisensory integration (MSI) can be described as the process of using information from different sensory modalities, to create a coherent and meaningful representation of the external environment (Talsma, Senkowski, Soto-Faraco, & Woldorff, 2010). Essentially, MSI helps to reduce noise within our perceptual system by combining information from different sources (ex. vision and audition) (Spence & Santangelo, 2009). With the advancement of technology in today’s society, the ability to perceive bimodal stimuli as a single percept is becoming increasingly important in order to engage more efficiently and effectively in our environment.

Smartphones provide a great example of how stimuli from two different sources interact to help guide and direct our attention. This is demonstrated in the way smartphones alert us that we have a new message. Visual notifications are accompanied by auditory notifications so as to direct our attention to the screen. As well, newer vehicles are now equipped with crash mitigation features using multisensory stimuli. For example, Honda builds a lane keeping assist system into their vehicles to improve safety and performance. If you cross a detected lane line without using your turn signal, a message appears on the dashboard accompanied by a loud string of beeps. As you can see, vision and audition are used together to ensure the driver’s attention will be directed to the sudden lane change and hopefully decrease the likelihood of an accident.

Competition exists for capturing attention, and while sometimes we are able to ignore things we do not want to attend, certain information is processed regardless of our intentions. This demonstrates that attention can be both intentional and incidental. In order to exert control over attention, we must be able to resist distractions while still carrying out movement goals (West & Alain, 2000). Intentional and incidental information processing is illustrated in the colour-word Stroop task. Since its debut in the early 1930’s, it has become one of the primary tools used to measure attention (MacLeod, 1992). The Stroop task requires participants to name the ink colour of either congruent or incongruent written colours words. It is well-known that participants make more errors in naming the ink colour of a written colour word when it is incongruent to the written word – known as Stroop interference. Stroop facilitation occurs when the written word and ink colour are congruent with each other (Roelofs, 2005) and therefore participants respond with faster and more accurate responses.

There are many possible explanations as to why the Stroop effect occurs, however, a popular view and perhaps the one most relevant to this project, is that the participant's inability to ignore the irrelevant message is evidence that the irrelevant signal (colour name) and relevant signal (ink colour) are processed in parallel, feasibly without any interference in the early stages of information processing (Schmidt et al., 2019). Another important illustration of the intentional and incidental effects of sensory-information processing is seen in the 'cocktail party phenomenon' where in noisy environments, attending to one conversation is often rather difficult. However, with effort, the various potentially interfering conversations can be tuned out. In some cases, we are unable to block out the noise. For example, if your name were to be spoken in one of these unattended conversations, your attention would be drawn to that particular conversation. This is because when the information is relevant to us, the stimulus is allowed to pass through for further processing and attention (Schmidt et al., 2019).

Traditionally, the Stroop task is used to investigate information processing under situations of differing stimulus compatibility and/or levels of conflict, in the visual realm (Augustinova, Silvert, Spatola, & Ferrand, 2016; Donohue, Appelbaum, Park, Roberts, & Woldorff, 2013; Shichel & Tzelgov, 2017; West & Alain, 2000). Some researchers have used the Stroop task and included auditory input however, responses were made via. key presses on a keyboard (Donohue et al., 2013; Roelofs, 2005). Although perceptual and cognitive processes have been inferred based on reaction times and accuracies from discrete responses, they do not reflect dynamic internal processes, occurring in parallel and unfolding over time (Song & Nakayama, 2009). Researchers have started to take advantage of overt actions such as reaching movements, as they expose underlying competing cognitive states. Examining movement trajectories during reaching movements help to reveal the temporal progression of hidden internal processing. This approach to studying human behaviour reveals parallel processing of perception, cognition, and action (Song & Nakayama, 2009).

The effects of a visual Stroop task have been well-established and documented however, with the increase of multisensory environments it is necessary to examine the effects of an audio-visual Stroop task. Donohue et al. (2013) conducted an experiment where participants performed a modified version of the Stroop task in which they were instructed to attend to either the auditory or visual modality, and to ignore the irrelevant information in the other modality. The irrelevant stimuli could be congruent, incongruent, or neutral with the attended-modality target, and presented across nine SOAs. Results indicated that visual distractors produced larger incongruency effects on auditory targets than vice versa. Relative to neutral stimuli, audio-visual stimuli resulted in substantially more behavioural facilitation than incongruency led to behavioural interference. Interestingly, error rates were higher for the incongruent trials, but no other factor influenced accuracy in the task. This suggests that cross-modal conflict alters the behavioural response speeds (Donohue et al., 2013). It is important to note that responses were made via keyboard presses and therefore do not illustrate the point at which response speed was altered during the task. As indicated above, reaching movements capture the dynamics of multiple cognitive states unfolding over time (Song & Nakayama, 2009). Research using choice reaching tasks has demonstrated that the progression of movement trajectories reveals the current locus of attention allocation, and the time course of target selection and response competition (Song & Nakayama, 2009). Therefore, a goal-directed reaching task may provide a clearer picture of when during information processing the auditory distractor affects response selection.

The following review of literature will examine the concept of attention and how it has been defined and explored previously. This includes theories relevant to my project that have been used to help understand constructs and influences of attention. Attention in the visual and auditory modalities will also be discussed in order to examine the symbiotic relationship between attention and multisensory stimuli. Attentional selectivity will then be explored to consider how attention can be focused on specific locations and modalities based on the task. Spatial and modality selectivity interactions will be discussed using examples from various studies to understand the interactions between attention and multisensory integration. Finally, I will introduce the Stroop task and its uses within the area of attention. I will present the results of an experiment using a modified Stroop task using reaching movement and discuss how competing and/or supporting sensory information is reflected in movement performance and trajectories.

Review of Literature

Attention

The concept of attention as central to human performance extends back to the start of experimental psychology (James, 1890 in Driver, 2001). According to Spence (2012), attention can be described as the neural mechanisms that give rise to a temporary enhancement (or prioritization) of the processing of certain stimuli relative to others. Attention has been proposed as the solution for the problem of information overload in cognitive processing systems by selecting some information for further processing, or by managing resources applied to several sources of information at once (Posner, Snyder, & Davidson, 1980). Attention plays a crucial role in choosing relevant, and ruling out irrelevant modalities, spatial locations, and task-related objects (Macaluso, 2010). Broadly speaking, the attention system is involved with three major functions; maintaining alertness, orienting to sensory events, and detecting signals for conscious processing (Posner & Petersen, 1990).

For years, selective attention research was focused on the point within information processing stages at which the selection of certain information, over other information, takes place. Within this area researchers have argued whether selection occurs early or late during information processing. The information-processing model proposes that there are three separate stages or processes between a stimulus and a response that can either be sequential or simultaneous in nature (Schmidt et al., 2019). The model begins with the stimulus identification stage, where the individual detects and identifies the occurrence of a stimulus. Once an environmental stimulus is detected, neurological impulses are sent towards the brain where it is processed until it reaches memory. Processing occurs so that the stimulus arouses the correct association in memory (Schmidt et al., 2019). It is important to note that the nature of the stimulus has a direct effect on the stimulus-identification stage. For example, increased stimulus clarity and stimulus intensity have been related to decreased reaction times and is attributed to increased processing speeds within this stage (Schmidt et al., 2019). Similarly, the modality of the stimulus has also been related to response latency. For example, individuals are slower to initiate their responses to a visual stimulus when compared to responses to an auditory stimulus. As we will discuss in further detail later on, spatially-congruent and temporally-congruent stimuli presented simultaneously in both the auditory and visual modality decreases reaction time relative to either modality presented alone (Stein & Stanford, 2008). After a stimulus has been identified the individual must then choose a response to make, known as the response-selection stage. Once a response has been selected, the individual enters the response-programming stage in preparation for the appropriate action. It is within this stage that researchers believe the attentional bottleneck occurs.

The early selection approach originally proposed by Broadbent in the 19th century, suggested that perception is a limited process that requires selective attention to proceed. Part of this proposed limited-capacity system has a filter that selects some of the information of peripheral processing for further processing (Lavie, 1995). In this case, attentional selection occurs after the basic physical features of the stimulus are analyzed, which is then used to classify between relevant and non-relevant stimuli. This means that as a result, stimuli that are classified as non-relevant are not fully perceived nor attended (Lavie, 1995). In contrast, the late selection view suggests that perception is of unlimited capacity and advances automatically randomly processing relevant and irrelevant stimuli (Murphy, Groeger, & Greene, 2016). Perceptual load theory is a hybrid of early and late selection models and states that perception is a limited-capacity process and proceeds automatically until that capacity is filled (Murphy et al., 2016). Perceptual load suggests that the complexity of the stimulus is the major determinant of the locus of attention. When a task imposes a high perceptual load, capacity is reached, and distractors cannot be processed, resulting in performance that is consistent with early selection (Lavie, 1995). This is because an individual will need to allocate more resources to processing task information and fewer resources will be left for the processing of any other incoming information (Lavie, 1995). Alternatively, when a task involves low perceptual load, all available stimuli are processed, imposing late selection.

Lavie (1995) used different manipulations of load, anticipating that these manipulations would all result in the elimination of distractor interference in high-load presentations, providing evidence for perceptual load on the processing of task irrelevant stimuli. Lavie used the Eriksen paradigm (Eriksen & Eriksen, 1974), which has been accepted as a valid way of measuring early or late selection. In this task participants were asked to identify which of the target letters X or N were present in a display. In a low-load trial, the target appeared alone, whereas in a high-load trial, the target was surrounded by six neutral letters. Participants were required to make a choice response and identify the target letter. The target was always located at the center of the display with distractors (critical, neutral, or compatible in relation to the target) located above or below the center. As a function of the nature of the critical distractor and the load of the relevant processing in the task, reaction times to the target were the primary outcome measure of the experiments. Results of the study suggest that perceptual load plays a fundamental role in determining the efficiency of selective attention (Lavie, 1995). Across all experiments, manipulations of perceptual load showed that interference from irrelevant distractions was found only when perceptual load was low. Manipulations included, manipulation of the display set size for the target task where the target was bigger and situated in remote and irrelevant positions. In the second experiment, load was manipulated by manipulation of the target shape and colour and in the third experiment, target letter was flanked by an additional character in the center of the display and an irrelevant distractor letter above or below the target letter (Lavie, 1995). Results indicated that irrelevant distractors had no effect on reactions times under high-load conditions. Together, the results of the experiments demonstrate the extent of the interference of incompatible distractors is more consistently associated with manipulations of load than with either overall reaction times or statistical variance (Lavie, 1995). High task load influences selective attention by eliminating interference that would arise otherwise because distractors are not processed when relevant processing consumes full perceptual load. This suggests that more difficult tasks can be performed better as they are shown to have less interference. Overall, the occurrence of selective processing depends entirely on the perceptual load imposed by external events (Lavie, 1995). Besides a resource view of attention (as described above), attention has also been explored when considered specific to a particular modality.

