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The Impact of Emotional Sounds on Arousal and Task Performance

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Abstract

In times of emotional arousal, it is hypothesized that neural processes are triggered to "heighten" our senses to better respond to threatening stimuli. Some studies have tested this by exposing participants to emotional sounds to determine their impacts on visual acuity but have found mixed results. Previous studies have not investigated interactions between arousal induced by emotional sounds and visual acuity. Participants ($N = 42$) performed an orientation detection task while presented in silence or with sounds that varied in valence. Results displayed comparable accuracy across conditions but significantly faster response times during the presentation of negative sounds on the opposite side of the Gabor patch compared to neutral sounds irrespective of spatial location. Additionally, pupil size was significantly greater in the negative condition than in the neutral condition. These findings delineate how changes in arousal due to environmental factors can lead to changes in human performance.

Keywords

Summary for Lay Audience

From athletes in professional sports to airline pilots, people are constantly exposed to emotional situations and have to perform at a high level. Although the impact of how emotional visual stimuli impact visual task performance is well understood, how emotional auditory stimuli impact visual task performance is unclear. Some studies find that emotional auditory stimuli can enhance task performance while other studies find that it disrupts performance or may have no effect at all. Furthermore, two factors that may affect these effects are when and where the auditory stimuli are presented in relation to the visual task stimuli. Moreover, physiological arousal may act as a mechanism by which these effects take place.

This study aims to explore how emotional auditory stimuli influence visual task performance using realistic sounds. Participants were recruited to complete a visual perception task in the presence of task-irrelevant emotional sounds. In the visual perception task, participants had to indicate whether a visual stimulus was tilted left or right by pressing the "F" or "J" key on the keyboard. To measure how physiological arousal was affected by emotional sounds, an eye tracker was used to record pupil dilation throughout the entire experiment.

 Response times were faster in the presence of emotional sounds, especially when the emotional sounds were presented on the opposite side of the visual target stimulus. Accuracy was comparable between exposure to emotional and non-emotional sounds. Pupil dilation was larger for emotional sounds compared to non-emotional sounds confirming that emotional sounds lead to greater physiological arousal compared to non-emotional sounds. Sounds led to an overall reduction in response time compared to silence. However, emotional sounds led to a more prolonged enhancement in response time compared to non-emotional sounds. A similar trend was seen for pupil dilation. Overall, emotional sounds led to an enhancement in performance compared to non-emotional sounds and physiological arousal may act as a mechanism by which this occurs.

Co-Authorship Statement

Brian Wu completed all experimental and written work for this thesis project. This included study design, participant recruitment, data collection and analysis, and writing the written work.

Dr. Derek Mitchell contributed to all aspects of this thesis project including the formulation of the research question, experiment design, data analysis, interpretation, and editing of the written work.

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Chapter 1

1 Introduction

Imagine you're an airline pilot. It's your first flight and everything is going well. You're about to start descending to the landing area when all of a sudden you hear a scream coming from the passenger area. You turn your head back for a millisecond to see what's going on. A woman in the back is giving birth. You quickly turn your head back and do your best to ignore the pained screams and the on-going encouragements of the flight attendant to "PUSH" in the background to land the plane safely. After 25 minutes, the plane gently lands on the runway, and you hear gasps of joy coming from the back. You turn around and see a new mother holding her baby son. In emotional situations, performance matters. Every flight, airline pilots have to ignore the emotional stimuli in their environment to ensure that the passengers of the flight get to their destination safely and on time. However, how emotional stimuli such as cries of pain or shrieks of joy, impact behaviour and human performance is not always clear.

The onset of emotional stimuli have been shown to inhibit human performance in some contexts but enhance it in others. The impact of emotional stimuli on performance has commonly been studied in the laboratory by exposing participants to task-irrelevant emotional visual stimuli while performing a visual task. In these studies, they commonly find that emotional stimuli impair performance which may be due to the emotional stimuli drawing attention away from the task-relevant stimuli. On the other hand, emotional stimuli may also enhance performance by increasing arousal and attention.

Although the findings on how task-irrelevant visual stimuli impact performance on visual tasks are well documented, the literature on how task-irrelevant auditory stimuli impact visual task performance is mixed. For example, some studies report enhancement effects (e.g., faster responses or higher accuracy), others show distraction effects (slower response times or reduced accuracy) or no effects at all. Additionally, little is known about how the level of physiological arousal induced by emotional sounds and visual task

performance. Thus, this thesis will explore how emotional sounds impact arousal and whether they result in enhancement or distraction effects on visual performance.

2   Attention, Emotion, and Performance

Attention can be thought of as the process by which stimuli are selected for further processing and is thought to be one critical determinant of the speed and accuracy of task performance (Posner, 2005; Prinzmetal et al., 2005). One current dominant model of attention is the biased competition model (Desimone & Duncan, 1995). This model postulates that attention is the result of multiple stimuli in the visual field competing for neural representation. Which stimuli end up receiving neural representation depends on bottom-up and top-down processes. Bottom-up processes refer to those processes that bias stimuli based on their low-level visual features such as size, color, and contrast (Beck & Kastner, 2009). Emotional qualities of a stimulus are also sometimes referred to as a bottom-up feature (Blair & Mitchell, 2008; Pessoa & Ungerleider, 2004). In contrast, top-down processes enhance the representation of stimuli that are task-relevant at the expense of the competing stimuli (Reynolds et al., 1999). Additionally, competition can also occur when two stimuli of the same modality are presented close in time to one another. This can be seen in studies investigating the attentional blink which find that the presentation of two stimuli with a short inter-stimulus interval results in the second stimulus not being perceived (Broadbent & Broadbent, 1987; Raymond et al., 1992).

In the context of visual performance, the biased competition model suggests that task-irrelevant visual stimuli may result in distraction effects by inhibiting the representation of the task-relevant visual stimuli. Moreover, this distraction effect may be accentuated when the task-irrelevant visual stimuli are emotional due to bidirectional interactions between the amygdala and the ventral visual stream (Blair & Mitchell, 2008). Furthermore, emotional stimuli may have a particular advantage in attention compared to non-emotional stimuli. Pessoa and Ungerleider (2004) propose a model in which representations of emotional stimuli are enhanced due to input from the amygdala into the ventral visual stream. In line with the model, studies find strong connections between the amygdala and the ventral visual cortex (Amaral et al., 2003; Vuilleumier, 2005) and

activity in both regions is increased during exposure to emotional stimuli (Pessoa et al., 2002).

3   Unimodal Effects

3.1   Unimodal Distraction Effects in Emotional Visual Paradigms

In the visual domain, distraction effects are observed when task-irrelevant emotional visual stimuli are presented during an ongoing visual task (Mitchell et al., 2008). These distraction effects can be seen through slower response times and impaired accuracy. For example, Vuilleumier et al., (2001) also found prolonged response times when participants were exposed to task-irrelevant fearful expressions during a same-different house judgement task. Similarly, increased response times were also found after exposure to task-irrelevant emotional images in an object feature detection task (Mitchell et al., 2008). Additionally, task-irrelevant emotional sounds presented during a delay interval have been found to impair accuracy in a delayed response working memory task (Dolcos & McCarthy, 2006), particularly under conditions of high cognitive load (Tavares et al., 2016). Studies investigating the emotional attentional blink by presenting an emotional word or image before or after a target stimulus during a rapid series visual presentation (RSVP) task have also found distraction effects on visual processing. These studies find that the emotional stimulus reduces the perception of the target stimulus and leads to prolonged attentional blinks (MacLeod et al., 2017; Mathewson et al., 2008; Most et al., 2005). These findings could be explained by the task-irrelevant emotional stimuli having preferential access to resources and taking attention away from target stimuli of the same modality (Anderson & Phelps, 2001; Vuilleumier, 2005).

3.2   Unimodal Enhancement Effects in Visual Paradigms

As discussed in the previous section, many studies have found that emotional visual stimuli can impair visual performance by inhibiting representations of non-emotional target stimuli (Mitchell & Greening, 2012). However, emotional visual stimuli can also improve visual performance in certain contexts. For example, when the emotional visual stimulus is task-relevant, enhancement effects in visual task performance are observed.

Enhancement effects can be seen in visual search paradigms (Barbot & Carrasco, 2018), stimulus-detection tasks (Padmala & Pessoa, 2008), and long-term memory tasks (Bradley et al., 1992; Christianson, 1992). Padmala and Pessoa, (2008) found that participants displayed increased accuracy at target detection when the target stimuli were paired with electric shocks via classical conditioning. Additionally, Schwabe et al., (2011) found reduced attentional blinks when the target stimulus in a rapid serial visual presentation task was emotional. Whether or not emotional visual stimuli lead to distraction or enhancement effects depends on the task relevance of the emotional stimuli and when the stimuli are presented.

In certain contexts, task-irrelevant emotional stimuli have also been shown to enhance task performance as long as the emotional stimuli aren't in competition with the target stimuli. Zsido et al., (2022) found that participants were faster to identify ascending numbers when exposed to threatening images during the task. Similarly, other studies have shown that the presentation of fearful faces before task-relevant stimuli can lead to faster (Olatunji et al., 2011) and more accurate target identification (Becker, 2010) and increased contrast sensitivity (Phelps et al., 2006; Barbot & Carrasco, 2018). These findings are aligned with an "arousal stimulation effect" (Zsido, Bernath, et al., 2020; Zsido, Matuz, et al., 2020) in which the arousal elicited by the threatening images facilitated visual search performance. Taken together, this suggests that emotional stimuli may facilitate visual performance through increasing arousal and increasing attention towards target stimuli.

Along the same lines, the timing of the emotional visual stimuli can be modified to reduce competition with the target stimuli. Bocanegra and Zeelenberg, (2009) investigated this by presenting participants with task-irrelevant emotional cues at short and medium inter-stimulus intervals during an orientation detection task. They found that accuracy was impaired when the emotional stimulus was presented at short and medium inter-stimulus intervals but was enhanced when presented at long inter-stimulus intervals. These findings suggest that as long as emotional visual stimuli do not divert attention away from the target task, emotional stimuli lead to improvements in performance.

4   Cross-modal Effects

4.1   Cross-modal Enhancement Effects in Visual Paradigms

In unimodal paradigms, emotional visual stimuli are thought to lead to enhancement effects on visual performance based on whether or not they divert attention away from the target stimuli. However, in cross-modal paradigms, stimulus competition is thought to be reduced (Desimone & Duncan, 1995).

Some studies suggest that the presentation of a non-emotional auditory cue can improve visual performance through multisensory integration (Gleiss & Kayser, 2013; Huang et al., 2011; Jaekl & Soto-Faraco, 2010) or faster response times (Lippert et al., 2007). These effects are thought to occur due to multisensory integration of the perception of the visual stimulus with the perception of the auditory stimulus (Jaekl & Soto-Faraco, 2010). These effects are considered to be driven by feedback connections from multisensory neurons in the cortex and superior colliculus to sensory cortical areas (Kayser & Logothetis, 2007) and audiovisual interactions within the magnocellular and parvocellular systems (Jaekl & Soto-Faraco, 2010).

Emotional auditory stimuli may lead to even greater enhancements in visual performance than neutral auditory stimuli by elevating arousal and increasing the salience of visual stimuli (Sutherland & Mather, 2018). Aligned with this, several studies have found that the presentation of a task-irrelevant emotional auditory stimulus can lead to enhancement effects on visual performance. Max et al., (2015) found that participants were faster to categorize visual stimuli while negative sounds were presented compared to neutral sounds. Similarly, Kryklywy and Mitchell (2014) found increased accuracy in a visual localization task when negative sounds were presented concurrently compared to neutral sounds. However, this effect was only seen when the task involved activation of the ventral visual stream and not when the task involved activation of the dorsal visual stream. Additionally, negative auditory stimuli consisting of spoken emotional words (e.g., rape, torture) have also been shown to increase accuracy in a two-alternative-forced-choice identification task in which participants had to choose between two words: a previously presented target word or a foil word (Zeelenberg & Bocanegra, 2010).

Furthermore, Lee et al., (2014) found that participants displayed higher contrast sensitivity when exposed to fear-conditioned-arousing tones.

Along the same lines, Sutherland and Mather (2018) found that arousal independent of valence correlated with identification of salient stimuli. These effects may occur due to arousal increasing the activity in the locus coeruleus norepinephrine system (Howells et al., 2012) which increases the attention placed on task-relevant stimuli and decreases attention on task-irrelevant stimuli (Mather et al., 2016).

4.2   Cross-modal Distraction and Null Effects in Visual Paradigms

Although there is a large body of work suggesting that emotional auditory stimuli enhance visual performance, some studies suggest that emotional auditory stimuli have distraction effects (Hjärtström et al., 2019) or no effects on visual performance (Parmentier et al., 2020).

In an emoji oddball task, negative tones can lead to slower response times during a visual categorization task compared to neutral tones (Hjärtström et al., 2019). In contrast, the presentation of disgusting words during a cross-modal oddball task led to no significant differences in a digit parity and semantic categorization task compared to neutral words (Parmentier et al., 2020).

In both these studies, the experimenters utilized an oddball task to measure visual performance. In oddball tasks, "oddball" stimuli have been consistently shown to lead to distraction effects compared to "standard" stimuli (Andrés et al., 2006; Escera et al., 2002). This suggests that if emotional auditory stimuli did result in an enhancement in visual performance, this enhancement effect may be nullified due to the inherent distraction effects of deviant sounds in oddball tasks. Therefore, oddball tasks may be biased to show null effects of auditory stimuli regardless of whether the auditory stimuli possess an enhancement effect or not.

4.3   Mechanisms of Cross-Modal Emotional Enhancement

During visual tasks, the task-relevant visual stimuli are represented as neural representations in the temporal cortex. In unimodal emotional tasks, emotional task-

irrelevant visual stimuli may impair performance by acting as a representational competitor to the task-relevant visual stimulus. Additionally, amygdala activation in response to emotional task-irrelevant stimuli may lead to disruption in top-down attention through connections to prefrontal areas. Furthermore, amygdala activation may strengthen emotional representations in the ventral visual stream and bias competition towards the emotional stimuli in the temporal cortex. This would result in impairments in visual performance due to reduced sensory representations of the task-relevant visual stimuli. However, in contexts, in which the emotional visual stimuli are relevant to the task, visual performance would improve due to reciprocal connections from the amygdala enhancing the sensory representation of the emotional stimulus (Blair & Mitchell, 2008).

In cross-modal tasks in which an emotional task-irrelevant auditory stimulus is presented, the emotional task-irrelevant auditory stimulus would not act as a representational competitor to the task-relevant visual stimulus due to it being a separate modality. This would result in a strong sensory representation of the task-relevant visual stimulus and improvement in visual task performance. Additionally, the emotional task-irrelevant auditory stimulus would also highly activate the amygdala and locus coeruleus, which would enhance visual task performance through connections to visual areas.

5   Neural Structures in Emotional Paradigms

Prior evidence suggests that emotional stimuli receive preferential access to processing resources (Mitchell & Greening, 2012). At a neural level, two brain regions that are particularly important are the amygdala and the locus coeruleus (LC).

The amygdala is a region of grey matter located in the medial temporal lobe and has been implicated in a wide range of emotional processes such as fear conditioning (Maren, 2001), emotional memory (Canli et al., 2000), and emotional face processing (Hariri et al., 2002). Importantly, the amygdala also plays a role in emotional attention. Vuilleumier et al., (2004) exposed healthy patients and patients with amygdala lesions to fearful and neutral faces while undergoing fMRI. They found that the healthy controls displayed activation in the fusiform and occipital cortex upon showing of fearful faces. Individuals with amygdala damage did not show an emotion-related enhancement in these areas

despite having undamaged visual areas. Additionally, the amygdala has connections to visual cortical areas such as the primary visual cortex, prefrontal areas involved in executive control (Amaral et al., 2003), and reciprocal connections between the temporal cortex (Amaral et al., 1992). Based on this connectivity, it is thought that the amygdala can potentiate the representation of emotional stimuli in sensory areas. Indeed, Morris et al., (1998) found that activity in the amygdala predicted emotion-specific activation in the extrastriate cortex, an area implicated in visual processing. Together, this suggests that the amygdala may enhance representations of emotional stimuli in sensory processing areas (LeDoux & Armony, 1999; Whalen et al., 1998).

Another region of importance is the LC. The LC is a structure in the pons of the brainstem and has been implicated in modulating levels of arousal through the release of norepinephrine (NE) (Aston-Jones & Cohen, 2005). The LC displays both phasic and tonic firing patterns. High phasic and moderate tonic firing patterns are associated with increased focus and high task performance (Aston-Jones & Cohen, 2005). In contrast, low phasic and high tonic firing patterns are associated with increased distractibility and reactivity to task-irrelevant stimuli (Aston-Jones et al., 1996). LC activity is triggered in response to target-relevant stimuli (Aston-Jones et al., 1994), emotional stimuli (Sterpenich et al., 2006), and environmental stressors (Abercrombie & Jacobs, 1987) and has been reliably found to modulate levels of arousal (Aston-Jones & Bloom, 1981) and visual attention (Ghosh & Maunsell, 2022). The LC is extensively connected to multiple brain regions such as the cerebral cortex, hippocampus, and cerebellum (Foote, Bloom, & Aston-Jones, 1983). Importantly, the LC also contains connections to the amygdala (Van Bockstaele et al., 1999), the occipital cortex (Waterhouse et al., 1983) and the dorsolateral PFC (Arnsten & Goldman-Rakic, 1984), a region involved in enhancing neural coding of task-relevant stimuli (Grueschow et al., 2020).

In studies of visual attention, research on cats (McLean & Waterhouse, 1994) and rats (Waterhouse et al., 1990) have found that injections of NE can enhance receptive field properties of visually responsive neurons in the primary visual cortex. Furthermore, phasic LC activity has been found to enhance the coding of salient stimuli in the sensory cortex suggesting that the LC may increase sensory representations through connections

to the primary visual cortex and the cerebral cortex (Vazey et al., 2018). Moreover, optogenetic excitation of the LC in monkeys has been found to increase sensory discrimination of attended Gabor patches (Ghosh & Maunsell, 2022). This demonstrates that not only does LC activity lead to greater sensory representations but LC activity leads to greater visual task performance as well. Overall, these studies suggest that activation of the LC may enhance visual performance through increasing sensory representations via connections to early visual areas and the dorsolateral PFC. This effect may be amplified in emotional paradigms in which the LC is highly activated (Sterpenich et al., 2006).

Taken together, emotional enhancement of visual performance can be caused by two interconnected pathways involving the amygdala and LC. After exposure to emotional stimuli, the amygdala and LC would be activated to a high degree. This activation would lead to the increased representation of visual stimuli through two pathways: the amygdala pathway and the LC pathway. In the amygdala pathway, activation of the amygdala enhances representations of visual stimuli through excitatory connections to the ventral visual stream. This pathway is modulated by reciprocal connections from the prefrontal cortex to the amygdala and early visual areas. The LC pathway impacts visual representations directly through noradrenergic projections to early visual areas and the dorsolateral PFC. The relative impact of this pathway can be measured by pupil dilation as prior work has shown it to be a strong proxy for LC activity (Clewett et al., 2018; Murphy, O'Connell, et al., 2014). Through both these pathways, exposure to emotional stimuli leads to the amplification of awareness and attention to visual stimuli. Importantly, however, there is significant overlap between these pathways due to reciprocal connections between the amygdala, LC, and the prefrontal cortex.

6   Arousal and Pupillometry

In recent years, pupillometry has become a popular method of quantifying physiological arousal likely due to the development of eye-tracking systems with automated pupillometry (Wang et al., 2018). Several studies have used pupillometry as an index of physiological arousal (Murphy, Vandekerckhove, et al., 2014; Urai et al., 2017) and

emotional arousal (Babiker et al., 2013, 2015; Bradley et al., 2008; Krejtz et al.,2020.; Nakakoga et al., 2020; Partala et al., 2000; Partala & Surakka, 2003). Bradley et al., (2008) found that pupil size increased upon viewing highly arousing emotional images compared to less arousing emotional images. Additionally, pupil size co-varied with the galvanic skin response (GSR) suggesting that pupil dilation is a reliable indicator of increased sympathetic activity. Furthermore, multiple studies have found that exposure to negative emotional sounds leads to greater pupil dilation compared to neutral sounds (Babiker et al., 2013, 2015; Nakakoga et al., 2020; Partala et al., 2000; Partala & Surakka, 2003). Taken together, these findings suggest that pupil dilation may be a strong measure of arousal.

Pupil dilation has also been shown to be indicative of LC activity. Murphy et al., (2014) had participants complete a two-stimulus oddball task while in a MRI scanner. An eye-tracker was also collecting pupil diameter continuously at rest and during the task. They found that pupil dilation was correlated to the BOLD activity of the LC at rest and during task performance. Similarly, Clewett et al., (2018) found the same correlation when participants completed a monetary incentive encoding task inside a MRI scanner while their pupil diameter was recorded through an eye-tracker. Moreover, Sterpenich et al., (2006) had participants perform a memory task using negative and neutral faces as targets while undergoing eye-tracking and fMRI. They found that pupil size linearly modulated LC activity. Together, these studies suggest that pupil dilation may act as an indirect measure of LC activity.

The amygdala has recently become a region of interest in relation to pupil dilation due to its two-way excitatory connection with the LC (Samuels & Szabadi, 2008). Kuniecki et al., (2018) found that pupil dilation correlated with BOLD activity of the amygdala when participants were presented with negative images but not neutral images. In contrast, Leuchs et al., (2017) found that pupil dilation did not correlate with BOLD activity of the amygdala during fear conditioning. Furthermore, Dal Monte et al., (2015) compared the pupil dilation response between rhesus monkeys with amygdala lesions and controls during an oculomotor saccade task while viewing emotional facial expressions. They found that lesions to the amygdala did not lead to significant changes in pupil dilation.

This suggests that the amygdala may not be necessary for pupil dilation to occur. Taken together, the role of the amygdala in the pupil dilation response is currently mixed and future research is needed to clarify its involvement.