Visual attention

The capacity of the visual system to process information about multiple objects at one time is limited by attention (Schneider & Shiffrin, 1977). Visual orienting is usually defined in terms of the foveation of a stimulus. This process improves target-processing efficiency through acuity and is also capable of changing the priority of a stimulus while still attending to its location covertly without any change in eye or head position (Posner & Petersen, 1990). The ability to survey a visual scene, then locate, and recognize an object of interest, is constrained by the mechanisms of perception and time (Das, Bennett, & Dutton, 2007). Since we are limited by the amount of visual information our visual system can process at once, multiple objects that exist in the visual field at the same time must compete for neural representation (Kastner & Ungerleider, 2000). If subjects are presented with two different objects and are asked to identify two different characteristics at the same time, the subject's performance is worse than if the task had been performed with only one object (Posner & Petersen, 1990). Not surprisingly, events occurring at a location that an individual is attending to are responded to more rapidly (Hoffman & Eriksen, 1972; Posner & Petersen, 1990). Thus, broadly speaking visual attention can be overt (i.e., selectively processing one location over others by moving the eyes to that location) or covert (i.e., paying attention without moving the eyes). Visual attention can also be captured exogenously (where attention is automatically drawn to a stimulus) or endogenously (where attention is voluntarily drawn to a stimulus) (Guzman-Martinez, Grabowecky, Palafox, & Suzuki, 2011; Tang, Wu, & Shen, 2016). In order to interact in our environment humans must use a combination of the above processes to accurately navigate and interact with their surroundings.

Visual pathway

The visual pathway consists of the series of cells and synapses that code and carry visual information from the environment to the cortex for processing. The visual field is produced by retinal stimulation of each eye and relates to what is seen by the individual while maintaining steady fixation (Rowe, 2019). The majority of the nerve fibers in the optic tract project to the lateral geniculate nucleus (LGN) in the dorsal part of the thalamus. The LGN is the main relay in the pathway to the primary visual cortex where basic coding (shape, size, texture of objects) of visual information occurs.

Information that is conveyed to the secondary visual cortex is analyzed for colours and motion (Lundy-Ekman, 2013). From there, visual information travels to other areas of the cerebral cortex, where it is used to adjust movements or to visually identify objects. The ventral stream plays a primary role in creating a perceptual representation of the visual world and the objects within it. The dorsal stream facilitates the visual control of actions directed at these objects (Goodale & Milner, 1992). In the ventral stream, information about an extensive range of parameters are transformed for perceptual purposes while, in the dorsal stream, these parameters are altered accordingly for the control of actions (Goodale, 2011).

Auditory attention

Sounds in everyday life rarely appear in isolation. We are flooded with a symphony of sounds from a variety of sources that need to be sorted through and searched for relevant information. Thus, auditory attention is also critical for effective daily interactions. A phenomenon known as the ‘cocktail party problem’ provides an everyday example of the need to filter auditory information (Kaya & Elhilali, 2017). At the source of this problem is the fact that human voices present in a noisy environment often overlap in frequency and in time. These overlapping sounds act as acoustic interference that can impair the perception of speech. The cocktail party problem tells us that the auditory system is unable to parse the composite acoustic waveform generated by multiple sources into perceptually coherent representations (Bee & Micheyl, 2009). However, a variation, known as the cocktail party phenomenon, tells us that humans can scan large amounts of auditory information. The cocktail party phenomenon is when the auditory system is able to deconstruct the composite acoustic waveform produced by multiple sources into perceptually coherent objects that represent different sound sources in the environment (Bee & Micheyl, 2009).

Auditory pathway

The auditory pathway consists of the series of cells and synapses that code and carry auditory information from the environment to the cortex for processing. It begins with stimulation of hair cells at a specific location along the basilar membrane of the cochlea that activates sensory neurons. These sensory neurons carry the sound information in the cochlear branch of the vestibulocochlear nerve to the ipsilateral cochlear nuclei where some of the neurons decussate. Some of the neurons travel to the contralateral inferior colliculus of the midbrain while some stay on the ipsilateral side and enter the inferior colliculus on the same side. Before reaching the cerebral cortex and conscious awareness, ascending acoustic information goes to the medial geniculate nucleus of the thalamus before projection fibers deliver information to specific locations within the auditory cortex of the temporal lobe (Martini, Timmons, & Tallitsch, 2015).

Audiovisual attention

A key component in deconstructing sounds in the external environment is the role of attention. Attention mediates perception and behaviour by focusing on both sensory and cognitive resources on critical information in the stimulus space (Kaya & Elhilali, 2017). The relevance of a sound event can be dictated by the scene itself or by the task at hand because visual events, such as bouncing a ball, are often associated with sound. The auditory information that accompanies visual events can facilitate the detection of these events and help to guide a person to a particular piece of information (Doyle & Snowden, 2001). Accompanying sound to visual events can also help facilitate response accuracy in choice-RT tasks. For example, Doyle and Snowden (2001), examined the influence of auditory accessory signals during a visual-discrimination task. When sound occurred, reaction times to correctly identify the target were reduced without any loss in accuracy. These effects were evident even when the quality of the visual information was very poor and when the spatial location of the auditory signal was deliberately misleading. If auditory information can aid the acquisition of visual targets (Doyle & Snowden, 2001) then sound may prove to be a method of enhancing acquisition of visual events in visually crowded environments.

Attention has been defined from a variety of viewpoints such as, attention as a limited resource and attention specific to different sensory modalities. In summary, attention can be referred to as the neural mechanisms giving rise to a temporary enhancement or prioritization of the processing of certain stimuli relative to others (Spence, 2012). Extending back to the early 1900s, there has been a large body of research dedicated to understanding the limits of the human attention system. Multisensory integration (MSI) and cross-modal attention (ie. The interaction between two or more different sensory modalities) have a large impact on how we perceive the world and it is therefore important to understand under what circumstances these processes take place (Koelewijn, Bronkhorst, & Theeuwes, 2010). MSI interactions may further help the attention system by allowing us to focus on relevant information and filter out irrelevant information.

Multisensory Integration

Due to the amount of sensory input that humans receive on a daily basis, integration from different sensory modalities is vital in order to interact successfully in complex environments. Multisensory integration (MSI) is the process of using the interaction of information from different sensory modalities (e.g., vision and audition), to create a coherent and meaningful representation of the external environment (Talsma et al., 2010). Combining information from different sensory modalities helps to reduce noise within our perceptual system (Spence & Santangelo, 2009). When different modalities (vision, audition, tactile, olfactory) provide consistent input, distinguishing events from background noise is done more efficiently as the relevant cues become more apparent.

When responding to bimodal stimuli (a combination of any two stimuli from two different modalities), MSI generally results in improvements of the given response. Behaviourally, this is illustrated by shorter reaction times and more accurate responses to multimodal stimuli as compared to unimodal stimuli (Stein & Stanford, 2008). Within the auditory and visual modalities specifically, multisensory performance improvements include faster responses to visual (Corneil, Van Wanrooij, Munoz, & Van Opstal, 2002) or auditory (Li, Wu, & Touge, 2010) targets, an increase in the perceived visual salience (Van der Burg, Talsma, Olivers, Hickey, & Theeuwes, 2011), and a decrease in the visual contrast thresholds (Noesselt et al., 2010).

Decreased reaction time (RT) is the most common performance improvement observed when responding to multimodal stimuli. This is otherwise known as the redundant signals effect. Todd (1912) (in Miller & Ulrich, 2003) reported that the RT to detect a visual target was decreased by as much as 80ms with the simultaneous presentation of an auditory stimuli. Similarly, Hershenson (1962), found that when participants were asked to respond as quickly as possible to the onset of any stimulus in a simple reaction time (RT) task, RT decreased as the number of redundant stimuli (as opposed to response stimuli) increased. This observation has been seen in stimuli of different modalities including, visual and auditory and can be explained in terms of statistical facilitation (Miller & Ulrich, 2003). This concept suggests that each stimulus is processed independently, but in trials with redundant stimuli, the stimuli are processed simultaneously and in parallel. A response is then triggered as soon as the first stimulus is detected. This means that the RT is determined by the latency of a single detection process in trials with one stimulus. In trials with multiple stimuli, RT is determined by the first stimuli to be detected and processed (Miller, Beutinger, & Ulrich, 2009) therefore, there is an advantage in RT with redundant stimuli as compared to trials with only one stimulus (Miller & Ulrich, 2003).

Determinants of multisensory integration

In natural environments different sensory stimuli occur at various positions in time and space. Multisensory cues are often linked together and must be integrated before we are able to recognize its significance and produce a correct response (Meredith, Nemitz, & Stein, 1987). Spence (2013), reported three key determinants of MSI: intensity, temporal coincidence, and spatial congruency. The intensity of the stimuli directly affects the intensity of the signal received by the sensory neurons and plays an important role in effective MSI (Spence, 2013). For example, in a study where participants were presented with either high or low intensity audiovisual stimuli demonstrated that behavioural gains in RTs (decreased RT) were more pronounced with high-intensity stimuli. Participants were also more likely to report asynchronous audiovisual stimuli as synchronous when stimulus intensity levels were lower (Fister, Stevenson, Nidiffer, Barnett, & Wallace, 2016). This finding demonstrates that stimulus intensity plays an important role in the perception of the timing of multisensory events which in turn affects the effectiveness of MSI. Previous research has shown that the way in which the nervous system integrates sensory information is adaptable according to the reliability of information in each sensory modality; especially when signals are noisy or less reliable (Fister et al., 2016).

Multisensory interactions also depend on the temporal relationship between the stimuli. The two sensory cues of a bimodal stimulus must be close in temporal proximity in order to be perceived as originating from the same event (Radeau, 1985). However, MSI allows for some asynchrony between two unimodal stimuli (Stevenson, Fister, Barnett, Nidiffer, & Wallace, 2012) and therefore occurs within a time-restricted window known as the time-window hypothesis (Meredith et al., 1987). This time-window is estimated to range from 40ms to 600ms, and sometimes up to 1500ms (Colonius & Diederich, 2010). For example, Frassinetti, Bolognini, & Làdavas et al. (2002) systematically varied the spatial and temporal proximity of visual and auditory events and found that an auditory cue enhanced the perceptual sensitivity of participants to the intensity of a light. Critically, the authors showed that this enhancement only took place when both visual and auditory events co-occurred (interval of 500ms) in time and space (Frassinetti et al., 2002). Thus, according to the time-window hypothesis, information from different sensory modalities must not be too far apart in time in order for integration into one multisensory perceptual unit to occur (Colonius & Diederich, 2010).

Specifically related to audiovisual events, a strong multisensory integration effect is obtained when the time window between the onsets of auditory and visual events is less than 100ms (Meredith et al., 1987). In order to examine the temporal limits of MSI in the brain, Meredith et al. (1987) used neurons in superior colliculus in the cat's brain as a model population. Results showed a distinct decline on the integration effect when the auditory and visual cues were separated by more than 100ms (Meredith et al., 1987). Suggesting that a further increase in discrepancy in time between a visual and auditory cue might actually inhibit the cells that are involved in MSI and performance improvements would therefore not occur (Koelewijn et al., 2010). This limited time-window effect of 100ms is a defining feature of MSI and sets it apart from attentional effects that can function at much larger time intervals.

An example of such is the foreperiod effect. The foreperiod is the interval between a warning stimulus and the onset of a reaction stimulus (Los & Schut, 2008). When participants are instructed to respond to the second event, the first event can act as a warning cue and prepares the participants for the upcoming response. This occurs even when the cue is nonspecific to any aspect of the target. The foreperiod allows for the perceptual system to enter a preparatory state which enables faster responses to the target. Manipulation of the foreperiod has been shown to have a significant effect on RT in a choice RT-experiment (Müller-Gethmann, Ulrich, & Rinkenauer, 2003). While MSI is at its highest when events co-occur in time (Meredith et al., 1987), these preparatory effects is at its maximum when the foreperiod is approximately 400ms before performance begins to deteriorate drastically (Müller-Gethmann et al., 2003).

Spatially, stimuli of different modalities also need to be congruent for MSI to occur (Spence, 2013). When two stimuli are spatially-congruent and presented simultaneously, multisensory performance improvements have been demonstrated in situations of both selective (Li et al., 2010) and divided spatial attention (Li, Yang, Sun, & Wu, 2015). Evidence from various spatial cuing studies that involve covert orienting of spatial attention is consistent with this spatial rule. Typically in a spatial cuing design, a spatially non-predictive and task-irrelevant cue is presented in one sensory modality briefly before a target stimulus is presented in another sensory modality (Spence, 2013). Research shows that participants respond more quickly and show better perceptual sensitivity when the cue and the target are presented at the same location. This is because the presentation of a sensory cue will cause a spatially localized shift of covert attention that will facilitate target detection and discrimination response. This occurs regardless of the modality of the cue, for several milliseconds after the onset of the cue (Spence, 2013).

In a behavioural study in which cats were trained to localize a visual cue, their accuracy was lower in peripheral locations, and they showed greater multisensory enhancements at these locations with the addition of a spatially congruent auditory cue (Stein, Huneycutt, & Meredith, 1988). In humans, Stevenson et al. (2012), found that multisensory enhancement of RT was greatest at central locations (0° of visual angle) and decreased with peripheral presentations. On average, the targets presented peripherally elicited slower responses (Stevenson et al., 2012). However, participants were more likely to perceive audiovisual stimuli as synchronous when they were presented in peripheral locations as compared to foveal ones. This demonstrates that there is a strong interdependency between time and space within MSI.

To further support the spatial-rule (Spence, 2013), there is evidence of enhanced MSI when stimuli from different modalities are presented from the same (as compared to different) spatial positions, in behavioural studies in which a spatial task is used (Simon & Craft, 1970; Spence, 2013). Results from experiments in which the participants were required to discriminate the location of target stimuli in one sensory modality while ignoring the distractor stimuli presented at the same time but in a different modality, generally follow the spatial rule. Distractors presented close to the target location seem to have a stronger effect on the speed and accuracy of participant's performance than targets presented farther away (Hughes, Reuter-Lorenz, Nozawa, & Fendrich, 1994; Simon & Craft, 1970; Spence, 2013) . Taken together, whenever a participant has to perform a spatial task, MSI is greater when the stimuli from different modalities are presented from the same spatial location as compared to when they are presented from different positions (Hughes et al., 1994).

Ventriloquism effect

One of the consequences of MSI is that the perception of stimuli in one modality can be influenced by simultaneous stimuli in another modality (Spence & Driver, 2000) . One example of this effect, known as the ventriloquism effect, arises because the outcome of MSI does not always reflect equal weighting of inputs (Hairston et al., 2003). It is well-established that visual events do not easily attract auditory attention (Spence & Driver, 2000), but visual stimuli can bias one's judgment of auditory location more easily than does auditory location on visual stimuli (Slutsky & Recanzone, 2001). In the ventriloquist effect, the spatial locations of the speech sounds are misjudged due to the influence of the location of the visual stimuli. Auditory and visual stimuli affect visual capture differently with different temporal disparities. This is due to the fact that light energy travels faster than sound energy. However, this is balanced by the fact that visual stimuli require a longer neural pathway to reach the cortex when compared to auditory stimuli. Slutsky and Recanzone (2001) found that when auditory stimuli preceded visual stimuli, the ventriloquism illusion was less obvious. Thus, there is a larger ventriloquism effect when visual stimuli are presented before auditory stimuli. In other words, humans are more willing to consider the audiovisual stimuli are from the same source when the visual stimulus precedes the auditory.

Studies on the ventriloquism illusion provide evidence that auditory and visual stimuli that are temporally-congruent, but spatially incongruent, are perceptually grouped into a single multisensory object (Busse, Roberts, Crist, Weissman, & Woldorff, 2005). In these situations, participants wrongly perceive the auditory stimulus as coming from the location of the visual stimulus (Hairston et al., 2003). We experience this phenomenon more often than we might think. When we are watching a screen for example, we perceive the audio as coming from the speaking mouths of the actors of the screen. When in fact, the actual source of the sound is coming from the speaker(s) (Spence & Driver, 2000). Research has confirmed this visual biasing of auditory localization, which occurs specifically with sounds that are difficult to locate uni-modally within audition (Bertelson & Radeau, 1976). In order to understand this cross-modal bias, some researchers have assessed whether participants perceive auditory and visual stimuli as originating from the same location by changing the degree of spatial disparity between the stimuli (Slutsky & Recanzone, 2001). Researchers have also used localization tasks to investigate how a visual cue alters the perceived location of an auditory target. Taken together these investigations indicate that there are a variety of methods in order to notably decrease the level of cross-modal bias between the visual and auditory modalities. This can be done by increasing the gap between the presentation of the visual and auditory stimuli (Bermant & Welch, 1976), decreasing the relative intensity of the visual stimulus (Radeau, 1985), or informing the participants of the discrepancy between the stimuli (Welch, 1972). This occurs because of the brain's capability to continuously recalibrate and update ongoing neural processes (Krueger Fister et al., 2016). In summary, the central nervous system will adapt so that what we see and hear will fit with our current understanding so that we are more likely to perceive two stimuli as originating from a single object when the information is congruent with our past experience.

A key element of the ventriloquism effect is that cross-modal stimuli that are temporally-congruent and spatially-incongruent, are grouped into one perceptual object (Busse et al., 2005; Charles Spence & Driver, 2000). Based on the literature review above, one can see that the ventriloquism effect does not follow the spatial rule, which states that cross-modal stimuli must be spatially congruent in order for MSI to occur (Spence, 2013). This is due to the fact that both stimuli must be meaningful in order for the ventriloquism effect to truly occur. If the brain cannot perceive the two different stimuli as coming from the same object, the ventriloquism effect will not occur. Thus, there is a mix of spatial limits that we are willing to accept that depend on experience and perceived meaning (Navarra, Hartcher-O 'brien, Piazza, & Spence, 2009).

Neural evidence of multisensory integration

Alongside behavioural measures, event-related potentials (ERPs) can be used to investigate the outcomes of MSI. Understanding the timing and anatomical distribution of cortical multisensory processing is crucial to determine the roles that MSI plays in information processing (Molholm et al., 2002). ERPs help to investigate how information from different sensory modalities come together in the brain (Foxe et al., 2000). ERPs provide high-resolution temporal information to better understand the neural activity related to a given task. Understanding neural responses is important because brain imaging might show effects of MSI not demonstrated through behaviour.

ERP research has provided further understanding of cognitive processing as it allows us to assess several stages of information processing as they unfold over time (Kornblum & Lee, 1995). In a study examining the timing and topography of cortical auditory-visual interactions using ERPs during a simple RT task, RTs to the auditory and/or visual stimuli when presented simultaneously were significantly faster than when they were presented alone (Molholm et al., 2002). ERPs elicited by the auditory and visual stimuli when presented alone were summed and compared to the ERP elicited when they were presented simultaneously. Auditory-visual (AV) interactions were seen in the C1 component of the ERP suggestive of activity exclusive to multisensory processing, and the modulation of unisensory activity. These results provide evidence that audiovisual MSI influences RTs (Molholm et al., 2002).

Interactions of multisensory integration with attention

In order to help the central nervous system integrate useful stimuli from various sensory modalities into coherent cognition, attention allows humans to focus on relevant stimuli from the sensory information that we are receiving (Giard & Peronnet, 1999). Due to its increased salience, an integrated multisensory stimulus can capture attention more efficiently under complex circumstances compared to a unisensory stimulus. Increased salience of multisensory stimuli also have the ability to influence exogenous orienting of spatial attention, and can improve visual search efficiency by increasing target sensitivity (Van der Burg, Olivers, Bronkhorst, & Theeuwes, 2008).

There have been various proposals put forth to explain the relationship between MSI and attention. For example, researchers have proposed that MSI has a stimulus-driven effect on attention but that top-down directed attention also influences multisensory processing (Talsma et al., 2010). In contrast, a recent review suggested that early MSI is independent of top-down attention control (De Meo, Murray, Clarke, & Matusz, 2015). The interaction between MSI and attention has also been proposed to depend on the level of processing at which integration occurs (Koelewijn et al., 2010). It is important to note that these studies focused primarily on the interaction between top-down attentional control (endogenous attention) and MSI, using auditory/visual stimuli. Based on these findings in the literature, Tang, Wu, & Shen (2016), have proposed a framework in which attention can modulate multisensory processing in a goal-driven (endogenous), and stimulus-driven (exogenous) manner. Therefore, MSI can exert both bottom-up and top-down control over attention (Tang et al., 2016).

Attentional selectivity

Endogenous attention can modulate multisensory performance improvements through spatial or modality selectivity. Based on task instructions, attention can be focused on a spatial location or on a specific modality (Tang et al., 2016). This is known as a focused attention paradigm in which responses are made to a stimulus from a pre-defined target modality, and stimuli from non-target modalities should be ignored (Colonius & Diederich, 2012). In this paradigm, participants must distinguish target modalities from non-target modalities. Note that the present experiment will be a focused attention paradigm.

Spatial attention

Spatial attention can occur in one of two ways. Selective spatial attention occurs when attention is focused on a specific location such as, above or below the point of fixation. Although controversial in the literature, attention can also be allocated to multiple locations at once and is referred to as divided spatial attention (Tang et al., 2016). Previous research has found that this endogenous attentional selectivity can facilitate responses to unimodal signals at the attended spatial locations compared to unattended locations (Posner et al., 1980). This effect of attended versus unattended attention is also evident for multisensory stimuli (Busse et al., 2005; Santangelo, Fagioli, & Macaluso, 2010).

Selective spatial attention allows an individual to focus on important aspects of the environment while ignoring irrelevant events (Couperus & Mangun, 2010). Selection is necessary due to the limits in our capacity to process information. An important factor that we must understand in order to fully understand selective attention is to determine which factors affect how efficiently the filtering of irrelevant information occurs (Driver, 2001). Perceptual load can be defined as the degree to which attended stimuli fill perceptual routines (Lavie, 1995). If attention is not filled by the attended information, the attention pool that remains will spill over to irrelevant information despite efforts to ignore it (Barnhardt, Ritter, & Gomes, 2008). When attention is focused, perception of stimuli at the center of this focus becomes most efficient (Gondan, Blurton, Hughes, & Greenlee, 2011).When there is enough relevant information available to fill attentional stores, the irrelevant information will not be processed past the perceptual stage and efficient selection occurs accordingly (Barnhardt et al., 2008). As an example of when parallel processing occurs, we can refer back to the cocktail party problem discussed earlier. Parallel processing occurs during processes that translate sound waves into neurological impulses in the ear (Schmidt et al., 2019). Broadbent (1950) would argue that this can occur because stimuli do not require attention before reaching the "filter" along the series of information processing stages. Only one stimulus can pass the filter at a time, and once it is reached, processing becomes sequential (Schmidt et al., 2019).