7   Factors Affecting Emotional Enhancement Effects

7.1   Spatial Location and Visual Performance

In the visual domain, the presentation of a task-irrelevant visual stimulus in the same spatial location as a target stimulus has been shown to improve visual task performance even without a change in head or eye position (Fernandez-Duque & Posner, 1997; Posner et al., 1980). Interestingly, these visual orienting effects have also been observed when the task-irrelevant stimulus is auditory. In cross-modal tasks, the spatial location of a task-irrelevant auditory cue could prime participants to respond in a certain location, leading to enhanced visual task performance. Aligned with this hypothesis, several studies show that the spatial location of a task-irrelevant cue leads to enhanced response time and accuracy for targets on the same side as the task-irrelevant cue. In a study by Mcdonald and Ward (2000), participants were exposed to a 70ms noise burst through either a left or right speaker before they performed a go/no-go task in which they responded to either a left or right target stimulus. They found that participants were faster when the sound was presented on the same side as the target stimulus but only when the stimulus onset asynchrony was short (100-300ms). The spatial location of a sound has also been found to influence accuracy. Mcdonald et al., (2000) presented participants with a tone through either a left or right speaker before performing a signal detection task in which the target stimulus was on the left or right side. They found that participants were more accurate when the tone was presented on the same side as the target stimulus. Furthermore, Leo et al (2011) sought to investigate this spatial cueing effect with more complex sounds. They exposed participants to bidirectional sounds that appeared to be coming towards them (looming), staying in place (static), or going away from them (receding) while they had to indicate the orientation of Gabor patches on the left and right. They found that participants displayed greater orientation detection when the sound was presented on the same side as the Gabor patch. However, this effect only existed for

sounds that were looming. This may be because looming stimuli act as warning signals and elicit greater arousal compared to static and receding stimuli (Bach et al., 2009). Overall, these findings suggest that the spatial location of an auditory cue may facilitate visual performance if the cue is presented on the same side as a visual target stimulus.

Interestingly, when the spatial location of emotional sounds is being studied, they seem to find different results. Zimmer et al., (2016) presented participants with disgusting, fearful, and neutral sounds on the left or right headphone channel. After the sound presentation, participants were presented with an arrow on either the left or right side of the fixation cross and would have to indicate whether the arrow was pointing up or down. They found that participants displayed faster response times when the fearful sounds were spatially congruent with the visual target compared too when the fearful sounds were presented spatially incongruent with the target. Interestingly, they found the opposite result for disgusting sounds in which participants were faster when the target was spatially incongruent compared to spatially congruent. In a later study by Zimmer et al., (2019), the same paradigm was used except participants had to indicate whether a schematic face (presented on the left or right of fixation) was happy or unhappy. This study replicated the effects of disgusting sounds and showed that this effect persisted regardless of the interstimulus-interval (ISI) between the sound and the target cue. However, spatially congruent neutral sounds enhanced response time but only at short ISIs and actually impaired response time at longer ISIs.

Taken together, these results suggest that when non-emotional sounds are spatially congruent with a visual target stimulus, they may facilitate visual task performance by orienting attention towards the spatial location of the visual target stimulus. However, when the sound is disgusting in emotional content, this results in faster response times when targets are presented spatially incongruent with the sound. Importantly, the opposite effect is observed for fearful sounds. Thus, future work is needed to disentangle these effects.

7.2   Stimulus Timing and Visual Performance

Another important factor that influences visual performance in cross-modal paradigms is stimulus timing. In the presentation of emotional auditory stimuli, the time between the onset of the emotional stimulus and the target stimuli plays an important role in whether enhancement effects or distraction effects are observed.

As discussed previously, Bocanegra and Zeelenberg (2009) found that when emotional stimuli were presented at short and medium-inter-stimulus intervals, participants displayed impaired accuracy during a visual orientation detection task. However, when the emotional stimuli were presented at long inter-stimulus intervals, this effect reversed and participants displayed increased accuracy compared to non-emotional stimuli. These results could be because when emotional stimuli are presented at longer inter-stimulus, there is less competition between the emotional stimuli and the task-relevant stimuli while still having the added arousal elicited by the emotional stimuli. In contrast, Bekhtereva et al., (2019) exposed participants to neutral or unpleasant images in an RSVP paradigm while they performed a visual target identification task and underwent EEG and found that sensory facilitation may occur before an attentional bias to emotional information. In sum, these findings suggest that emotional stimuli may offer an enhancement effect if presented close in time to the target stimuli.

8   Current Study

The effect of emotional stimuli on visual task performance is complex. In unimodal emotional paradigms, the effects are better understood. However, in cross-modal emotional paradigms, the results are mixed. Some studies demonstrate emotional enhancement effects (Kryklywy & Mitchell, 2014; Max et al., 2015; Zeelenberg & Bocanegra, 2010) while others show distraction effects (Hjärtström et al., 2019) or no effects at all (Parmentier et al., 2020). Although the reason for these inconsistencies is unclear, it appears that whether emotional enhancement or distraction emerges may depend on a number of factors including the timing of the visual target stimulus (Bekhtereva et al., 2019; Bocanegra & Zeelenberg, 2009), and spatial congruence between the visual and auditory stimuli (Zimmer et al., 2016, 2019). Furthermore,

although previous studies have investigated how auditory cues can affect visual performance (Kryklywy & Mitchell, 2014; Lee et al., 2014; Sutherland & Mather, 2018; Zeelenberg & Bocanegra, 2010), to our knowledge, no studies have directly compared emotional and neutral sound-related enhancement effects relative to both each other and to a silence condition.

This study aimed to determine the impact of emotional sounds on visual task performance as a function of the relative timing and spatial location of auditory and visual cues. To test whether emotional sounds led to an enhancement in performance compared to non-emotional sounds, participants completed an orientation detection task in the presence of negative or neutral sounds. To investigate timing effects, visual target stimuli were presented at 4 different time points (250ms, 1675ms, 3100ms, and 4525ms following task-irrelevant stimulus onset) throughout the presentation of the emotional sound. Trials were categorized based on whether sounds were presented on the same or opposite side of the visual target stimuli to explore the effects of spatial location. Silence trials were also included where participants completed the orientation detection task in complete silence. Data in this block was used to baseline correct the performance metrics for the negative and neutral conditions to investigate the benefit of negative and neutral sounds compared to silence.

The current study also drew on previous work suggesting that arousal and increased noradrenergic activity may be a mechanism by which emotional stimuli impact visual performance (Zsido et al., 2020; Zsidó et al., 2022). Previous work has shown pupil dilation to be an indirect measure of both physiological arousal (Murphy, Vandekerckhove, et al., 2014; Urai et al., 2017) and LC activity (Clewett et al., 2018; Murphy, Vandekerckhove, et al., 2014; Sterpenich et al., 2006). Thus, pupil dilation was recorded throughout the experiment to investigate the degree of physiological arousal elicited by the emotional stimuli and to act as an indirect measure of LC activity.

We hypothesized that emotional stimuli would enhance visual attention compared to non-emotional stimuli through processes linked to arousal. We predicted that both negative and neutral sounds would result in enhancements in accuracy and RT compared to silence but that negative sounds would result in significantly greater enhancement than neutral sounds. Moreover, we expect that this enhancement in visual performance will be accentuated when sounds are presented on the same side as the visual target stimulus. Furthermore, we also predict that the presentation of sounds would increase pupil dilation compared to silence but that this increase in pupil dilation would be greater after exposure to negative sounds compared to neutral sounds.

Chapter 2

9 Methods

9.1 Participants

Forty-six healthy adult participants between the ages of 18- and 45-years completed the study. Four participants were excluded due to poor eye-tracking calibration and validation. This resulted in 42 participants being analyzed (*M*age = 24.12 years, Range = 18-41 years, *SD* = 5.50 years, 76% female). Behavioral results from studies looking at the effects of emotional stimuli on emotion yield effect sizes of η_p^2 = .16 or higher for the main effects of emotion (Bocanegra & Zeelenberg, 2009; Zeelenberg & Bocanegra, 2010). The *a priori* power analysis used an estimated effect size of η_p^2 = .16 for 42 participants, resulting in power in excess of .95.

The Western OurBrainsCAN Research Registry was used to recruit participants. Participants were also recruited via flyers around the Western campus or elsewhere in London, social media advertisements, and emails to previous participants who expressed interest in being contacted. All participants had normal or corrected to normal vision. Participants provided written informed consent to the study and received $15 per hour compensation. This study was approved by the University of Western Ontario Health Sciences Research Ethics Board

9.2   Stimuli

The sounds were selected from the International Affective Digitized Sounds database (IADS; Bradley & Lang, 1999). The IADS is an empirically validated dataset of sounds that contains normative ratings of valence, arousal and dominance from self-report data provided by 103 men and 103 women (Mage = 21.32, SD = 2.38). For the current study, we were particularly interested in normative ratings for valences which range from 1-9 (with lower scores indicating negatively valenced stimuli) and arousal, which also ranged from 1-9 (with higher scores indicating more arousing stimuli). Twenty negative sounds were selected from those with an average valence rating below 4 (M = 2.41, SD = 0.62, Range = 1.28-3.09) and an average arousal rating of above 6 (M = 6.79, SD = 0.64, Range = 6.00-8.46). In contrast, 20 neutral sounds were selected from those with average valence ratings between 4 and 6 (M = 4.84, SD = 0.42, Range = 4.17-5.82) and average arousal ratings below 6 (M = 4.87, SD = 0.68, Range = 3.50-5.82). Negative and neutral sounds differed significantly in valence ($t(19)$ = -15.356, $p < .001$) and arousal ($t(19)$ = 11.064, $p < .001$). In addition, to control for the potential influence of low-level acoustic features, negative and neutral sounds were selected such that they did not significantly differ on root-mean-squared amplitude, onset amplitude, mean harmonicity, spectral centroid or spectral entropy (all p's > .05 uncorrected). For details of sounds, see Appendix A.

The experiment also included visual stimuli consisting of Gabor patches (2D sinusoidal luminance gratings). The Gabor patches had a Gaussian amplitude envelope of standard deviation of 0.1° and were tilted between -3.5° to 3.5° from vertical.

9.3   Procedure

The visual acuity tasks used in this study were based on prior studies that examined visual acuity in the presence of sounds (Leo et al., 2011; Stewart et al., 2020) with modifications that allowed for examination of visual acuity in the presence or absence of emotional sounds. We operationalized visual acuity as the ability to discriminate the direction in which Gabor patches were tilted. To establish the contrast levels to be used in the experimental task, we first had participants complete an Orientation Detection

Threshold Task to ensure identification accuracy fell within a given range (approximately 70% correct). Afterwards, participants had a short break before undergoing the Emotional Orientation Detection Task using their designated contrast levels.

All tasks were completed on an LG Flatron 22" monitor and all sounds were presented through dual Moloroll computer speakers positioned on the left and right of the monitor. The fixation box was located in the center of the screen and occupied a 17.19° x 9.72° visual angle at a viewing distance of 80 cm. The Gabor patches were located at a 6.25° eccentricity, on either the left or right side of the fixation box. They occupied a 1.25° x 7.79° visual angle.

The initial brightness was set at maximum brightness of 250 cd/m^2 and the sounds ranged from 59.1 db SPL to 87.7 db SPL. Ambient lighting was measured using the Konica Minolta Luminance Meter LS-110 and adjusted to match the brightness of the monitor. The Extech Sound Level Meter was used to measure the sound levels for all auditory stimuli. The Eyelink 1000 software and eye-tracker were used to measure pupil dilation and to ensure participants maintained fixation throughout the experiment.

9.4   Orientation Detection Threshold Task

Evidence suggests that participants vary in their ability to detect orientation significantly (Leo et al., 2011). Thus, to prevent floor or ceiling effects, participants completed an orientation threshold detection task (see Figure 1a) to gain an estimate of the orientation deviation needed to obtain an accuracy of approximately 70% in the experimental task. The accuracy level was chosen as it is comparable with the level of difficulty associated with previous experiments in our group that explored emotional distraction and facilitation effects (Stewart et al., 2020; Tavares et al., 2016)

To establish this threshold, we had participants complete an orientation detection task. In the orientation detection task, a fixation box appeared at the center of the screen (participants were told to maintain fixation on the fixation box throughout the entire experiment). Gabor patches of varying orientations (ranging from –3.5 to 3.5 degrees

from vertical) flashed on either the right or left side of the fixation box. The participant's task was to identify whether the Gabor patch was tilted left or right by pressing the "F" or "J" key respectively.

The task consisted of 600 trials. The trials were divided into 3 identical blocks (200 trials each) with each block presenting each unique orientation of the Gabor patch (20 unique combinations) 5 times on both the left and right side of the fixation box. The task lasted 45 minutes.

After participants completed all 3 blocks, the experimenter ran the output file of the experiment through an R script for curation and a Python script, utilizing the psignifit toolbox (http://bootstrap-software.org/psignifit/) version 2.5.6 to determine the orientation of the Gabor patch that participants identified correctly 70% of the time for the left and right side. This orientation of Gabor was then used for the emotional orientation detection task that followed.

9.5   Emotional Orientation Detection Task

Once the orientation detection threshold was established, participants had a short break before completing the main experimental task. Task Parameters are presented in Figure 1B. In brief, participants were presented with Gabor patches and were asked to indicate whether the Gabor patch was tilted left or right by pressing the "F" or "J" keys respectively. While participants completed the task, they were presented with either 10 negative sounds, 10 neutral sounds, or no sounds at all (the silent condition). Each sound was 6 seconds in duration, during which 4 Gabor patches were displayed at 250 ms, 1675 ms, 3100 ms, and 4525 ms following sound onset.

There were 480 trials broken up into 4 phases of 120 trials each. In each phase, there were three blocks of 40 trials for each sound condition (negative, neutral, silence). In each block, 10 different sounds of the appropriate emotion were presented. In the first 2 phases, each of the sounds were randomly presented once in their appropriate block. The sounds were then repeated in randomized order for the latter 2 phases. The ordering of

the blocks was pseudo-randomized such that identical blocks were not presented consecutively. Phases were separated by a break in which participants took a self-timed break before proceeding to the next phase.
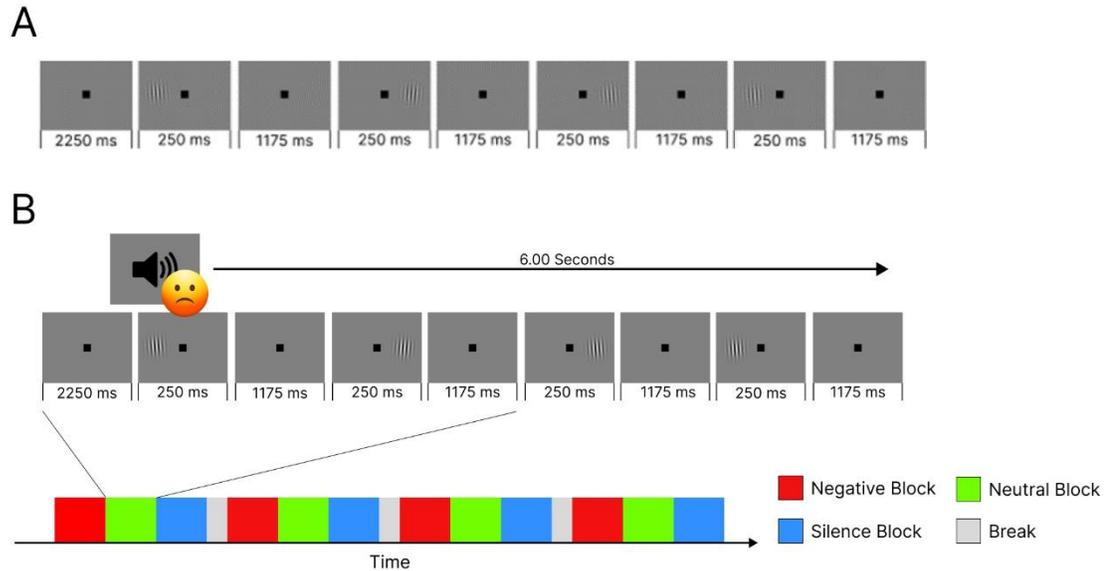
Figure 1. Experiment and trial structure of the orientation detection threshold task and emotional orientation detection task.

An Eyelink 1000 eye-tracker was used to track the participants' fixation throughout the experiment and ensure that the participants were fixating on the fixation box and not saccading to the Gabor patches. Trials in which participants saccaded to the Gabor patch were discarded during analysis ($M = 20.61$, $SD = 27.96$, Range = 0-101). Additionally, the eye-tracker also collected pupillometry data (pupil dilation) as a measure of physiological arousal.

9.6 Data Analyses

Errors and non-responses were excluded from the RT analysis as were trials in which subjects failed to fixate centrally (4.3%). Additionally, outlier trials were identified within each condition. Outliers were defined as trials where the response times were greater or less than 3 median absolute deviations (MAD) for that trial type (e.g. negative

(*M* = 6.26, *SD* = 4.31, Range = 0-23), neutral (*M* = 6, *SD* = 4.38, Range = 0-23), silence (*M* = 7.14, *SD* = 4.27, Range = 1-24)) in line with recommendations (Leys et al., 2013).

Four participants were excluded because their average RT was more than 3 MAD above or below the median for one or more trial types. This left 38 participants for the main analyses. A 3-way repeated measures analysis of variance (ANOVA) was performed using the within-subjects factors of Valence (negative, neutral), Congruence (congruent, incongruent), and Timing (time point 1, time point 2, time point 3, time point 4). Similar to prior work (Mitchell et al., 2008; Tavares et al., 2016), the primary variable of interest was response time, and accuracy was examined as a secondary measure. The interaction between valence and congruence was of particular interest. Greenhouse-Geisser adjusted degrees of freedom were used when the assumption of sphericity was violated.

Before analysis, pupillometry data underwent blink interpolation, baseline correction, and trial exclusion based on baseline (first 50 ms after sound onset) as suggested by Mathot and Vilotijević (2022). The pupil sizes during the presentation of the Gabor patches were then extracted and analyzed using the same 3-way repeated measures ANOVA that was used for response time and accuracy.

In light of prior evidence that the presentation of innocuous sounds can also enhance concurrent visual acuity (Gleiss & Kayser, 2013; Huang et al., 2011; Jaekl & Soto-Faraco, 2010; Lippert et al., 2007), we conducted planned comparisons to quantify the relative benefits of any sound versus a silent baseline at various time points. Specifically, we sought to replicate the finding that any sound would enhance visual acuity relative to the silence condition (Kim et al., 2012). Next, we sought to compare the relative size of the advantage conferred by neutral sounds over no sounds, with that of negative sounds over neutral sounds. To do this, we conducted one-sample t-tests comparing negative and neutral values at each time point with baseline. Next, we conducted paired samples t-tests to examine whether this advantage differed between conditions (negative, neutral). This procedure was performed for RT, accuracy, and pupil dilation.

Our planned comparisons included those main effects and interactions involving emotion. The Benjamini-Hochberg procedure was used to correct for all unplanned, post-hoc comparisons not involving emotion. Unless stated otherwise, all post-hoc tests survived correction.

10   Results

10.1   Response Time

The 2 (Valence: negative, neutral) x 2 (Congruence: congruent, incongruent) x 4 (Timing: 1, 2, 3, 4) repeated measures ANOVA of the RT data revealed a significant main effect of Valence ($F(1, 37) = 4.42$, $p = .042$, $\eta_p^2 = .107$). Participants categorized visual stimuli faster in the presence of negative versus neutral sounds. A significant Valence X Congruence interaction also emerged ($F(1, 37) = 10.32$, $p = .003$, $\eta_p^2 = .218$). Pairwise t-tests revealed that orientation detection was significantly faster in the presence of spatially incongruent negative sounds versus spatially congruent negative sounds ($t(38) = 2.367$, $p = .023$), spatially congruent neutral sounds ($t(38) = -2.072$, $p = .045$) or spatially incongruent neutral sounds ($t(38) = -2.830$, $p = .007$).

In addition, a Congruence X Timing interaction emerged ($F(3, 111) = 4.49$, $p = .005$, $\eta_p^2 = .312$). For spatially congruent sound-Gabor presentations, participants displayed significantly slower orientation detection at time point 3 compared to time point 1 ($t(41) = -2.882$, $p = .006$) and time point 4 ($t(39) = 2.467$, $p = .018$). For incongruent presentations, participants displayed significantly slower orientation detection at time point 1 compared to time point 2 ($t(39) = 2.163$, $p = .037$). Additionally, participants were significantly faster to incongruent sounds at time point 2 compared to incongruent sounds at time point 3 ($t(39) = 3.193$, $p = .003$). However, none of these contrasts survived correction. The 3-way interaction was not significant ($F(3, 111) = 1.10$, $p = .354$, $\eta_p^2 = .029$).
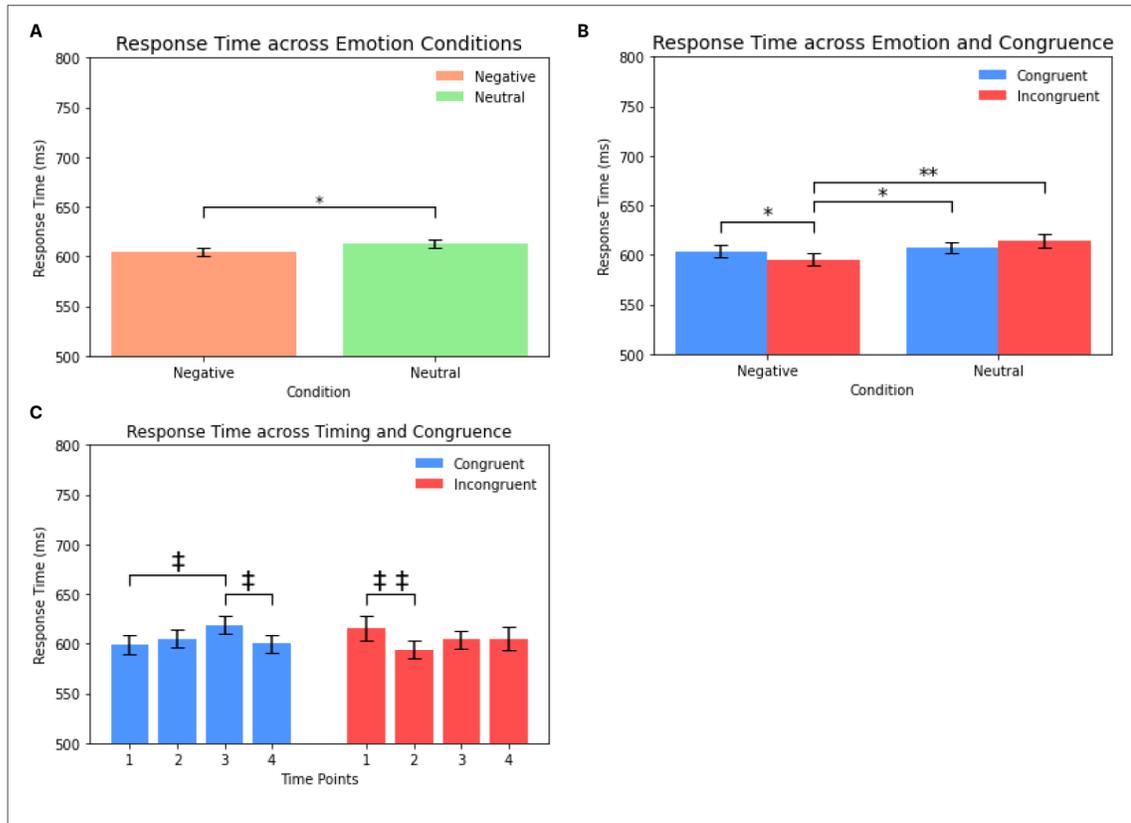
Figure 2. (a) *Depicts the main effect of Valence whereby participants were fastest for identifying Gabor patch orientations in the presence of negative sounds compared to neutral sounds. (b) Depicts a significant Valence X Congruence interaction was observed. (c) The significant Congruence X Timing interaction is characterized.* ‡ *p* < .05 *and* ‡‡ *p* < .01 *indicate p values which did not survive correction. *p < .05; **p < .01; ***p < .001*