With increased perceptual load, the availability of resources for the processing of distractors decreases. Barnhardt et al., (2008) suggests that there may also be an increase in target processing when perceptual load is increased. Top-down selection through augmentation of attended compared to unattended stimuli have been seen in visual processing using ERPs (Couperus & Mangun, 2010). Researchers have suggested the notion that stimulus enhancement works via a gain control mechanism, increasing sensitivity of neurons to properties of the attended stimulus (Mangun & Hillyard, 1987). In divided spatial attention conditions, the perceptual selectivity to a visual target can be enhanced by audiovisual interactions when a simultaneous auditory signal is presented in the spatially congruent/coincident location instead of a spatially incongruent or different location (Frassinetti et al., 2002). That is, locating a visual target is done so more quickly and accurately when an auditory signal originating from the same location and at the same time as the visual signal.

Evidence supporting perceptual load theory stems primarily from studies that use a paradigm in which subjects respond to targets located centrally, while trying to ignore peripheral distractors (Eriksen & Eriksen, 1974). The purpose of this interference paradigm is to determine the efficiency of attentional selection by determining the extent to which irrelevant information is processed. This is gathered by participant's behavioural performance as perceptual load is being manipulated (Barnhardt et al., 2008). Directing attention to a stimulus leads to lower perceptual thresholds, shorter reaction times (RTs), and increased discrimination accuracy (Busse et al., 2005).

ERPs have also been used to study spatial and non-spatial attention. In spatial attention tasks, participants are instructed to attend to a specific area of the visual field, specified by a cue that indicates the location of an impending stimulus that requires the participant's response (Barnhardt et al., 2008). ERPs are used to compare performance measures such as RT, of trials in which the target appeared in the cued locations (attended) versus trials in which the target appeared in uncued locations (unattended). In general, ERP studies show that there is increased brain activity when responding to targets at cued (attended) locations, which is indicative of increased processing.

Divided spatial attention allows an individual to allocate their attention to more than one location at a time. More specifically, divided attention is the "ability to split attention into multiple, spatially non-contiguous distributions of enhanced processing that remain stable throughout the time the divided attention task or trial is carried out" (Jans, Peters, & De Weerd, 2010, p. 640). However, the extent to which attention can be divided between objects is still not fully understood. There is notable flexibility in the way that attention is allocated due to the fact that individuals seem to be able to divide attention when instructed to do so, without any prior training (Jans et al., 2010). It is important to note, that the notion that attention can be divided and allocated to different locations at once only pertains to spatial attention (Maunsell & Treue, 2006). Spatial attention, and specifically, the capability for visual attention to be divided across multiple locations simultaneously is necessary for target-discrimination paradigms in which participants must choose between multiple possible targets in more than one location. The present experiment will use a target-discrimination paradigm where participants will be required to choose between right and left targets.

Two additional models that have been proposed to explain performance in tasks that require attention to be divided include the serial shifting theory and the zoom lens theory. According to the serial shifting theory of attention (Eriksen & Eriksen, 1974), the rapid shifting of a single, invisible focus of attention that is fixed in size allows for the quasi-simultaneous processing of two objects in parallel. The zoom lens theory of attention (Eriksen & James, 1986 in Jans et al., 2010) suggests that attentional focus can be regulated to match the spatial scale of the attended objects. Due to the fact that processing within the focus of attention is assumed to occur simultaneously, this could explain simultaneous processing of two target stimuli falling within the zoomed attentional focus. Serial mechanisms are compatible with shifts of attention where attention is always "on" and briefly turns "off" during discrete changes of the locus of attention during movement when switching from one attended object to another (Jans et al., 2010). If attention moved from one target location to another during a single trial, the attentional resources available would not truly be split between two locations. In this case, it does not matter if moving attention is carried out through a serial mechanism or a continuous mechanism where attention would be turned up in one location and turned down in the other (Jans et al., 2010). The target stimuli could not be processed simultaneously in either case. The absence of a stable division of attention might be inherent to difficult tasks that require individual analysis of target stimuli located in different locations (Jans et al., 2010).

Spatial and Modality Selectivity Interactions

The fact that attended stimuli are responded to more quickly and accurately has also been found for stimuli from multiple sensory modalities. Such as the simultaneous presentation of auditory and visual stimuli. When stimuli from different modalities are spatially-congruent, MSI occurs and performance improves (Li et al., 2010; Wu, Li, Bai, & Touge, 2009). In attempts to further understand the interactions between attention and MSI, researcher's direct participant's attention to either a spatial location or a specific modality.

For example, Fairhall and Macaluso (2009) instructed participants to direct their attention to a modality-specific stimulus at a specific location. Participants were instructed to attend to the left visual stimuli while ignoring all of the auditory stimuli as well as all visual stimuli on the right. MSI at the attended location was more salient as compared to the unattended location (Fairhall & Macaluso, 2009). Even though the auditory stimuli were ignored, attention directed to the visual stimuli at the attended location spreads to auditory stimuli that are simultaneously presented at the attended location and even at the central location (Busse et al., 2005). Senkowski, Talsma, Herrmann, and Woldorff (2005) used focused attention instructions, but instead of modality they instructed participants to focus on stimuli from multiple modalities presented at a specific location. Participants were asked to attend to the left visual and auditory stimuli while ignoring all of the stimuli presented on the right side. MSI integration was found to be better at the attended location as compared to the unattended (Senkowski et al., 2005). In contrast, Santangelo, Fagioli, and Macaluso, (2010) had participants attend to visual stimuli while ignoring all auditory stimuli from all locations of presentation. Responses to audiovisual stimuli were still faster than responses to visual stimuli, even when participants were instructed to only focus on the visual stimuli (Santangelo et al., 2010). Wu, Yang, Gao, and Kimura (2012), had participants attend to both audio and visual modalities in all presentation locations and found that participants responded more quickly to audiovisual stimuli as compared to the unimodal stimuli. By manipulating different foci of attention between spatial location and modalities researchers are better able to understand the relationship between attention and MSI. As one can see, whether participants were instructed to attend to a specific modality (auditory or visual) or a specific location (left or right), performance still improved so long as the auditory and visual stimuli were presented simultaneously. This was still true when participants were instructed to ignore auditory stimuli and focus solely on the visual stimuli. Based on task instructions, participants were able to consciously direct their attention.

Stroop

The Stroop effect is one of the most long-standing phenomena in cognitive science after having been reported by John Ridley Stroop in the published version of his doctoral dissertation in 1935. The Stroop effect is the result of the inability to inhibit word reading when instructed to name the ink colour of an incongruent written colour word – known as the Stroop task. The Stroop task has been recognized as the gold standard of attentional measures and is used to study human limitations in the ability to fully suppress the influence of a dominant source of information (Alain & West, 2000; MacLeod, 1992). The Stroop task gained its prominence when the distinction between automatic and controlled processing emerged (Posner & Snyder, 1975). Because the Stroop task pits the automatic process of word reading against the controlled process of colour naming it has become the single most popular phenomenon in cognitive science (Eidels, Townsend & Algom, 2010; MacLeod, 1992). The shift towards parallel models of processing has led researches to focus on situations where multidimensional stimuli are processed under attentional control, as observed in the Stroop task.

Despite the popularity of the Stroop task, researchers have yet to determine a single cause for the colour-word asymmetry that occurs. The following section will review some of the theories that have been put forth in attempts to understand. The automaticity account holds that people cannot follow instructions to ignore the written word, because reading is an automatic process (i.e., unintentional, unconscious, fast) and cannot be “turned off”. This guarantees that incongruent words will cause interference. The relative speed of processing account argues that faster processes can affect slower processes but not vice versa. This means that since words are read faster than colours can be named, interference occurs when instructed to name the ink colour while ignoring the written word. The relative pathway strength model holds that the colour-word Stroop asymmetry is due to the difference in strength between colour and word naming pathways (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Cohen, Dunbar, & McClelland, 1990). The inadvertent activations of a stronger pathway interfere with the use of a weaker pathway. Pathway strength is reflected by speed of responding and word naming is faster than colour naming, so the pathway for word naming is stronger than the one for colour naming. The word production architecture theory suggests that the colour-word asymmetry arises from the structure of the word production architecture (Smith & Magee, 1990). Colour naming is slower as it requires conceptual preparation and planning of the spoken colour name. This includes selecting the “lemma” – the representation of the word as a syntactic entity mediating between word and meaning. Word naming is faster because it does not require lemma selection (Brown, 2011).

The Stroop effect is a good example of the human failure to attend selectively to an individual aspect of a stimulus. Better performance (faster and fewer errors) with congruent compared to incongruent colour words shows that people attend to and integrate task-irrelevant stimuli, thereby compromising exclusive focus on the ink colour. Stroop tasks have been used to study key aspects of attention, learning, reading and memory. More recently the task has been extended to investigate neural mechanisms and clinical disorders.

Summary of Current State of Knowledge

From the above literature it is evident that the capacity of our attention system is limited to the number of stimuli we are able to attend to at once. We know that objects in the visual field compete with one another, which is evidence that humans prioritize their attention to specific locations. This is supported by the fact that events occurring at a location that an individual is attending to, in other words focusing on, are responded to more quickly when compared to unattended locations (Macaluso, 2010; Posner et al., 1980).

Since it is unrealistic to assume that we only ever receive information from one sensory source or modality at one time, it is important to fully understand the limits of the human attention system. Most of the sensory information that we receive is multisensory. That is, we can hear the sound of the ball hitting the concrete as we see it bouncing up and down in the same way that we hear the key tones as we type a message on our smartphones. It is for this reason that understanding the underlying mechanisms of MSI and the role it plays in attention is crucial to optimizing human performance.

Our central nervous system is capable of integrating sensory information from different modalities in order to be perceived as a single percept. When considering ways to optimize human performance, utilizing MSI is crucial. MSI refers to the process by which a combination of stimuli from different senses produces a neural response that differs from that evoked by the individual component stimuli, indicating a synthesis of information. For example, auditory information that accompanies visual events can facilitate the detection of such events and help guide a person to a particular piece of information (Doyle & Snowden, 2001). If auditory information can help an individual to successfully identify a correct visual target in a crowded environment, can auditory information help an individual choose a correct target with competing information?

Since we are concerned with the limits of the human attention system, it is crucial that we select an appropriate task. The Stroop task has been considered the “gold-standard” of attentional measures since the late 1900s (MacLeod, 1992 in Roelofs, 2005). One of the fundamental processes of selective attention is the ability to process one source of information while disregarding another. During a Stroop task, individuals are presented with a colour word and are asked to name the colour of the ink. In congruent trials, the colour word and ink colour match while in incongruent trials, the ink colour differs from the written word colour (Roelofs, 2005). The Stroop task is used to study human limitations in the ability to fully suppress the influence of a dominant source of information (West & Alain, 2000). It reflects a slowing of response latency and increase in error rate when required to identify the colour of a written word when ink colour and word colour are incongruent (West & Alain, 2000).