10.2 Accuracy

A 2 (Valence: negative, neutral) x 2 (Congruence: congruent, incongruent) x 4 (Timing: 1, 2, 3, 4) repeated measures ANOVA was conducted using the proportion of correct responses to the total number of valid responses as the dependent variable. The analyses revealed no significant main effect of Valence ($F(1, 40) = 0.38$, $p = .544$, $\eta_p^2 = .009$). A main effect of Timing emerged ($F(3, 120) = 11.44$, $p < .001$, $\eta_p^2 = .222$); participants were more accurate at identifying the orientation of the Gabor patch at time point 1 compared

to time point 2 ($t(40) = 3.082$, $p = .004$)., 3 ($t(41) = 5.109$, $p < .001$)., or 4 ($t(41) = 4.254$, $p < .001$). Accuracy at time points 2 was also significantly higher than accuracy at time point 3 ($t(40) = 2.529$, $p = .015$).

The analyses revealed no Valence X Congruence interaction ($F(1, 40) = 0.13$, $p = .722$, $\eta_p^2 = .003$) and no three-way interaction ($F(3, 120) = 0.34$, $p = .799$ $\eta_p^2 = .008$).
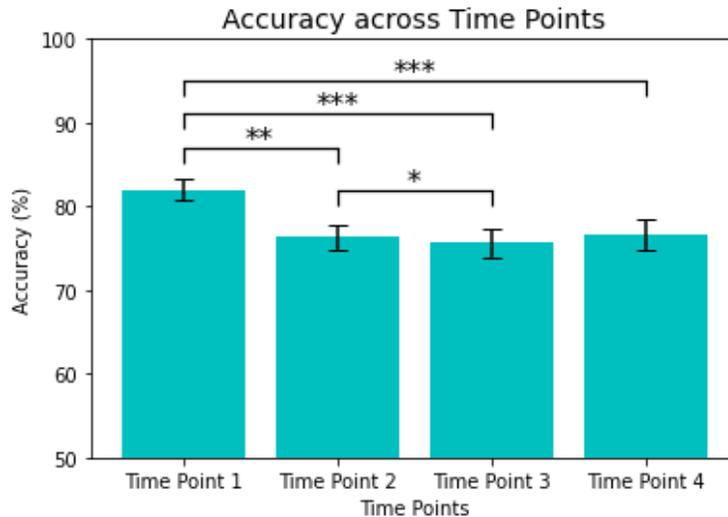
Figure 3. *A main effect of Timing was observed whereby participants were more accurate when identifying the orientation of the first Gabor patch relative to all other time points****p < .001*

10.3 Pupillometry

A 2 (Valence: negative, neutral) x 2 (Congruence: congruent, incongruent) x 4 (Timing: 1, 2, 3, 4) repeated measures ANOVA was conducted on the pupil dilation data during the presentation of the Gabor patch relative to the baseline period as the dependent variable. The analysis revealed a main effect of Valence ($F(1,34) = 21.60$, $p < .001$, $\eta_p^2 = .389$); negative sounds were associated with significantly greater increases in pupil size compared to neutral sounds. A main effect of Timing also emerged ($F(3,102) = 96.90$, $p < .001$, $\eta_p^2 = .740$). Pupil size was significantly smaller at the presentation of the first Gabor patch than any other time-point ($p < .001$).

A Valence X Timing interaction also emerged ($F(3,102) = 7.61$, $p = <.001$, $\eta_p^2 = .183$) in which negative sounds elicited greater pupil sizes compared to neutral sounds at time points 2 ($t(38) = 2.713$, $p = .010$), 3 ($t(35) = 3.308$, $p = .002$), and 4 ($t(35) = 4.129$, $p <.001$), but not at time point 1 ($t(36) = .07$, $p = .944$). However, there was no significant Valence X Congruence interaction ($F(1,34) = 0.013$, $p = .908$, $\eta_p^2 < .001$) or 3-way interaction ($F(3,102) = 0.53$, $p = .661$, $\eta_p^2 = .015$).
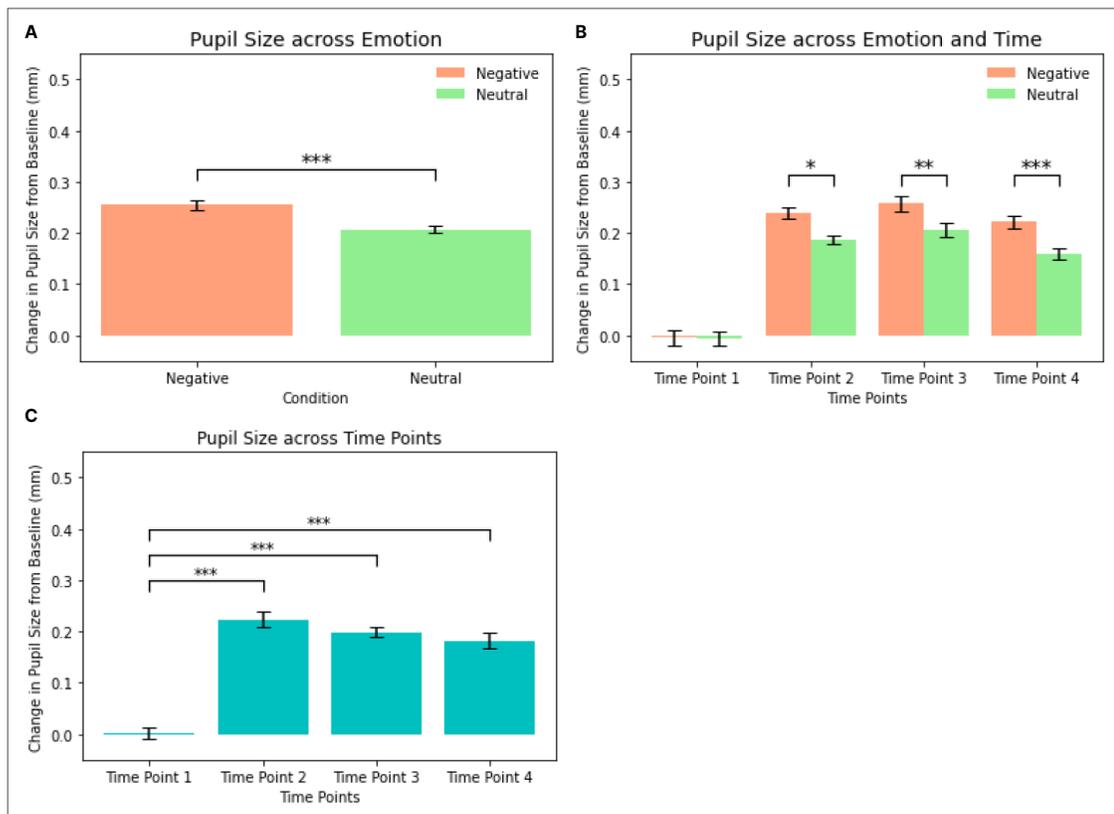
Figure 4. (a) *Depicts* the *main effect of Valence whereby participants displayed greater pupil dilation in response to negative sounds compared to neutral sounds. (b) Displays the significant Valence X Congruence interaction whereby pupil size was greater for negative relative to neutral sounds across all time points except time point 1 (c) Shows the main effect of Timing in which pupil size was significantly smaller at time point 1 compared to the following time points. *p < .05; **p < .01; ***p < .001*
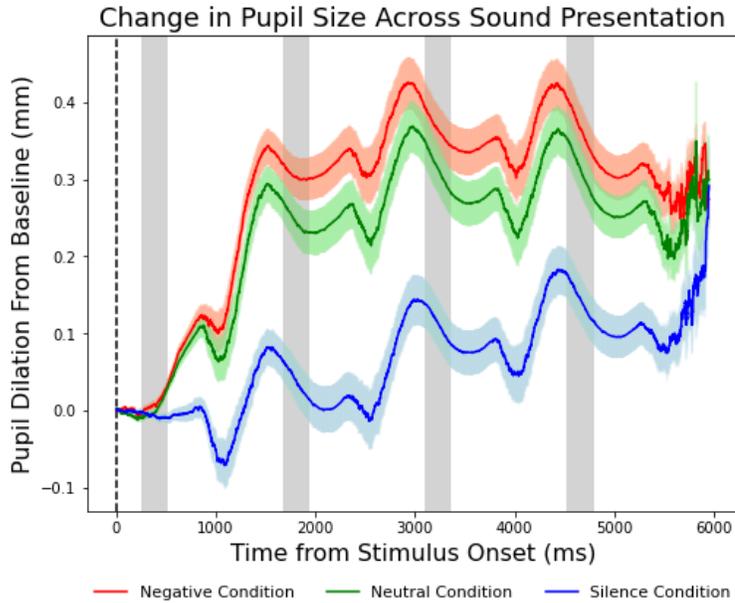
Figure 5. Time series graph showing the change in pupil dilation from the baseline
period throughout the sound presentation for all three conditions. Grey columns indicate
the times in which the Gabor patches were presented and are the data points used in the
subsequent analyses.

10.4 Quantifying the sound versus no-sound advantage

In order to quantify the relative benefits of any sound versus a silent baseline at various
time points, planned comparisons were conducted between the negative and neutral
baseline-corrected values at each time point with the silent baseline. When the advantage
of sound was significant, paired samples t-tests were then conducted to examine if the
advantage of sound was enhanced for negative sounds compared to neutral sounds.