Despite the well-known effects of the visual Stroop task, relatively little is known about the effects of simultaneously presented congruent and incongruent auditory verbalizations on performance, or how this affects movement trajectories. Investigating reach trajectories is important because discrete responses, like key presses, do not capture dynamic internal processes unfolding over time (Song & Nakayama, 2009). Analyzing reaching movements can reflect underlying competing cognitive states that occur during a Stroop task (Song & Nakayama, 2009). For example, rapid correction of a trajectory is indicative of stimuli that are facilitated in parallel during a target selection before the movement is initiated. Overall, the progression of trajectories of reaching movements reveals the allocation of attention, and the time course of target selection and response competition (Song & Nakayama, 2009).

Objectives

The objective of the current experiment was to examine how competing and/or supporting audiovisual sensory information influenced task performance as measured by changes in RT and MT, as well as how the impact of the different combinations of stimuli were reflected in movement trajectories. Dependant variables measured included performance measures such as reaction time (RT), movement time (MT), variable error (VE), and constant error (CE), as well as kinematic measures such as movement trajectory variability, and mean marker position throughout the movement.

Hypothesis

I hypothesized that participants would exhibit shorter RTs and MTs, and earlier trajectory deviations, during the respond-visual condition compared to the respond-auditory condition. Additionally, I hypothesized that auditory stimuli would have a greater impact on performance speed and accuracy when visual stimuli were incongruent, compared to congruent or neutral visual stimuli. For performance measures, I hypothesized that the respond-auditory condition would result in longer RT and MT and later trajectory deviations; especially when visual stimuli were incongruent.

Participants

Seventeen right-handed neurotypical young adults (mean 26.35, SD 4.23, 8 female) from the University of Manitoba community participated in the experiment. Four participants were excluded from data analysis due to missing data points in over 30% of trials. Thirteen participants were included in statistical analysis (mean 26.31, SD 4.66, 6 female). All participants reported right-hand dominance, normal or corrected-to-normal vision and hearing, no neurological conditions, orthopedic injuries or surgeries to the dominant arm within the last six months. Prior to participating in the experiment, participants completed written informed consent (Appendix A) and a demographics questionnaire (Appendix B). Participants were compensated for their time with a $10 honorarium. All procedures were approved by the Educational/Nursing Research Ethics Board (ENREB) of the University of Manitoba ((Protocol #E2018:089 (HS22295)).

Apparatus

A touch screen computer monitor displaying 1920 x 108 pixels (Dell ST2220T, dimension of 37.99 x 52.81 x 5.84 cm) was positioned on a table. The home button was embedded in the table at the midline and 19.5cm from the edge of the table. The monitor was positioned 40cm from the edge of the table and was used to present two target boxes at a distance of 14.75cm (to the left and right) from the center of the screen (Figure 1). Participants sat on an adjustable chair of which the distance varied from the edge of the table depending on the comfort level of the participant. The distance of the targets from the home button remained consistent for all participants.

Figure 1. Set up and dimensions of the apparatus. The home button is located 19.5cm away from the edge of the table. Targets displayed on the screen are located 14.75cm to the left and right of the center of the screen.

Data Recording

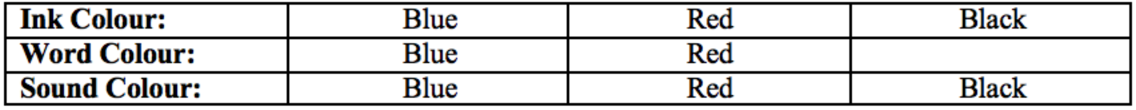
An Optotrak 3-D Investigator (Northern Digital, Inc., Waterloo, ON) was used to capture and quantify upper limb movement throughout the reaching task (spatial accuracy of 0.4mm). Infrared markers (IREDS) were placed on the participants dominant hand on the posterior surface just below the nailbed of the second phalanx of the index finger, using Blenderm (3M) medical tape. To prevent excessive IRED movement, wires were secured to the forearm of the participant with medical tape. The Optotrak captured 3-D positional data in the medio-lateral, anterior-posterior, and vertical axis and collected data points at a sampling frequency of 500Hz. At the end of each testing session, target files were collected to quantify the relative location of the IREDS at each target location. This was used to calculate constant and variable error. E-prime software (version 2.0.8.74, Psychology Software Tools) was used to control all commands including the timing of cue and target presentation, triggering the Optotrak as well as recording the location of IRED for offline analysis. Throughout the protocol, the experimenter recorded field notes to confirm E-Prime trial numbers and Optotrak files, and to note any errors that occurred during the testing session (Appendix C).

Procedure

Conditions were blocked, and the condition order was randomized and counterbalanced between participants. Participants performed a 20-trial familiarization block, which included two blocks of 10 trials of each condition. Following the familiarization block, participants performed 108 trials in each condition, resulting in a total of 216 trials. There was a short break between each experimental condition, and participants were permitted to take additional breaks at any point in the experiment. At the beginning of each experimental condition, participants were informed of the visual and auditory condition that they would be performing in the upcoming block of trials.

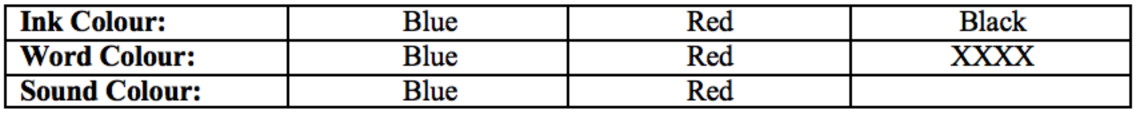
After initial instructions regarding the procedure, participants were tested in a single session of approximately 60 minutes. Participants performed two experimental conditions: i) respond-visual and ii) respond-auditory. In both response conditions, there were two different factors (auditory-congruency and visual-congruency) and within these factors was three levels (congruent, incongruent, neutral). In the respond-visual condition, participants were required to respond to the colour of the written colour word (Table 1) whereas, in the respond-auditory condition, participants were required to respond to the colour of the colour verbalization (Table 2).

Table 1 – Colours in respond-visual condition



Ink Colour:	Blue	Red	Black
Word Colour:	Blue	Red	
Sound Colour:	Blue	Red	Black

Table 2 – Colours in respond-auditory condition



Ink Colour:	Blue	Red	Black
Word Colour:	Blue	Red	XXXX
Sound Colour:	Blue	Red	

Participants were instructed to begin each trial by placing their right index finger on the home position thereby depressing it. Following presentation of a "ready" sign on the screen, it was replaced by a fixation cross that remained on the screen for 500ms. The fixation cross was then replaced by the stimulus word located at the center of the screen and remained for 500ms. An auditory verbalization of a colour word (red, blue, black) of 500ms was also presented over speakers located behind the computer monitor. After 500ms the stimulus word was replaced by two 1.5cm x 1.8cm target boxes, located 6.8cm from either sides of the screen and 6cm from the top of the screen. Participants were instructed to reach to the corresponding colour box as quickly and as accurately as possible, which then terminated the trial (Figure 2). Each session consisted of 20 familiarization trials and 108 test trials per condition. Order of conditions was counterbalanced across participants to control for confounding effects such as order and learning effects.

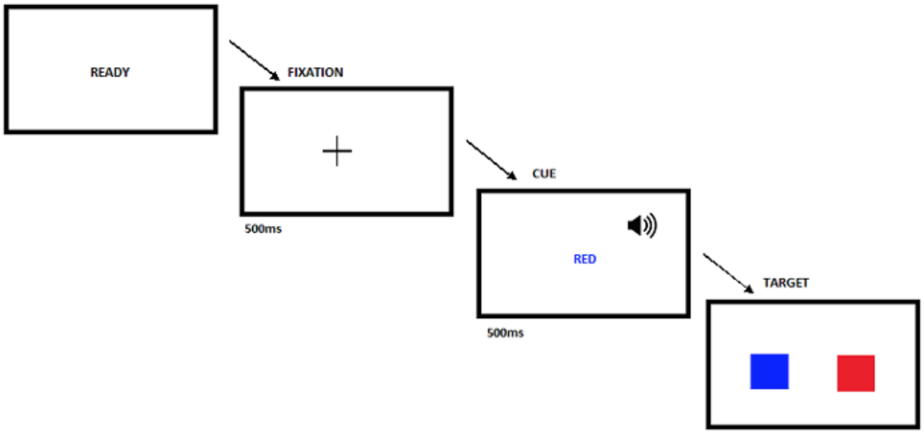


Figure 2. Illustration of a single trial of the experimental procedure.

Data Treatment

Raw data points collected with the Optotrak 3-D Investigator ((Northern Digital, Inc., Waterloo, ON) were processed using MatLab (The Mathworks, Inc.). The reaching analysis program was created by Kinsilico Labs (Toronto, ON). Prior to analysis, blank files were deleted and excluded from analysis. Blank files occurred when E-Prime software automatically externally triggered the Optotrak when switching condition during the protocol. Any trial errors and trials with low IRED visibility were noted in the field notes. Movement onset was defined as the first frame that the marker on the limb reached a velocity of 30mm/s and maintained that velocity for 30ms. Movement offset was defined as the first frame that the marker velocity fell below 30mm/s and remained as such for 30ms. Gaps up to 10 points large after movement initiation were filled in MatLab (The Mathworks, Inc.). Any trials with gaps larger than 10 data points in movement trajectory were excluded from further data analysis. The mediolateral axis was defined as the primary axis, and anterior posterior as the secondary axis.

Statistical Analysis

Prior to statistical analysis, outlier trials were manually removed. Upper and lower limits were calculated for each participant with 2.5 standard deviations above and below the mean in reaction time and movement time in the primary axis. Trials that fell outside of these limits were excluded from analysis. In addition, any incorrect trials were removed prior to analysis, which were defined as selecting the incorrect target based on condition and colour stimulus. A total of 13.4% of trials were excluded from data analysis. Trials were removed during data processing due to missing data points (9.08%), manual outliers (3.24%) and incorrect target selection (0.64%).

Statistical analysis was performed with Statistica software v.12 (Statsoft, Inc.). All black font trials were submitted to a 2 Response modality (visual, auditory) x 3 Congruency (congruent, incongruent, neutral) repeated measures, within factors ANOVA. The dependant variables analyzed were mean reaction time, movement time, constant error and variable error. A 2 Response modality x 3 Congruency x 2 Target location x 5 Marker position ANOVA investigated mean marker position at 15, 30, 45, 60 and 75 percent of movement trajectory.

All trials were submitted to a 2 Response modality (visual, auditory) x 2 Word congruency (congruent, incongruent) x 2 Ink congruency (congruent, incongruent) repeated measures, within factors ANOVA. The dependant variables analyzed were mean reaction time, movement time, constant error and variable error. A 2 Response modality x 2 Word congruency x 2 Ink congruency x 2 Target location x 5 Marker position ANOVA investigated mean marker position at 15, 30, 45, 60 and 75 percent of movement trajectory. Significance (alpha) was set at $p<0.05$, and main effects were investigated with a Tukey's HSD post hoc at a significance (alpha) set at $p<0.05$).