10.4.1 Response Time

To examine the differential impact of sound compared to silence as a function of time,
one-sample t-tests were conducted comparing the baseline corrected RTs for the negative
and neutral condition at each time point with the baseline values. These analyses revealed
that negative sounds produced a significant advantage in RT at time points 1 ($t(39) = -
6.701, p < .001$), 2 ($t(39) = -4.007, p < .001$), 3 ($t(39) = -2.115, p = .041$), and 4 ($t(39) = -
2.221, p = .032$), compared to baseline. In contrast, neutral sounds produced a significant

advantage in RT at time points 1 ($t(40) = -7.072$, $p < .001$), and 2 ($t(40) = -2.248$, $p = .03$) but not time points 3 ($t(40) = -.573$, $p = .57$) and 4 ($t(40) = --.879$, $p = .385$).

To evaluate whether the advantage of sound on RT differed between negative and neutral sounds as a function of time, paired sample t-tests were conducted between baseline corrected negative and neutral RTs for the time points in which there was a significant advantage for both negative and neutral sounds. These analyses revealed that negative sounds elicited a significantly greater RT advantage at time point 2 ($t(38) = -2.487$, $p = .017$) compared to neutral sounds but not at time points 1 ($t(39) = .012$, $p = .991$).
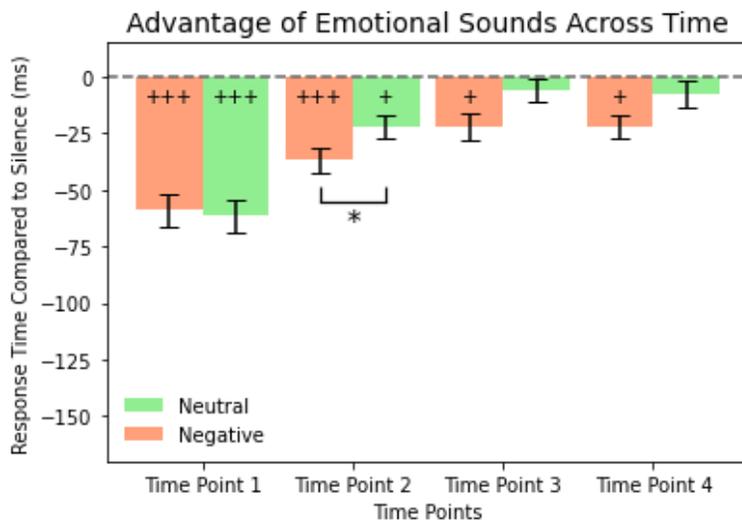
Figure 6. Negative sounds elicited a prolonged reduction in RT throughout all time points while neutral sounds only elicited reduction in RT at the first two time points. Plus signs (+) indicate the degree to which the condition is significantly different compared to silence. $^+p < .05$; $^{++}p < .01$; $^{+++}p < .001$. $^*p < .05$; $^{**}p < .01$; $^{***}p < .001$.

10.4.2   Accuracy

Similar to RT, one-sample t-tests were conducted to compare the accuracy values for the negative and neutral condition at each time point compared to baseline. The analyses showed that accuracy was not significantly different from baseline at any time point for both negative and neutral conditions.

10.4.3   Pupillometry

Like both accuracy and RT, one-sample t-tests were conducted on the baseline corrected pupillometry values for both emotion conditions at each time point compared to baseline. For the negative condition, pupil dilation was significantly greater than baseline at time points 2 ($t(41) = 12.637$, $p < .001$), 3 ($t(39) = 10.611$, $p < .001$), and 4 ($t(37) = 9.720$, $p < .001$) but not at time point 1 ($t(39) = -1.074$, $p = .290$). Similarly, pupil dilation in the neutral condition was also significantly greater than baseline at time points 2 ($t(40) = 12.574$, $p < .001$), 3 ($t(39) = 9,557$, $p < .001$), and 4($t(38) = 9.078$, $p < .001$), but not at time point 1 ($t(40) = -1.420$, $p = .163$).

Finally, pairwise t-tests were conducted examining whether pupil dilation was different between emotion conditions at each time point. The analyses revealed that the increase in pupil dilation over silence was significantly greater in the negative relative to the neutral condition at time points 2 ($t(40) = 4.326$, $p < .001$), 3 ($t(39) = 2.693$, $p = .01$), and 4 ($t(37) = 4.114$, $p < .001$).

Figure 7. Pupil dilations compared to baseline values (dashed line) were significantly greater at all time points but time point 1 with an added advantage for th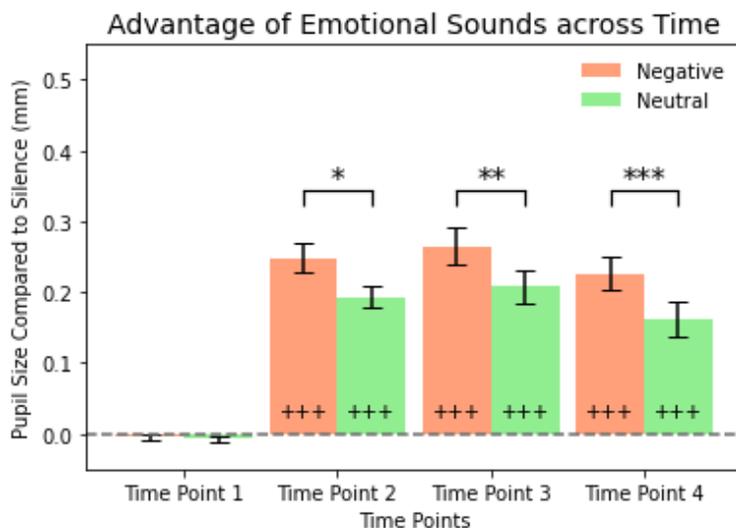e negative condition. Plus signs (+) indicate the degree to which the condition is significantly different compared to baseline. $^{+}p < .05$; $^{++}p < .01$; $^{+++}p < .001$. $^{*}p < .05$; $^{**}p < .01$; $^{***}p < .001$.

Chapter 3

11   Discussion

Studies exploring the impact of emotional stimuli on visual task performance using cross-modal emotional stimuli commonly find mixed effects. Some studies find evidence for enhancement effects (Kryklywy & Mitchell, 2014; Max et al., 2015; Zeelenberg & Bocanegra, 2010) while other studies show distraction effects (Hjärtström et al., 2019) or no effects at all (Parmentier et al., 2020). Two factors that may contribute to these effects are the spatial location of visual and auditory objects and the timing of visual target stimuli in relation to the emotional auditory stimuli. However, how both of these factors simultaneously influence the impact of emotional auditory stimuli on visual task performance is unclear. No studies to our knowledge have examined the additive impact of sound and emotion on visual task performance, and few have investigated how emotional sounds influence both physiological arousal and visual task performance. The current study sought to address these gaps in knowledge by manipulating both the timing and spatial location of an emotional sound in relation to visual target stimuli as participants performed an orientation detection task. In addition, a silent condition was included to delineate any additive effects of sound and emotion on visual performance. Lastly, we also examined how physiological arousal was affected by the emotional content, spatial location, and timing of an auditory stimulus by measuring pupil dilation throughout the experiment. As predicted, the presence of negative sounds was associated with faster RTs overall. Surprisingly, this effect was driven by significant RT reductions when negative sounds were presented on the opposite spatial side as the visual target stimuli. Contrary to predictions, negative sounds did not lead to significant differences in accuracy. However, aligned with predictions, pupil dilation was significantly greater after exposure to negative sounds compared to neutral sound, and sounds led to faster RT and increases in pupil dilation compared to silence. Furthermore, these effects were more prolonged after exposure to negative sounds.

This study demonstrated that negative sounds did not lead to significant differences in accuracy but did lead to significant enhancement in RT compared to neutral sounds. This

is not unexpected as other studies in emotional attention observe a similar pattern of results (Mitchell et al., 2008; Tavares et al., 2016; Asutay & Västfjäll, 2017; Zimmer et al., 2022). These results reflect an enhancement in performance in which participants display faster RTs with no cost to accuracy. Based off this, it can be speculated that our effects reflect a motor response to negative sounds compared to an attentional enhancement. However, it is unlikely that the results are the outcome of motor enhancement as if they were; we would see a general improvement in RT irrespective of spatial location. Another possibility is that accuracy and RT may be affected by different mechanisms with accuracy being influenced through voluntary attention and RT being influenced through involuntary attention (Prinzmetal et al., 2005). However, reductions in RT are unlikely to be caused entirely by attention and likely involve some form of motor enhancement (Boulinguez & Nougier, 1999). Thus, these enhancement effects may be due to a combination of improved involuntary attention and motor enhancement.

Interestingly, negative sounds enhanced response times compared to neutral sounds but only when sounds were presented incongruently. This was unexpected as prior work has found that the presentation of sounds on the same spatial side as the visual stimulus leads to faster RTs (McDonald & Ward, 2000; Mcdonald et al., 2000). These effects are thought to occur as an involuntary orientation of attention to the spatial location of the sound and the visual target stimulus (McDonald et al., 2000). Thus, we expected this effect to be enhanced for negative sounds since negative sounds are more arousing and may impact involuntary attention more than neutral sounds. However, it should be noted that some prior work has found a similar effect in which incongruently presented negative sounds elicited significantly faster RTs in a spatial cueing task than incongruently presented neutral sounds (Harrison & Davies, 2013). These findings have been interpreted as reflective of an attentional disengagement and avoidance of the negative stimulus (Koster et al., 2006; Lee et al., 2012). According to this idea, negative sounds may trigger attentional avoidance of the location it appears, increasing resource allocation to the opposite spatial location.

In line with predictions, the presentation of negative versus neutral sounds was associated with increased pupil dilation, but only after time point 1. This enhancement in pupil dilation by negative sounds is in accordance with prior studies that have found a similar effect (Babiker et al., 2013, 2015; Nakakoga et al., 2020; Partala et al., 2000; Partala & Surakka, 2003). As previous work has found a correlation between pupil dilation and LC activity (Clewett et al., 2018; Murphy et al., 2014; Sterpenich et al., 2006), these results suggest that negative sounds elicit significantly greater phasic LC activation compared to neutral sounds. Since prior work has found the LC to be involved in attention (Ghosh & Maunsell, 2022), this may explain one mechanism in which emotional stimuli enhance visual task performance.

A potential explanation for why differences in pupil size in response to emotional sounds were not observed at time point 1 could be due to the response latency of pupil dilation. Previous studies have found that the pupil can take anywhere from 200 ms (Nakakoga et al., 2020) to 1250 ms (Babiker et al., 2013) to dilate after the onset of an emotional sound. Thus, differences elicited by emotional sounds may not be observable at time point 1 because the pupil has not had enough time to dilate. Another explanation could be that the emotional salience of the sound is not apparent at time point 1 and is only apparent from time point 2 onwards. To investigate this, a follow-up study was conducted to investigate whether participants were able to detect the emotional content of sounds (negative vs neutral) at time point 1 compared to time point 2. The results revealed that participants were only able to accurately identify the emotional content of negative sounds above chance levels at time point 2. This suggests that the emotional salience of negative sounds may only become apparent after time point 1, which may explain the slight delay in the pupil response.

Although previous studies have examined the impact of sound on visual performance (Clewett et al., 2018; Gleiss & Kayser, 2013; Jaekl & Soto-Faraco, 2010; Lippert et al., 2007), the current study is among the first to quantify the additive impact of sound and emotion on visual task performance compared to silence. Both negative and neutral sounds led to an enhancement in RT compared to silence. However, neutral sounds only

elicited an enhancement at the first two time points while negative sounds elicited this enhancement at all four time points. This replicates previous work finding that sounds produce an enhancement effect compared to silence (Kim et al., 2012; Lippert et al., 2007). Moreover, an ERP study examining the difference in auditory N1 after exposure to negative and neutral sounds found that negative sounds elicited a higher and more prolonged amplitude of N1 compared to neutral sounds (Folyi et al., 2016). For accuracy, sounds did not lead to significant differences compared to silence.