Results

Response Modality by Auditory Congruency

Reaction Time

There was a significant main effect of congruency (F (2, 24) = 4.27, p = 0.025851) on mean reaction time (RT). As illustrated in Figure 3, post hoc analysis using Tukey's HSD revealed that RT auditory-congruent trials were significantly shorter than auditory-neutral trials. The auditory-incongruent condition was not significantly different from either the auditory-congruent or auditory-neutral conditions. There was no interaction between response modality and congruency (F (2, 24) = 0.56, p = 0.579292).

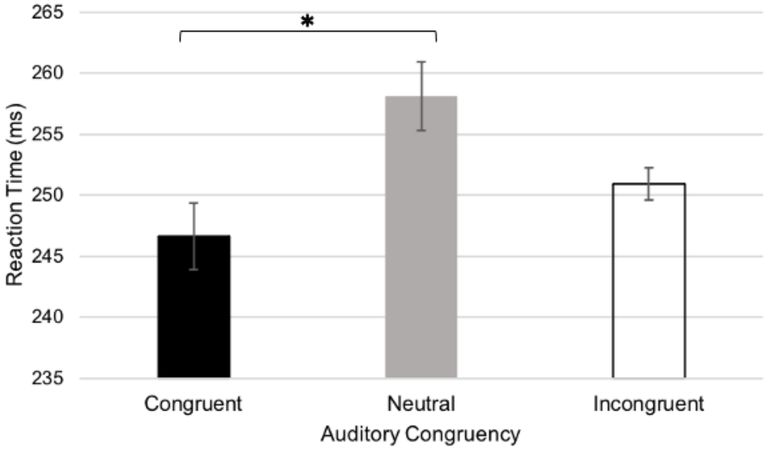


Figure 3. Mean reaction time (ms) as a function of auditory congruency. Error bars represent standard error. * indicates significant difference (α<0.05).

Movement Time

There was no effect of auditory congruency on movement time (MT) (F (2, 24) = 0.14, p = 0.114008) (Appendix D).

Movement Trajectory

There was a significant main effect of target location (F (1, 12) = 456.37, p = 0.000000), and marker position (F (4, 48) = 2043.61, p = 0.000000) on trajectory deviation. There was a significant interaction between target location and marker position (F (4, 48) = 756.87, p = 0.000000) and a significant 4-way interaction between response modality, congruency, target location, and marker position (F (8, 96) = 2.19, p = 0.035044) on trajectory deviation (Figures 4-6). Post hoc analysis using Tukey's HSD revealed that in the respond-visual condition the word-congruent trials had the earliest trajectory deviations when compared to word-neutral and word-incongruent trials. Word-congruent trials in the respond-visual condition also had earlier trajectory deviations compared to the respond-auditory condition, regardless of word congruency.

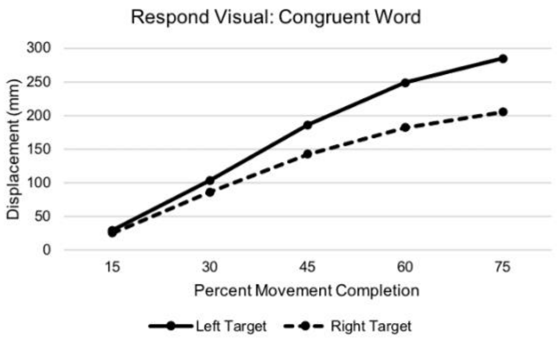


Figure 4a. Mean marker throughout movement trajectory. Interaction between response modality, congruency, target location and marker position. Measured in millimetres.

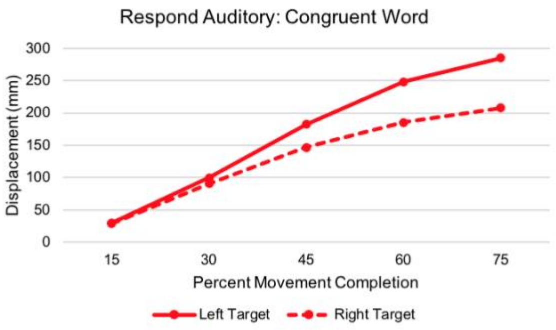


Figure 4b. Mean marker throughout movement trajectory. Interaction between response modality, congruency, target location and marker position. Measured in millimetres.

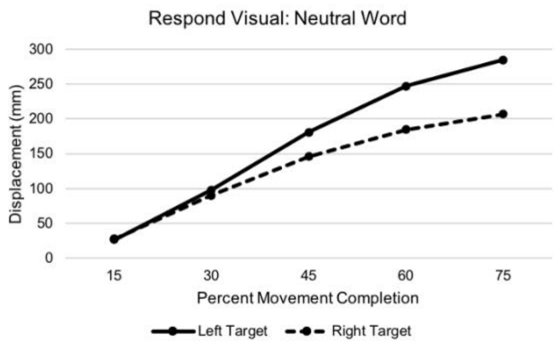


Figure 5a. Mean marker throughout movement trajectory. Interaction between response modality, congruency, target location and marker position. Measured in millimetres.

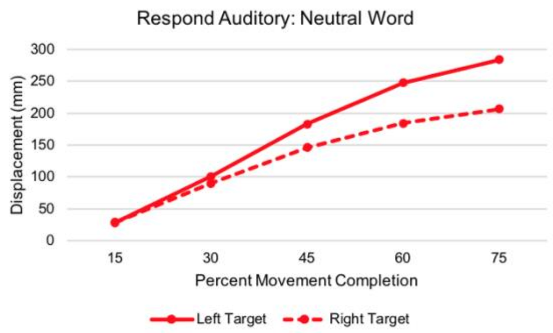


Figure 5b. Mean marker throughout movement trajectory. Interaction between response modality, congruency, target location and marker position. Measured in millimetres.

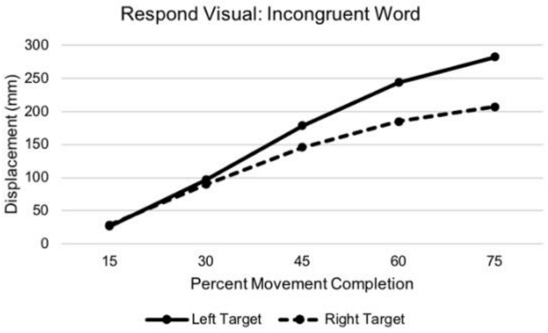


Figure 6a. Mean marker throughout movement trajectory. Interaction between response modality, congruency, target location and marker position. Measured in millimetres.

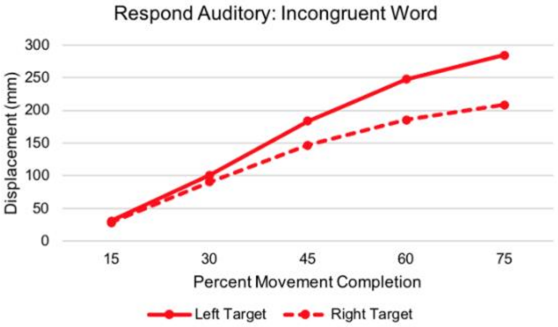


Figure 6b. Mean marker throughout movement trajectory. Interaction between response modality, congruency, target location and marker position. Measured in millimetres.

Response Modality by Visual Congruency

Movement Trajectory

There was a significant main effect of target location (F (1, 12) = 280.667p = 0.000000), and marker position (F (4, 48) = 1884.82, p = 0.000000) on trajectory deviation. There was a significant interaction between target location and marker position (F (4, 48) = 569.78, p = 0.000000). There was a significant 3-way interaction between ink congruency, target location, and marker position (F (4, 48) = 5.46, p = 0.001050) (Figure 10 and 11). Post hoc analysis using Tukey’s HSD revealed earlier trajectory deviations on trials where ink was incongruent. The largest difference between right and left targets occurred at 30 and 60 percent of movement trajectory in both, respond-visual and respond-auditory conditions.

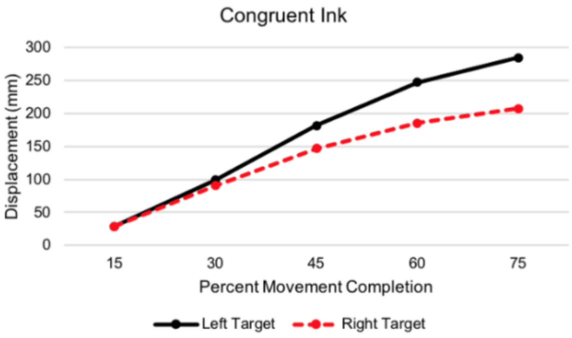


Figure 7. Mean marker position throughout movement trajectory. Interaction between ink congruency, target location and marker position. Measured in millimetres.

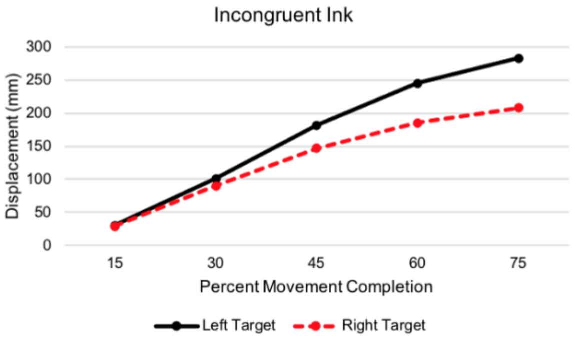


Figure 8. Mean marker position throughout movement trajectory. Interaction between ink congruency, target location and marker position. Measured in millimetres.

Variable Error

For variable error, there was a significant main effect of word congruency (F (1, 12) = 5.07, p = 0.043891) and ink congruency (F (1, 12) = 9.34, p = 0.009982). There was a significant interaction between word congruency and ink congruency (F (1, 12) = 9.39, p = 0.009810) (Figure 12).

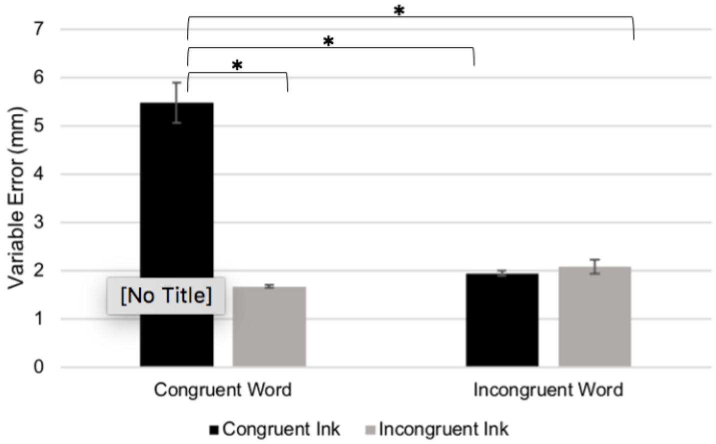


Figure 9. Variable error (mm) as a function of visual congruency. Error bars represent standard error. * indicates significant difference ($\alpha < 0.05$).