Pupil dilation exhibited a similar effect to RT in which negative and neutral sounds elicited significantly greater pupil dilation compared to silence but this increase was significantly greater for negative sounds compared to neutral sounds. Importantly, these effects are only observed after time point 1. This is in accordance with previous work that showed that pupil size increases in response to sound compared to silence (Frith, 1981). This extends prior work by showing that pupil size increases through exposure to sound but that this increase is accentuated by emotion. This suggests that negative sounds lead to a more prolonged increase in physiological arousal compared to neutral sounds. Further, pupil dilation exhibits a similar trend to RT suggesting that physiological arousal may act as a mechanism in which behavioral performance is enhanced.

These results suggest that negative sounds may elicit a more prolonged attentional enhancement compared to neutral sounds. Further, this suggests that the presence of sound elicits greater pupil dilation compared to silence and that this effect is accentuated by negative sounds. Taken together, these results suggest that the presentation of sound leads to an enhancement effect in visual performance and greater physiological arousal compared to silence but that these effects are greater and more sustained in the presence of emotional sounds. This may be because when visual stimuli and sounds are presented closely in time, their representations merge into one representation through multisensory integration (Jaekl & Soto-Faraco, 2010). Furthermore, as the stimulus onset asynchrony between the two stimuli grows, the advantage of sound in improving RT decreases. This is reflected in neutral sounds only enhancing RT at the initial two time points. In contrast, negative sounds resulted in enhancement in RT at all time points. This could be because

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emotion extends the multisensory binding window between the visual target stimulus and the sound.

11.1   Limitations and Future Directions

One limitation is that the negative sounds conveyed emotions ranging from sadness, disgust, and fear. As discussed previously, task performance may be affected differently based on the specific negative emotion elicited by the stimuli. For example, one study found that sad sounds elicited prolonged response times compared to angry sounds (Hjärtström et al., 2019). Additionally, research on spatial orienting found that participants displayed faster RTs when a visual target appeared on the opposite spatial side as disgusting sounds; however, an opposite effect was observed for fearful sounds (Zimmer et al., 2016). These results suggest that different negative emotions may affect task performance differently. Thus, future work should aim to disentangle the effects of each emotion on task performance. This study provides an experimental paradigm to examine cross-modal emotional enhancement of visual task performance. However, this study does not examine the areas that may be activated during cross-modal emotional enhancement. Insight into these areas would contribute to our understanding of the neural structures activated during emotional enhancement. Two key regions of interest include the amygdala and LC for their roles in processing emotion and modulating levels of arousal. Other areas of interest include the dlPFC and lateral parietal cortex for their roles in modulating attention and early visual areas. Future studies can investigate how these areas are activated during these processes by having participants perform the task during fMRI or by using transcranial magnetic stimulation to inhibit regions of interest.

Future research could also look to examine how trait anxiety influences the impact of emotional sounds on arousal and task performance. Past research has found that participants with high-trait anxiety have a more difficult time disengaging with negative sounds compared to participants with low-trait anxiety (Wang et al., 2019). Hence, patients with high trait anxiety may not display enhanced response times when exposed to spatially incongruent negative sounds. This research would allow us to gain a deeper

understanding of how patients with anxiety engage with the emotional stimuli in their environment.

11.2   Conclusions

The impact of emotional sounds on visual processing is complex and varies based on factors such as timing (Bocanegra & Zeelenberg, 2009) and spatial location (Zimmer et al., 2016, 2019). Understanding how these factors affect visual performance is crucial in gaining a deeper understanding of how human performance is affected in real-world emotional situations. The current study aimed to investigate how the emotion of sounds impacted arousal and task performance. This study manipulated both the timing and the spatial congruence of visual target stimuli during the presentation of emotional sounds to investigate how emotion, stimulus timing, and spatial congruence all impact visual task performance. We established that emotional sounds produce an enhancement in RT in an orientation detection task compared to non-emotional sounds. Moreover, this effect may be driven by attentional disengagement and avoidance of the spatial location of an emotional sound. As expected, we found that emotional sounds lead to greater arousal compared to non-emotional sounds. This suggests that the LC and amygdala may be involved in increasing visual attention and performance in response to emotional sounds. Future research is needed to determine how individual differences influence one's susceptibility to emotional enhancement and what neural processes are responsible for this enhancement. Overall, the current research extends the field by manipulating the emotion, timing, and spatial location of sounds to investigate the impact of sounds on human performance. This work lays the groundwork for gaining a deeper understanding of how human performance is affected in emotional situations such as in professional sports, aviation, and defense contexts.

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Appendices

Appendix A. Sound Information Chart

Sound ID	Valence	AroMN	AroSD	ValMN	Centroid (Hz)	RMS	Entropy	Onset Amplitude	Mean Harmonicity
115	Negative	6.21	1.98	2.13	882.37	0.16	0.69	0.05	6.57
379	Negative	7.80	1.71	1.28	5272.00	0.30	0.77	0.31	8.20
802	Negative	6.00	1.90	2.14	1456.39	0.14	0.68	0.10	0.47
463	Negative	6.05	1.70	2.82	2155.28	0.12	0.77	0.03	-2.73
789	Negative	6.71	1.85	2.04	2918.75	0.20	0.68	0.20	-2.87
281	Negative	6.72	1.81	1.80	1386.10	0.12	0.86	0.00	10.77
290	Negative	6.91	2.00	2.09	1560.23	0.12	0.74	0.10	6.76
292	Negative	6.32	1.73	2.18	1173.14	0.15	0.69	0.01	12.86
795	Negative	7.09	1.87	2.23	4649.36	0.27	0.77	0.00	29.44
422	Negative	6.71	1.37	2.67	2065.54	0.16	0.84	0.14	1.26
711	Negative	7.41	1.05	3.23	2213.34	0.17	0.78	-0.17	7.70
595	Negative	6.64	1.26	2.73	4010.53	0.07	0.84	-0.02	5.32
276	Negative	7.73	0.98	1.73	1949.69	0.17	0.81	0.00	9.24
699	Negative	6.80	1.80	3.04	1575.47	0.16	0.68	0.01	1.30
702	Negative	6.09	1.87	1.36	1483.72	0.14	0.79	0.02	2.01
167	Negative	6.64	1.79	2.86	1902.78	0.14	0.64	0.01	4.51
630	Negative	6.86	1.64	3.50	4092.98	0.20	0.85	-0.15	-3.18
1039	Negative	6.29	1.49	3.00	1602.41	0.26	0.48	0.32	11.63
1390	Negative	6.45	1.71	3.09	1877.24	0.10	0.66	-0.13	6.18
762	Negative	8.46	0.83	2.33	4604.85	0.26	0.86	0.46	1.06
102	Neutral	5.17	1.95	5.33	2466.63	0.08	0.71	0.13	18.07
107	Neutral	5.73	1.39	4.91	2079.16	0.05	0.80	0.12	2.53
113	Neutral	5.24	2.01	4.56	1243.43	0.16	0.70	0.23	12.56
836	Neutral	4.77	1.45	4.50	1339.18	0.13	0.65	0.07	2.15
206	Neutral	4.96	1.86	5.12	1245.85	0.14	0.86	-0.04	3.21
342	Neutral	4.52	1.45	4.32	602.78	0.18	0.51	0.21	-0.75
170	Neutral	4.12	1.67	4.76	3937.48	0.10	0.88	0.05	3.81
171	Neutral	3.50	1.26	5.32	2002.65	0.08	0.70	0.00	5.34
1005	Neutral	4.29	1.57	4.17	2110.87	0.11	0.75	0.01	1.18
403	Neutral	5.82	1.37	4.64	1599.66	0.10	0.81	0.09	-1.05
837	Neutral	4.96	1.46	4.83	3059.20	0.13	0.80	-0.04	-1.40
85	Neutral	4.00	1.69	4.50	542.57	0.11	0.46	0.09	-8.73
376	Neutral	5.33	1.58	4.33	3691.24	0.05	0.92	0.02	-2.11
417	Neutral	5.55	1.82	4.68	790.79	0.76	0.37	0.62	31.87
701	Neutral	3.92	1.56	5.33	2272.87	0.06	0.62	0.00	10.76
921	Neutral	4.95	1.73	4.95	2605.73	0.12	0.80	0.01	-1.77
278	Neutral	5.45	1.37	4.91	1356.00	0.02	0.84	0.01	-3.65
705	Neutral	4.14	1.36	5.82	2724.25	0.02	0.89	0.03	-1.71
233	Neutral	5.77	1.23	4.59	1784.01	0.16	0.67	0.14	4.47
886	Neutral	5.17	2.01	5.25	3021.09	0.05	0.82	0.06	-1.33

Appendix B. Baseline Accuracy Results

Variables	t	P-value
Negative Time 1 Accuracy	-0.909	0.369
Negative Time 2 Accuracy	1.203	0.236
Negative Time 3 Accuracy	-1.608	0.115
Negative Time 4 Accuracy	-1.686	0.099
Neutral Time 1 Accuracy	0.739	0.464
Neutral Time 2 Accuracy	0.539	0.593
Neutral Time 3 Accuracy	-0.887	0.380
Neutral Time 4 Accuracy	-0.538	0.593

Appendix C. Baseline Corrected Response Time, Timing X Congruence
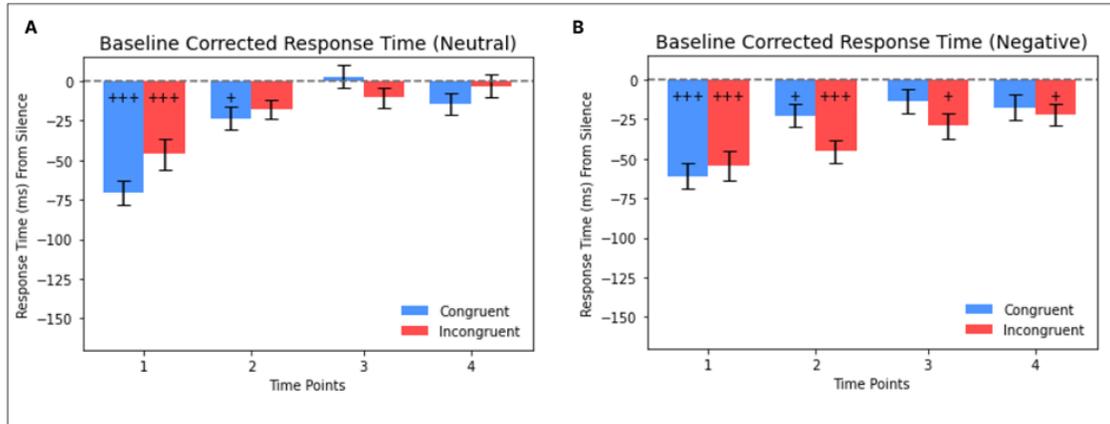
Figure 8. Depicts the response times in the neutral condition (a) and the negative condition (b) compared to baseline. Plus signs (+) indicate the degree to which the condition is significantly different compared to baseline. $^+p < .05;$ $^{++}p < .01;$ $^{+++}p < .001.$ *p < .05; **p < .01; ***p < .001