All significant effects are reported in the text and all other effects are reported in Appendix E.

Discussion

The purpose of this thesis was twofold. First, to investigate if and how movement trajectories (i.e., early vs. late deviations) reveal the impact of congruent and incongruent sensory information during a reaching task. Second, to determine how changing task requirements influenced in reaction times and movement times to the targets. A modified Stroop task was used to examine the effects of congruent and incongruent visual and auditory sensory information on performance of a goal-directed reaching task. Changes in reaction time, movement time and movement trajectory were measured to assess how stimulus characteristics impacted movement performance under different task requirements. I predicted that participants would be able to effectively ignore the auditory stimulus, leading to faster responses in the visual condition. As well, I predicted that auditory stimuli would have a greater impact on performance when the visual stimuli were incongruent. Thus, I expected to see longer RTs and MTs, and later trajectory deviations, in the respond-auditory condition when visual stimuli were incongruent.

Overall, response modality did not influence the temporal characteristics (RT and MT) of the movement. However, it did affect the execution of the movement, where participants consistently made earlier trajectory deviations when instructed to select their response based on the visual stimulus. Performance as a whole was more heavily influenced by the congruency of the auditory stimuli and less influenced by the response modality. The following discussion considers the effects of congruent and incongruent auditory and visual stimuli on performance of a goal-directed task.

Early versus late trajectory deviations

Analysis of reaching movements provides insight into visuomotor behaviour by capturing dynamic internal processing unfolding over time and/or underlying competing cognitive states (Song & Nakayama, 2009). More specifically, it allows the examination of the temporal evolution of decision making. Changes in the direction of curved reach trajectories have demonstrated that inhibitory attention mechanisms are slower than facilitatory ones (Welsh & Elliott, 2004). Welsh and Elliott (2004) found that hand movements deviated towards a non-target stimulus at stimulus onset asynchronies of 0 and 250ms, but away from a non-target at stimulus asynchronies of 750ms. More recently, Welsh (2011) tested attention-action coupling by examining movement trajectories in the presence of non-target stimuli that do or do not capture attention. Participants aimed to the location of a single white square or a single red square presented with two white squares. In separate blocks, targets were preceded by non-predictive cues that did or did not share the target feature. Results revealed that trajectory effects mirrored the temporal interference effects, where deviations were only observed when cue and target properties matched. This suggests that a non-target response causing trajectory deviations towards the location of the cue was present at movement initiation. Since the cue and target were presented relatively close temporally (onset asynchrony of 150ms), there was not enough time for inhibitory processes to eliminate the non-target response (Welsh, 2011; Welsh & Elliott, 2004). Overall, the temporal evolution of reach trajectories allows us to study the time course of response competition and target selection processes (Buetti & Kerzel, 2009).

As predicted, participants made earlier trajectory deviations during the respond-visual condition. This was most evident in trials where the written word was congruent with the auditory stimulus. Incongruent and neutral written colour words did not cause earlier trajectory deviations, but they also were not unhelpful. Earlier trajectory deviations in the respond-visual condition reflects visual dominance in object recognition. The modality appropriateness hypothesis suggests that each sensory modality is capable of a variety of functions but are better suited for certain functions over others (Welch and Warren, 1980). For example, if vision is against audition and the task requires a spatial judgment, vision will have a stronger effect because it is better designed for spatial tasks (when compared with audition). This model of cross-modal integration suggests that in cases of conflict, the dominant modality is the modality better equipped for processing a specific stimulus dimension (Yuval-Greenberg & Deouell, 2009). According to the modality appropriateness hypothesis participants had a visual bias therefore relying more on visual information because their response was a visual-based task. The magnitude of bias depends on the relative allocation of attention to the two modalities, while the distribution of attention depends on the relative appropriateness of the two modalities for the event. In this case, participants were instructed to direct their attention to the visual stimulus while ignoring the auditory stimulus, which is why they allocated more of their attention to the visual system. This led to faster planning of the entire reaching movement, which is illustrated by earlier deviations in the reach trajectory to the target.

Earlier trajectory deviations in the respond-visual condition can also be attributed to the stimulus-response compatibility. This stimulus-response compatibility model infers that some tasks are easier or more difficult to perform for one of two reasons: due to the sets of stimuli and responses that are used or because of the way the stimuli and responses are paired with each other. Effective performance depends on the properties that result from the combination of the stimulus and response sets (Fitts, 1959 as cited in Donohue et al., 2013). The rate at which the perceptual-motor system can process information is a function of the degree to which the sets of stimuli and response match. Participants made earlier trajectory deviations when responding to visual stimuli, as a result of early information processing and thus faster decision-making because it was a visual-based task.

Focused-attention paradigm

The present experiment used a focused attention paradigm where participants were informed for a given block of trials if the target was to be selected based on visual or auditory information. Overall, response modality had no effect on RT and MT. That is, participants responded equally as fast in the respond visual and respond auditory conditions. This is inconsistent with what is predicted by the literature. When simple auditory tones and visual flashes are used, auditory targets generally produce faster RTs compared to visual ones (Gielen, Schmidt, & Vandenheuvel, 1983). Using flashes of light and bursts of noise, Santangelo and colleagues (2010) found a main effect of attended modality with faster responses to auditory targets compared to visual targets. When complex stimuli such as letters and words are involved, visual processing is typically faster as reflected by RTs (Donohue et al., 2013; Yuval-Greenberg & Deouell, 2009). The rationale is that complex sounds take more time to be processed because information must be gathered over time before recognition can occur. In contrast, visual information appears simultaneously on the retina, thus recognition can be more instantaneous. Donohue et al., (2013) observed greater incongruency effects when participants attended the auditory stimulus where participants exhibited overall faster RTs for visual targets as compared to auditory targets. The present study followed the same procedure except ink colour was not black in all trials and did not produce any main effects of response modality on reaction time or movement time. Perhaps the additional visual stimulus of varying ink colour was enough to hinder the effects observed by (Donohue et al., 2013).

In the present study, participants displayed faster MTs when the ink colour was congruent (compared to incongruent), relative to the response modality. This means that participants took less time to reach their target when font colour was congruent with the target response modality. When instructed to select the target based on the visual stimulus, movement time was shortest when font colour was congruent with the written word. When instructed to select the target based on the auditory stimulus, movement time was shortest when font colour matched the colour verbalization. Overall, font colour had consistent impact on performance which is consistent with the idea that we are not capable of fully ignoring visual stimuli even when they are not relevant to the task.

Auditory influence

Auditory congruency influenced RT where participants had the fastest RTs when the auditory stimulus was congruent with the visual stimulus (ex. heard “blue” and read blue). Using simultaneous presentation of pictures and vocalizations of animals, Yuval-Greenberg and Deouell (2009) found similar congruency effects. Reaction times were fastest when the vocalization was of the same animal as the visual stimuli. Typically, information originating from an object is attuned across different modalities (a bird opening its mouth will chirp, not meow). This redundancy of information facilitates recognition and cross-modal interaction (Yuval-Greenberg & Deouell, 2009).

Although there was a benefit for congruent auditory stimuli, incongruent auditory stimuli did not help, nor hinder, performance. Surprisingly, neutral auditory stimuli had the largest impact on performance and resulted in the longest RTs. It is possible that the neutral auditory stimulus acted more as a distractor than a true neutral stimulus. Since the verbalization “black” was not part of the response set and therefore not mapped to a response, it is possible that it conflicted with participants’ decision-making because it was not included in their response set. When increased engagement is promoted by an increase in task demands, certain kinds of auditory distraction are attenuated (Marsh, Campbell, Vachon, Taylor, & Hughes, 2020). For example, serial recall performance is impaired if auditory distractors are presented during the task even when instructed to ignore auditory stimuli (Marsh et al., 2020; Hughes & Jones, 2001). *Interference by process* occurs when the involuntary processing of the sound interferes directly with a similar process used to perform the task. In this case, the processing of the verbalization “black” would have interfered with the processing of the visual colour word on the screen. Brown (2011) referred to this phenomenon as a lexicality cost. Meaningful, known words, influence stimulus processing from whether the meaning is directly congruent or incongruent with the desired response. Unlike meaningless non-words, meaningful words require greater processing times due to the activation of lexical representation of these stimuli (Donohue et al., 2013). This aligns with conclusions drawn from research using an oddball paradigm task where reaction times to a target stimulus are measured in the presence and absence of an "oddball" within a sequence of irrelevant stimuli (Dalton & Hughes, 2014). Results of this task show that responses to the visual target stimulus are slowed in the presence of an irrelevant sound. The behavioural distraction showcased by the increase in reaction times in the auditory neutral trials was likely due to the time penalty associated with the orientation of attention to and from the irrelevant auditory stimulus (Li, Parmentier, & Zhang, 2013). This *deviance distraction* can be worsened by a conflict between the involuntary processing of the content of the irrelevant sound and the voluntary processing of the target stimulus, hence the increased reaction times. Reaction time (as opposed to movement time) was most affected because it is the selection and initiation of the movement to target stimulus that is delayed by an irrelevant auditory stimulus (Marsh et al., 2019).

Participants also made earlier trajectory deviations in the respond-visual condition on trials where ink was incongruent to the written word. Since incongruent visual stimuli typically lead to slower response times in the traditional Stroop task, this could suggest that auditory stimuli may have helped with decision-making and therefore earlier trajectory deviations.

An a priori power analysis was conducted using G*Power 3.1.9.3 (Faul, Erdfelder, Lang, & Buchner, 2007) using an effect size (ηp^2=0.255) which indicated that a sample size of 43 was required to reach a power of 0.9. However, due to restrictions related to the COVID-19 pandemic, data from only 17 participants were collected.

Conclusion

Multisensory integration depends largely on the compatibility of different sensory inputs and the way in which attention is allocated. Examining how competing and supporting information using movement trajectories can help us to better understand nonconscious processing of congruent and incongruent multisensory stimuli. Overall, the auditory stimulus did have an impact on performance. Contrary to my predictions, participants were not able to ignore the colour-word verbalizations even when they were not pertinent to the task. More importantly, colour-word verbalizations that were not a part of the response set were even more of a detriment to performance as compared to incongruent colour-word verbalizations (that were a response option). This suggests that auditory stimuli are still processed regardless of task instructions and the incongruence between visual and auditory stimuli influences the speed of cognitive processing. We cannot assume that humans can choose and are able to ignore extraneous auditory information. This is important as it relates to the design of technological interfaces. It is imperative that interactive technology is designed in such a way that it actually facilitates human performance. The thoughtful application of these attentional factors could prevent error with possible serious implications.

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Appendix A

INFORMED CONSENT -

The impact of response modality in an audiovisual Stroop task

Principal Investigator: Stephanie Tomy
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University of Manitoba
tomys@umanitoba.ca

Student Research Assistants:
Preston Tran, Brittany Elliott
Perceptual Motor Integration Lab
Rm 234, Investors Group Athletic Centre
Faculty of Kinesiology & Recreation Management
University of Manitoba

This consent form, a copy of which will be left with you for your records and reference, is only part of the process of informed consent. It should give you the basic idea of what the research is about and what your participation will involve. If you would like more detail about something mentioned here, or information not included here, you should feel free to ask. Please take the time to read this carefully and to understand any accompanying information.

PURPOSE: We are interested in learning how competing and/or supporting sensory information influences movement trajectory.

DESCRIPTION: During the study, you will be asked to make a series of pointing movements to target in front of you. An OPTOTRAK 3-D motion capture system will be used to record your hand movement. Prior to this task, you will be asked to fill out a brief demographics questionnaire that inquires about your age, gender, handedness, whether or not your vision and hearing are corrected (glasses, contact lenses, hearing aids). The whole procedure will take 60 minutes to complete.

RISKS AND BENEFITS: There are no evident risks inherent in the tasks you will perform but some of the tests may become repetitive and you may experience boredom and/or mild muscle fatigue in your arms. While this may be frustrating, the investigator with you will provide breaks throughout and you may request a break at any time.

Your participation in this study will help us to investigate the role or impact of multisensory integration and attention on voluntary movement.

COSTS AND PAYMENTS: There are no fees or charges to participate in this study. However, you will receive a small honorarium for your participation.

CONFIDENTIALITY: Your information will be kept confidential. Once you begin the study your name, information, and results will be referred to by a code number. All files containing identifying information will be stored in a locked cabinet separate from data with your code number. Your files will only be accessible by the investigators and will be destroyed by Dr. Glazebrook seven years after the completion of the study (approximately August, 2026). All papers containing personal information will be shredded. All electronic files will be deleted. Any CDs or DVDs containing data will be physically destroyed. Only Dr. Cheryl Glazebrook and the student research assistants listed will have access to any lists that contain identifying information.

DEBRIEFING: Upon completion of the study the experimenter will describe the research questions being considered. If the participant would like to know the results of the study please indicate ‘yes’ on the consent form where indicated and the student research assistant will contact you with a summary of the findings in approximately 4 months.

VOLUNTARY CONSENT: If the participant *does not wish to participate* in the study or wishes withdraw from the study, you are free to leave without consequence at any point in time and we thank you for your consideration.

Your signature on this form indicates that you have understood to your satisfaction the information regarding participation in the research project and agree to participate as a subject. In no way does this waive your legal rights nor release the researchers, sponsors, or involved institutions from their legal and professional responsibilities. You are free to withdraw from the study at any time, and /or refrain from answering any questions you prefer to omit, without prejudice or consequence. Your continued participation should be as informed as your initial consent, so you should feel free to ask for clarification or new information throughout your participation. If you choose to withdraw from the study you will still receive compensation for the time you have participated. The University of Manitoba may look at your research records to see that the research is being done in a safe and proper way.

A copy of this consent form has been given to you to keep for your records and reference.

This research has been approved by the Education/Nursing Research Ethics Board. If you have any concerns or complaints about this project you may contact any of the above-named persons or the Human Ethics Coordinator (HEC) at 474-7122 or humanethics@umanitoba.ca.

INFORMED CONSENT

Research Study: The Impact of Response Modality in an Audiovisual Stroop Task

Signature of Participant______________________________________ Date ____________

Researcher/ Delegate's Signature __________________________________Date ___________

SUMMARY OF FINDINGS: Would you like to be contacted by a student research assistant with a summary of the overall findings of this study? ☐ YES ☐ NO

If yes, please complete the following:

Name: ____

Phone Number: ____

Email Address: ____

Appendix B

Demographics Questionnaire

Participant Number: ______________________________

Age of Participant: _____________ Gender: _________________

Dominant Hand (check one): Right ☐ Left ☐

Vision (check one): Normal ☐ Corrected to Normal (contact lenses/eye glasses) ☐

Hearing (check one): Normal ☐ Corrected to Normal (hearing device) ☐

Is there any history of neurological or orthopedic injury in the last year? Yes ☐ No ☐

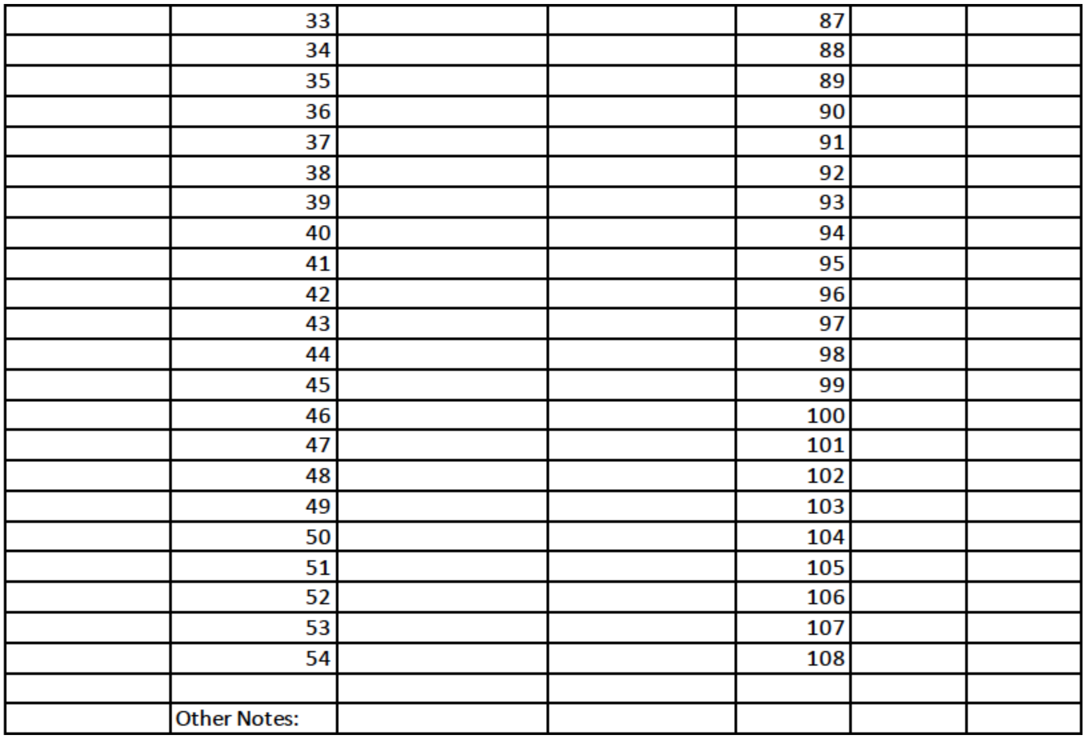
Is there any history of neurological or orthopedic surgeries in the last year?

Yes ☐ No ☐

Appendix C

Field Notes

Participant ID:						
Date:						
NDI Session Number:						
E-Prime Subject Number:						
Condition:						
E-Prime Session Number:						
	Trial Number	Observation				
Aiming Trials	**Square**					
Left	1					
Right	2					
Collection Trials						
E-Prime Session Number:						
	1			55		
	2			56		
	3			57		
	4			58		
	5			59		
	6			60		
	7			61		
	8			62		
	9			63		
	10			64		
	11			65		
	12			66		
	13			67		
	14			68		
	15			69		
	16			70		
	17			71		
	18			72		
	19			73		
	20			74		
	21			75		
	22			76		
	23			77		
	24			78		
	25			79		
	26			80		
	27			81		
	28			82		
	29			83		
	30			84		
	31			85		
	32			86		



	33			87		
	34			88		
	35			89		
	36			90		
	37			91		
	38			92		
	39			93		
	40			94		
	41			95		
	42			96		
	43			97		
	44			98		
	45			99		
	46			100		
	47			101		
	48			102		
	49			103		
	50			104		
	51			105		
	52			106		
	53			107		
	54			108		
	Other Notes:					

Appendix D

Summary Tables – Response Modality by Auditory Congruency

Movement Time (ms)
M (sd)

	Congruent	**Neutral**	**Incongruent**
Visual	607 (105)	620 (105)	608 (113)
Auditory	604 (72)	597 (75)	608 (86)

	Degrees of Freedom	**F**	**P**
Response Modality	1	0.55	0.474520
Error	12		
Congruency	2	0.14	0.868952
Error	24		
Response*Congruency	2	2.38	0.114008
Error	24		

Variable Error (mm)
M (sd)

	Degrees of Freedom	**F**	**P**
Response Modality	1	1.733783	0.212022
Error	12		
Congruency	2	1.39176	0.267992
Error	24		
Response*Congruency	2	0.15984	0.853183
Error	24		

Constant Error (mm)
M (sd)

	Congruent	**Neutral**	**Incongruent**
Visual	0.63 (1.24)	0.53 (1.73)	0.37 (1.76)
Auditory	0.81 (1.19)	0.94 (1.47)	0.58 (1.28)

	Degrees of Freedom	**F**	**P**
Response Modality	1	0.610434	0.449764
Error	12		
Congruency	2	0.774695	0.472029
Error	24		
Response*Congruency	2	0.128091	0.880370
Error	24		

Appendix E

Summary Tables – Response Modality by Visual Congruency

Reaction Time (ms)
M (sd)

	WC_IC	**WC_II**	**WI_IC**	**WI_II**
Visual	250 (38)	276 (69)	261 (58)	256 (45)
Auditory	241 (39)	237 (33)	246 (55)	254 (47)

	Degrees of Freedom	**F**	**P**
Response Modality	1	2.67	0.127959
Error	12		
Word Congruency	1	0.91	0.357971
Error	12		
Ink Congruency	1	1.92	0.190614
Error	12		
Response*Word Congruency	1	2.20	0.164032
Error	12		
Response*Ink Congruency	1	1.78	0.206691
Error	12		
Word Congruency*Ink Congruency	1	1.66	0.221958
Error	12		
Response*Word Congruency	1	3.98	0.069132
Error	12		

Movement Time (ms)
M (sd)

	WC_IC	**WC_II**	**WI_IC**	**WI_II**
Visual	604 (100)	625 (117)	613 (107)	617 (107)
Auditory	605 (77)	621 (88)	614 (75)	618 (92)

	Degrees of Freedom	**F**	**P**
Response Modality	1	0.00	0.947147
Error	12		
Word Congruency	1	0.18	0.681517
Error	12		
Ink Congruency	1	4.27	0.061193
Error	12		

Response*Word Congruency	1	0.15	0.709340
Error	12		
Response*Ink Congruency	1	0.07	0.803111
Error	12		
Word Congruency*Ink Congruency	1	2.45	0.143326
Error	12		
Response*Word Congruency	1	0.07	0.79283
Error	12		

Constant Error (mm)
M (sd)

	WC_IC	**WC_II**	**WI_IC**	**WI_II**
Visual	0.46 (1.28)	0.60 (1.95)	0.46 (1.06)	0.21 (1)
Auditory	1.53 (2.91)	0.57 (0.96)	0.67 (1.07)	0.76 (1)

	Degrees of Freedom	**F**	**P**
Response Modality	1	1.38	0.262396
Error	12		
Word Congruency	1	2.48	0.141613
Error	12		
Ink Congruency	1	2.07	1.175492
Error	12		
Response*Word Congruency	1	0.11	0.74088
Error	12		
Response*Ink Congruency	1	0.52	0.484026
Error	12		
Word Congruency*Ink Congruency	1	0.43	0.526278
Error	12		
Response*Word Congruency	1	1.95	0.188004
Error	12		