Appendix D. Duration on Valence Identification Results

Figure 9. The valence of negative sounds are accurately identified at medium durations but not short durations. Plus signs (+) indicate the degree to which the condition is significantly different compared to chance levels. $^+p < .05;$ $^{++}p < .01;$ $^{+++}p < .001.$ $^*p < .05;$ $^{**}p < .01;$ $^{***}p < .001$

Appendix E. Research Ethics and Approval Number

Western Research

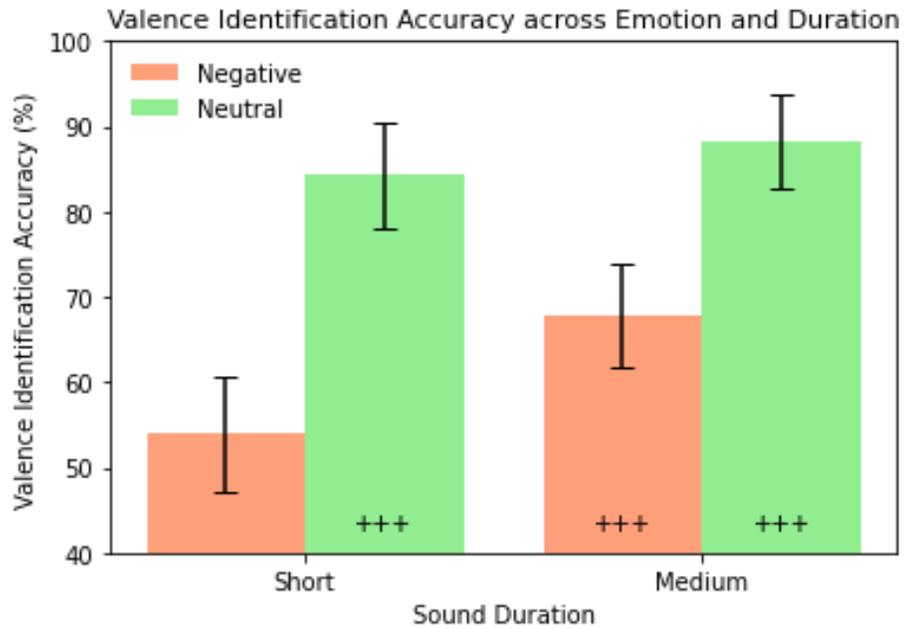**Date:** 20 September 2023

To: Dr. Derek Mitchell

Project ID: 113655

Review Reference: 2023-113655-84110

Study Title: Emotional distraction, focus, and control

Study Sponsor: Natural Sciences and Engineering Research Council

Application Type: HSREB Amendment Form

Review Type: Delegated

Date Approval Issued: 20/Sep/2023 12:31

REB Approval Expiry Date: 30/Apr/2024

Dear Dr. Derek Mitchell,

The Western University Health Sciences Research Ethics Board (HSREB) has reviewed and approved the WREM application form for the amendment, as of the date noted above.

Documents Approved:

Document Name	Document Type	Document Date	Document Version
Protocol_V4	Protocol	31/Aug/2023	4
Direction Rating Question	Online Survey	31/Aug/2023	4
Emotional distraction, focus, and control-- Consent (behavioural)_V5	Consent Form	15/Sep/2023	5

Documents Acknowledged:

Document Name	Document Type	Document Date	Document Version
Protocol_V4_TRACKED	Summary of Changes	31/Aug/2023	4

REB members involved in the research project do not participate in the review, discussion or decision.

The Western University HSREB operates in compliance with, and is constituted in accordance with, the requirements of the TriCouncil Policy Statement: Ethical Conduct for Research Involving Humans (TCPS 2); the International Conference on Harmonisation Good Clinical Practice Consolidated Guideline (ICH GCP); Part C, Division 5 of the Food and Drug Regulations; Part 4 of the Natural Health Products Regulations; Part 3 of the Medical Devices Regulations and the provisions of the Ontario Personal Health Information Protection Act (PHIPA 2004) and its applicable regulations. The HSREB is registered with the U.S. Department of Health & Human Services under the IRB registration number IRB 00000940.

Please do not hesitate to contact us if you have any questions.

Electronically signed by:

Melanie Munroe, Ethics Officer on behalf of Dr. Naveen Poonai, HSREB Chair, 20/Sep/2023 12:31

Reason: I am approving this document.

Note: This correspondence includes an electronic signature (validation and approval via an online system that is compliant with all regulations).

Page 1 of 1

Brian Wu

EDUCATION

MSc in Neuroscience   **2022 - Present**
University of Western Ontario

BSc (Honours) In Psychology And Neuroscience   **2018 - 2022**
University of Toronto
- Graduated with High Distinction

ACADEMIC HONOURS & AWARDS

NSERC CGS-M Scholarship	**2023 - Present**
Western Graduate Research Scholarship	**2022 - Present**
Neuroscience Research Day 2024 Presentation Award	**2024**
University of Toronto Scarborough Dean's List	**2020 - 2022**
University of Toronto Summer Research Award	**2020**

RESEARCH EXPERIENCE

Emotional Cognition Laboratory   **2022 - Present**
Masters Student - Supervisor: Dr. Derek Mitchell
- Led 2 behavioral experiments over the past 2 years on emotion and human performance
- Created experimental scripts using E-Prime software
- Integrated experimental scripts with eye-tracking software to collect pupillometry data
- Collected data from 50 participants using behavioral measures, online surveys, and eye-tracking
- Conducted data curation and statistical analysis of datasets of over 1.6 GB using R, Python, and SPSS
- Presented results at 2 poster presentations and 1 oral presentation

Ontario Brain Institute   **May 2022 - August 2022**
Neuroinformatics Analyst Intern
- Worked with research program partners to gather information about different data curation and data analytics tools
- Used Markdown and GitHub to create an open-source catalogue of over 190 neuroscience tools

- Created and presented Powerpoint to present and demo the catalogue to staff and Roche partners
- Expanded on pre-existing Powerpoints to create summary PowerPoints of the Integrated Discovery Program Brain-CODE data releases

cOgs1m Lab   **2021 - 2022**
Thesis Student - Supervisor: Dr. George Cree
- Developed a neural network of stereotyping in Python
- Brainstormed ideas on how to expand a neural network of impression formation
- Conducted literature reviews on current neural network models of person perception
- Experimented with learning rates, hidden units, and optimizers in a neural network using Tensorflow and Keras
- Wrote research paper on a neural network of impression formation
- Presented work at the NeuroXChange 2022 conference

Rozeske Lab   **2021 - 2022**
Research Assistant - Supervisor: Dr. Robert Rozeske
- Discussed articles related to the neuroscience of fear, social dominance, and psychopathology in lab meetings
- Created DeepLabCut pipeline in Google Collaborate to analyze mouse movements
- Produced DeepLabCut documentation for other lab members to utilize

Decision Neuroscience Laboratory   **2020 - 2022**
Supervised Study Student - Supervisor: Dr. Cendri Hutcherson
- Co-authored research paper on impression formation (submitted)
- Wrangled and analyzed data from experimental questionnaires using R
- Developed experimental surveys on Qualtrics
- Conducted literature reviews on impression formation

Decision Neuroscience Laboratory   **2019 - 2022**
Research Assistant - Supervisor: Dr. Cendri Hutcherson
- Programmed introduction of experiment questionnaires using Python and PsychoPy
- Engaged in weekly meetings and discussions about computational modeling, framing effects, dual process models, and effects of attention on decision making
- Executed experiments and collected data from participants using EyeLink
- Learned how to analyze EEG data using MATLAB

PUBLICATIONS

- Roberts, I.D., Wu, B., & Hutcherson, C.A. (submitted). Predictability increases interpersonal trust independent of expected value.

CONFERENCE ABSTRACTS AND PRESENTATIONS

- Wu, B., Stewart, E. K., Butler, B.E., & Mitchell, D.G.V. (2024, February). The impact of emotional stimuli on arousal and task performance. [Conference oral presentation]. Neuroscience Research Day 2024, London, ON, Canada. https://songsuwo.ca/nrd2024.
- Wu, B., Stewart, E. K., Butler, B.E., & Mitchell, D.G.V. (2023, November). The impact of emotional stimuli on arousal and task performance. Poster presented at Society for Neuroscience's Neuroscience 2023 Conference, Washington, DC.
- Wu, B., Stewart, E. K., Butler, B.E., & Mitchell, D.G.V. (2023, October). The impact of emotional stimuli on arousal and task performance. Poster presented at Joint Mental Health Research and Innovation Day 2023 Conference, London, ON.
- Cree, G. S., Yilma, R. M., & Wu, B. (2022, July). Representation matters: A PDP model of impression formation and person knowledge. Poster submitted to the 44th Annual Meeting of the Cognitive Science Society, Toronto, ON, Canada.
- Wu, B., & Cree, G, S. (2022, May). A Neural Network Model of Impression Formation [Conference oral presentation]. NeuroXChange Conference, Toronto, ON, Canada. https://www.nxc2022.ca/.

TECHNICAL & PROFESSIONAL SKILLS

- Proficient in Data Wrangling and Data Analysis using R (ANOVA, T-tests, Correlational Tests, Moderation Analyses, Data Plotting)
- Proficient in Python (Numpy, Tensorflow, Keras, DeepLabCut)
- Proficient in Data Analysis using SPSS (ANOVA, T-tests, Correlational Tests)
- Proficient in Qualtrics (Question Creation and Labeling, Answer Customization, Survey Flow Modification, Question Randomization)
- Proficient in MATLAB: EEGLAB
- Proficient in using Eye-Tracking Software: EyeLink
- Proficient in Markdown markup language
- Proficient in Microsoft Office: Word, Excel, PowerPoint, Teams

LEADERSHIP & VOLUNTEER EXPERIENCE

Society of Neuroscience Graduate Students　　　　　**September 2023 - Present**
Mentorship Committee Member

- Aided in the organization of social events that promote mentorship among the neuroscience graduate population

BrainHack Western 2023   **November 2023**
On-site Volunteer
- Helped organize food delivery and room maintenance throughout the duration of the conference

Psychological Health Society   **January 2021 - April 2021**
Neuroscience Academic Study Group Leader
- Created study guides with practice questions for midterm and final review
- Conducted study group sessions to go over course content and practice questions
- Collaborated with other Academic Study Group Leaders to hold and lead study group sessions.

The University of Toronto Canadian Asian Student Society   **2019 - 2021** President
- Held monthly social events to foster connection among the executive members
- Led a group of 15 executive members to create social events for the students on campus
- Promoted inclusion by creating a sense of community and belonging

PROFESSIONAL EXPERIENCE

Baskin Robbins - Scarborough, ON   **July 2020 - August 2021**
Server
- Worked independently in a high-paced environment
- Collaborated with others to ensure high-quality customer service
- Communicated with customers on a regular basis to ensure customer satisfaction

ADDITIONAL TRAINING

Teaching Assistant Training Program, Centre for Teaching and Learning, UWO

Animal Ethics Course, Department of Comparative Medicine, UofT

Hands-On Mouse Training Module, Department of Comparative Medicine, UofT

Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans