# ACTION EFFECTS ON THE PERCEPTION OF MULTISENSORY EVENTS

# ACTION EFFECTS ON THE PERCEPTION OF MULTISENSORY EVENTS

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# Abstract

Voluntary actions affect subsequent perception. For example, an action that precedes an auditory stimulus is perceived to have occurred later in time than is actually the case, while the auditory stimulus is perceived earlier in time. This effect is known as intentional binding. Current literature regarding action effects focuses on perception of a single sensory modality while the effects on perception of multiple modalities remain largely unknown. The present thesis explored how actions influenced the timing of perceived multisensory events. Additionally, this thesis investigated differences in voluntary compared to involuntary actions on subsequent perception. In Chapter 2, action effects on perceived onsets of visual and tactile stimuli were explored. This question was extended to other bimodal pairs, including audiovisual and audiotactile, in Chapter 3. Lastly, in Chapter 4, action effects on temporal resolution were investigated.

In all the experiments, participants performed a chosen or a fixed button press that followed a bimodal temporal order judgment (TOJ) task. To investigate the influence of spatial proximity between actions and stimuli on binding, in Chapters 2 and 3, each stimulus modality appeared on different sides. In Chapter 4, the critical stimuli appeared at the same location, either close to or far from the preceding action, to explore the effect of action on temporal resolution. The present data provide evidence that actions affect the perceived onsets of multisensory events in an idiosyncratic manner, depending on the subsequent stimuli. Actions appear to preferentially bind to vision, then touch, and lastly, audition, but actions do not always bind to subsequent stimuli. Furthermore, actions degrade temporal resolution of bimodal stimuli. Lastly, the type of action, whether chosen or fixed, did not impact the degree of binding. Together, these data contribute to the action-perception literature, illustrating that our behaviours dynamically affect how we perceive the world.

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# Table of Contents

## List of Tables and Figures

Chapter 2

Chapter 3

Chapter 4

Chapter 5

## List of Abbreviations

ANOVA: analysis of variance

JND: just noticeable difference

PSS: point of subjective simultaneity

TOJ: temporal order judgment task

SOA: stimulus onset asynchrony

TMS: transcranial magnetic stimulation

## Declaration of Academic Achievement

This thesis was written in the format of a "sandwich" thesis. The empirical Chapters 2–4 are intended to be formatted for submission. I am the primary author of the entire dissertation under the supervision of David Shore. The research questions of the empirical chapters along with the experimental design were developed with the help of my supervisor, David Shore. The set-up and design of the stimuli were accomplished with the help of David Shore, and Miroslav Cika. For all the empirical chapters, I programmed the experiments, analyzed all of the data, and created all of the graphs and figures.

Data collection was completed with the assistance of undergraduate students. For Chapter 2, I collected all of the data. For Chapters 3 and 4, data collection was completed with the help of Zachary Livshin and Carleigh Piché.

# Chapter 1: Introduction

Successful interactions with our surrounding require coordinated actions and perceptions. The simple act of walking requires coordination of leg movements with perceptual surroundings, including information regarding steepness and texture of the ground. To anticipate consequences of our behaviours, we must be aware of the temporal onsets and overall timing of events (Press, Berlot, Bird, Ivry, & Cook, 2014; Hommel, 1996). Imagine an individual about to cross the road at a busy intersection—he pushes a button to signal the light to switch from red to green; the switching stoplight is a direct consequence of a preceding action (the button press). On the other hand, an individual who approaches a crosswalk and observes the stoplight change from green to red must stop to avoid dangerous crossing; a preceding sensory signal provides the observer with necessary information to act upon. Although understanding onsets and order of events may appear trivial, many internal and external factors influence this ability. Precise temporal estimates can enhance our experience with the environment. In this thesis, I investigate how self-generated actions influence perceived timing of multisensory events.

## 1.1 The Perception of Time: Models of Time Keeping

The experience of time is ubiquitous; it underlies all of our encounters and interactions, yet it is not easily measured or quantified (Orenstein, 1969). Temporal estimates are subjective constructs of the brain based on relative relations between the observer and events (c.f., van Wassenhove, 2009; Eagleman, 2008). The underlying mechanisms of temporal perception are poorly understood (Eagleman et al., 2005). Early theories on temporal encoding centered on the biological system as a timekeeper (e.g., Hoagland, 1933). The observation that temporal durations were dilated as a function of body temperature implicated a "master clock" linked to metabolic processes (Hoagland, 1933). In later models, emphasis was shifted from biological functioning to cognitive mechanisms in time keeping (Orenstein, 1969; Poynter & Homa, 1983; Fraisse, 1963).

Temporal processing is malleable and is governed by cognitive mechanisms (c.f., Brown, 1965). Perceived durations do not necessarily coincide with clock time and are subject to illusions (Poynter & Homa, 1983; Eagleman, 2008). The filled-duration illusion—the observation that intervals filled with numerous stimuli lead to an overestimation of duration (Fraisse, 1963)—was one of the first illusions to shift theoretical thinking from biological to cognitive. The illusion occurs with visual, tactile and auditory stimuli (Fraisse, 1963). Crucially, temporal dilatation following the presentation of increased stimuli could not be linked to bodily functions, and instead, was attributed to available memory storage space (Orenstein, 1969). According to the storage space model, complex or numerous events increase awareness and require more space, and are therefore perceived as occurring for longer durations (Orenstein, 1969). Later research demonstrated cases in which numerous events did not lead to overestimation—however overestimation was reported when stimuli increased in speed and motion (Brown, 1995). Illusory temporal estimates were then attributed to changing stimuli instead (Brown, 1995; Poynter & Homa, 1983). These early attempts to explain factors influencing temporal judgments do not account for how time is measured as a whole.

How time is perceived in the brain remains poorly understood. One underlying question regarding temporal perception is whether time is coded via one central time-keeping mechanism, or rather, whether time is encoded through intrinsic mechanisms that are dispersed in the brain (e.g., see Muller & Nobre, 2014 for a review). It is possible that a combination of temporal encoding mechanisms exist. Although the primary focus of this thesis is not to understand time-keeping mechanisms, but to understand how actions influence the perceived timing of events, considering this background literature will allow the application of the present thesis findings in the context of temporal perception in the brain.

A prevalent time-keeping model is the internal pace maker model (Treisman, 1963; Hodinott-Hill, Thilo, Cowey, & Walsh, 2002; Tse, Intriligator, Rivest, & Cavanagh, 2004). The internal pacemaker model assumes a centralized amodal timekeeper that computes the number of "ticks" per unit of time to generate temporal estimates (Treisman, 1963; Hodinott-Hill et al., 2002; Tse et al., 2004). Upon encountering a stimulus, a pacemaker produces pulses that are computed by a "counter" and compared with measures within stored memory to construct a temporal estimate (Treisman, 1963; Muller & Nobre, 2014). This model assumes time is computed in a linear manner. It can account for some temporal distortions (e.g., Muller and Nobre, 2014). The amount of information processed per unit of time influences the amount of "ticks" computed by the counter. For example, with increased information processing (such as following increased arousal), the internal clock computes more units per time resulting in subjective temporal expansion (Eagleman, 2008; Tse et al., 2004). In contrast, temporal compression occurs when the pacemaker computes fewer ticks, so less information is processed (Eagleman, 2008; Tse et al., 2004).

The state-dependent network model posits that temporal information is coded through changes in neuronal activity through time (Buonomano & Merzenich, 1995; Karmarkar & Buonomano, 2007). According to this model, local neural circuits code for spatiotemporal information and changes in neural trajectories provide temporal estimates (Buonomano & Merzenich, 1995). In other words, stimulus inputs lead to specific neuronal firing patterns that are based on the stimulus's spatial and temporal properties. As some neurons continue to fire through time, they activate other neurons. The overall changes in neuronal activity through time, code for temporal information (Buonomano & Merzenich, 1995). A commonly used analogy to describe this model refers to changes in water ripples following a toss of a stone—the temporal and spatial patterns of the ripples can be used to determine when the stone was thrown (Karmarkar & Buonomano, 2007). Unlike the pacemaker model that assumes time is centrally encoded, the state-dependent network model assumes time is coded within local cortical circuits (Karmarkar & Buonomano, 2007).

The internal timekeeper and state-dependent models may work in concert rather than being mutually exclusive (Eagleman et al., 2005). Estimates obtained from quick neuronal activity changes may account for very short intervals (10s to 100s of ms), while slightly longer intervals may be obtained via the centralized pacemaker (Karmarkar & Buonomano, 2007; Eagleman et al., 2005). Further research is required to empirically support these models. Again, although the present thesis did not focus on the mechanisms of time keeping, studying actions' influence on perceived timing of events could provide a deeper understanding on how temporal information is encoded. The relation of the present thesis findings to time-keeping mechanisms will be addressed in the General Discussion (Chapter 5).

## 1.2 Temporal illusions

Producing accurate temporal estimates is difficult. Stimulus properties impact temporal estimates, making temporal judgments prone to illusions (Eagleman, 2008). Overestimates of temporal intervals have been reported during saccades (Morrone, Ross & Burr, 2005; Yarrow, Haggard, Heal, Brown & Rothwell, 2001), while viewing novel/oddball stimuli (Tse et al., 2004; Pariyadath & Eagleman, 2008**)**, while viewing moving stimuli (Brown, 1995), during arousal and during frightening events (Hodinott-Hill et al., 2002; Stetson, Fiesta, & Eagleman, 2007) and after executing a motor movement (Park, Schlag-Rey, Schlag, 2003; Press et al., 2014). It is evident that temporal perception is a dynamic process, influenced by external factors.

One temporal illusion commonly reported in the literature is chronostasis (or the "stopped clock" illusion) (Hodinott-Hill et al., 2002; Morrone, Ross, & Burr, 2005; Yarrow et al., 2001). In this illusion, time appears frozen when first looking at an analog clock—the seconds hand appears stationary at a first glance leading to an overestimation of time (Morrone et al., 2005). Temporal expansion during chronostasis was first attributed to the brain compensating for time "lost" during a saccade (Morrone et al. 2005; Yarrow et al., 2001). However, chronostasis-like effects have been reported within the auditory and tactile modalities (Hodinott-Hill et al., 2002; Yarrow & Rothwell, 2003).

Temporal illusions like chronostasis illustrate the malleability and subjectivity involved in temporal perception.

Temporal dilation occurs as a function of increased arousal. Executing motor movements and viewing novel stimuli increase levels of arousal (Park et al., 2003; Tse et al., 2004). Observers judged visual stimuli to last longer after executing a motor movement compared to when no motor movement was executed (Park et al., 2003). Similarly, tactile and visual stimuli were judged to last longer when the stimuli appeared at the same location of a preceding finger movement, but not if they appeared at the location of a neighbouring stationary finger (Press et al., 2014). Temporal expansion also occurs after viewing novel stimuli. An oddball stimulus presented in a stream of high probability targets is perceived to last longer (Tse et al., 2004). As mentioned earlier, the pacemaker model can account for these types of temporal distortions. Raised arousal levels following an action or after viewing a novel event may lead to more ticks counted by the pacemaker, leading to an increase in information processing, and ultimately, perceived temporal expansion (Park et al., 2003; Hagura, Kanai, Orgs, & Haggard, 2012; Tse et al., 2004). In the present thesis, I was particularly interested in the effect of motor movement on the relative temporal perception of multiple modalities.

## 1.3 Perceiving Multiple Modalities

Efficient interaction with objects requires observers to decipher stimuli belonging to multiple events from those that are part of a single event. Low-level stimulus properties and high-level expectations influence whether multiple stimuli are perceived as bound or segregated (Vatakis & Spence, 2007). Low-level properties are based on the temporal and spatial relations between stimuli. For example, stimuli presented close together in space or in time are more likely to be perceived as concurrent or belonging to one object (Jackson, 1953; Vatakis & Spence, 2007; Nicol & Shore, 2007). These spatial and temporal laws have also been observed crossmodally (Spence, Shore, & Klein, 2001; Zampini et al., 2003; Kitawaga, Zampini, & Spence, 2005). Audiovisual and visuotactile stimuli presented close together in external space are more likely to be perceived as belonging to a single percept compared to when presented a larger distance apart (Spence et al., 2001; Zampini et al., 2003). In contrast, audiotactile stimuli presented in external space are not bound together as a function of spatial location (Zampini, Brown, Shore, Maravita, Roder, & Spence, 2005). However, the spatial law does apply for audiotactile stimuli presented in proximity—auditory and tactile stimuli presented on the same side of the head, but not to different sides of the head, were more likely to be perceived as occurring concurrently (Kitawaga et al., 2005). Similarly, stimuli appearing close in time are more likely to be attributed to a single object (Vatakis & Spence, 2007). In nature, temporal and spatial coincidence often indicates stimuli belong to the same object, thus, brain mechanisms allow such proximate stimuli to be seen as a single percept.

Our expectations and previous experiences (high-level properties) also influence temporal processing of stimuli. The assumption that two objects *should* belong together encourages binding (Jackson, 1953; Vatakis & Spence, 2007). For example, observers were more likely to perceive a bell and a light as a single event when they were presented from the same angle (Jackson, 1953). As the angle of separation between the bell and light increased, binding was less likely to occur; this was due to a prior expectation that the sound should accompany the location of the bell (Jackson, 1953). The role of expectation on the unity assumption was also demonstrated with other, more ecologically valid, stimuli (Vatakis & Spence, 2007). Participants performed an audiovisual temporal order judgment (TOJ) task for sex-matched or sex-mismatched voices and faces. Participants had more difficulty reporting which modality they observed first when the sex of the speaker matched the sex of the voice compared to when the sex of the speaker did not match the sex of the voice. Prior expectation influences our perception—stimuli are more likely to be observed as simultaneous if a prior assumption that they occur together exists.

### 1.4 The Role of Expectation on Perceived Temporal Order of Stimuli

Expectation also influences the perceived order of events (Eagleman, 2008; Harrar & Harris, 2008). For example, observers were continuously exposed to either a condition in which a light stimulus preceded a sound stimulus separated by a fixed SOA, or a condition in which a sound stimulus preceded a light stimulus separated by a fixed SOA. At test, observers were more likely to perceive stimuli in the same order as during exposure (Vroomen, Keetels, de Gelder, & Bertelson, 2004; Harrar & Harris, 2008). Similarly, when participants repeatedly viewed a light following a sound and then performed an audiovisual temporal order judgment (TOJ) task or simultaneity judgment task, they were more likely to perceive the light as occurring before the sound. This is contrary to the fact that sounds are generally perceived before lights (c.f., King, 2005; Zampini et al., 2003). Together, these finding suggest a flexible and dynamic mechanism for temporal encoding that is based on experience.

Actions can also influence temporal recalibration of event order (Stenson, Cui, Montague & Eagleman, 2006). Participants repeatedly executed an action and a flash either followed immediately after the action or after a 100 ms delay. Upon adaptation, exposure to an immediate light (with no delay) following the action led participants to falsely view the light as occurring *before* the action (Stenson et al., 2006). Prior expectation as a result of adaptation led to motor-sensory recalibration. It is evident that temporal order of events can be recalibrated for both sensory modalities presented together and for sensory modalities presented with actions. These findings implicate shared qualities between actions and sensory stimuli. In Chapters 2 and 3, I further investigate the impact of spatial separation between action and stimuli to investigate if actions follow the spatial rule of integration similar to multiple stimuli.

## 1.5 Common-Coding between Action and Perception

Actions and perceptions share common codes (Hommel, 1996; Hommel, 2004; Musseler & Hommel, 1997; Zmigrod, Spapé, & Hommel, 2009). Perceptual events that frequently follow motor movements form a contingency and are stored together as “event files” (Hommel, 2004). The event files contain information of context, along with the perceptual and motor representations of that event (Hommel, 2004). Under the common-coding assumption, actions and related perceptions should influence each other bi-directionally, so planning or executing an action that share codes with a stimulus feature may either impair or aid performance (Prinz, 1997). A code that is in use for planning an action would impede identification of related stimulus features. In contrast, performing an action while observing complementary perceptual features may enhance performance (Prinz, 1997; Hommel, 1996; Zmigrod et al., 2009).

Executing actions while viewing related stimulus features can either impair or enhance performance (Hommel, 1993; Hommel, 1996; Zmigrod et al., 2009). Observers executed left or right button presses in response to visual lights (Hommel, 1996). At the same time, they were presented with auditory stimuli previously associated with the action location, and were instructed to ignore the tones. Left button presses were associated with low-pitched tones, while right button presses were associated with high-pitched tones (Hommel, 1996). Notwithstanding instructions to ignore the tones, participants revealed faster reaction times for tones compatible to the to be-signaled action location. Similarly, after contingencies were formed between actions and stimulus features, slower reaction times were observed for partially repeated stimulus features (Zmigrod et al., 2009). For example, if an action became associated with a certain event (e.g., high-pitch and blue stimulus), then presenting participants with partial event features (e.g., high-pitch and red stimulus) resulted in slower reaction times than presenting participants with complete repetition (high-pitch and blue stimulus) or no repetition (e.g., low-pitch and green stimulus). Activation of previous event codes resulted in interference (Zmigrod et al., 2009). Together, these findings indicate a common storage space for motor events and perceptions.

Stimulus identification also suffers when a particular code is busy with action planning (Prinz, 1997; Musseler & Hommel, 1997). Identifying the direction of a briefly presented arrow while preparing a spatially compatible or incompatible button press revealed slower reaction times when the arrow direction and action location matched (Musseler & Hommel, 1997). A transient decrease in sensitivity was observed when action planning and stimulus identification shared features (Musseler & Hommel, 1997). Together, these findings support a neural link between actions and perpetual features (Zmigrod et al., 2009; Prinz, 1997; Hommel, 1996; Hommel, 1993). Shared codes between actions and sensory stimuli implicate the possibility for actions and stimuli to adhere to similar perceptual rules.

## 1.6 Action and the Rules of Multisensory Integration

It is possible that actions can follow the same laws of multisensory integration as observed with sensory stimuli (Vallet & Shore, unpublished). Under this assumption, actions presented in close space and/or time to sensory stimuli would be bound as one event. In support of the assumption that action can follow the multisensory rules of integration, executing a button press slightly before the presentation of a tone led the tone to be perceived earlier in time, while the action was perceived later in time (Haggard, Clark, & Kalogeras, 2002). In other words, a motor movement executed close in time to stimulus presentation resulted in binding between the action and the tone. Similarly, motor movements performed immediately prior to an audiovisual TOJ task led to faster visual perception (Vallet and Shore, unpublished). In audiovisual TOJ tasks, visual stimuli generally need to lead auditory stimuli for the two modalities to be perceived as occurring simultaneously (Zampini, Shore, & Spence; Vroomen, Keetels, de Gelder, & Bertelson, 2004). However, visual stimuli presented immediately following an action, but not delayed by 500 ms, required auditory information to lead visual information to achieve simultaneous perception (Vallet and Shore, unpublished). This implies that motor movements presented close in time to audiovisual stimuli bind to the visual modality (Vallet and Shore, unpublished).

The effect of space on binding between motor movements and sensory stimuli has produces mixed findings (e.g., Vallet & Shore, unpublished; Press et al., 2014). The spatial distance between finger movements and tactile or visual targets influenced duration judgments (Press et al., 2014). Tactile and visual targets delivered to the location of a moving finger (e.g., index finger) as opposed to a neighboring stationary finger (e.g., middle finger of the same hand) resulted in temporal dilation (Press et al., 2014). However, the study did not specifically address the spatial relation of the action relative to the stimulus, but rather the effects of observing a sensory stimulus at the location of the movement versus at a location without action. Consequently, the findings may reflect high-level properties that are expectation based (Hommel, 1996; Press et al., 2014) rather than low-level binding based on spatial location. Vallet and Shore (unpublished) also manipulated the location of the button press relative to sensory stimuli locations and did not observe a spatial binding effect; executing actions either close or further away from visual and auditory stimuli locations did not influence binding. It remains unclear whether this finding reflects a general rule of action-binding effects, or rather, whether spatial/temporal binding between actions and stimuli depend on the modality that follows the action. Actions could follow the temporal and spatial law for some sensory modalities but not others. This possibility is further investigated in Chapters 2 and 3.

## 1.7 The Link Between Action and Perception

The observation that motor movements can influence subsequent perception challenges traditional views of perception as a passive process, independent of behaviour (Witt, 2011). Anecdotal reports by professional athletes suggest that perceptions are altered during performance (Murphy & White, 1978). For instance, batters describe the ball slowing down as it flies toward the bat (Murphy & White, 1978). A dynamic interplay between motor and perceptual processes has been observed experimentally. Subjects perceived a ping-pong ball as moving slower when playing with a larger paddle, and a hill as being steeper when carrying a heavier load (c.f., Witt, 2011). Rather than perception providing a passive representation of our environment, perception instead appears to be influenced by individual abilities and goals (Witt, 2011).

Behavioural evidence supports the influence of action on subsequent visual processing (Fagioli, Hommel, & Schubotz, 2007; Wykowska, Schubo, & Hommel, 2009; Hagura et al., 2012; Vallet & Shore, unpublished). In a size or location discrimination task, faster reaction times were revealed when a preparatory hand configuration matched the parameters of the target (Fagioli et al., 2007; Wykowska et al., 2009). In addition, observers identified targets presented via rapid serial presentation faster if a reaching action was performed prior to identification as opposed to no action performed prior (Hagura et al., 2012). Executing or preparing an action prioritizes and enhances early stages of processing for relevant stimuli (Wykowska et al., 2009; Hagura et al., 2012).

Motor movements also influence subsequent processing of auditory information (Haggard et al., 2002; Haggard & Clark, 2003; Haggard & Cole, 2007). Participants judged temporal onsets of either a voluntary action or a subsequent tone; voluntary actions were judged to occur later in time while tones were judged to occur earlier in time (Haggard et al., 2002; Haggard & Clark, 2003; Haggard & Cole 2007). This effect, known as "intentional binding", represents a pulling together between the action and the tone (Haggard et al., 2002; Haggard & Clark, 2003; Haggard & Cole 2007). In contrast, when the action was involuntary, or induced via transcranial magnetic stimulation (TMS), then the action and the tone appeared to repulse from each other—the opposite of an intentional binding effect (Haggard et al., 2002; Haggard & Clark, 2003; Haggard & Cole 2007). Different action types, whether voluntary or involuntary, appear to have differential effects on binding. The intentional binding effect observed after voluntary movements has been robustly replicated within the auditory, visual, and tactile modalities (Strother, House, & Obhi, 2010; Engbert, Wohlschlager, Thomas & Haggard, 2007; Engbert, Wohlschlager, & Haggard, 2008; Moore, Lognado, Deal, & Haggard, 2009). The differential effects of voluntary actions versus involuntary actions on perception will be further addressed later on in this chapter.

The existing literature regarding action effects on perception focuses on single sensory modality presentation (Haggard et al., 2002; Haggard & Clark, 2003; Haggard & Cole, 2007; Strother et al., 2010; Engbert et al., 2007; Fagioli et al., 2007; Wykowska et al., 2009; Press et al., 2014). However, perception is seldom unimodal—and often requires information be combined across multiple modalities (Vatakis & Spence, 2007). Based on the current literature, it is difficult to predict how actions would influence subsequent perception of more than one modality.

As discussed above, executing actions speeds up subsequent visual perception, and separately, subsequent auditory perception. However, how would action affect subsequent perception of multiple modalities? It is unclear whether actions would speed up perception of one modality over another, or both modalities equally. One study (discussed above) did look at action effects on multiple (audiovisual) modalities (Vallet & Shore, unpublished). While they concluded that visual information was processed sooner than auditory following a button press, this effect has yet to be replicated. Replicating this effect with a different experimental design would implicate the robustness of action effects on audiovisual perception and would rule out the possibility that the effect is based on equipment or methodology. Crucially, perception of multiple stimuli involves discrete mechanisms for each bimodal combination (Harrar & Harris, 2008). It is therefore possible that actions may have different effects on other competing bimodal pairs. The effect of action on perception of competing bimodal stimuli is the main topic of this thesis.

## 1.8 The Link between Action and Attention

Action and attention are linked—actions influence attentional capture (Gherri & Eimer, 2010; Press et a., 2014; Tipper, Lortie, & Baylis, 1992, Welsh & Pratt, 2008). The association between motor mechanisms and attentional processes has been observed empirically. First, hand positions impact how target and distractor stimuli influence performance—hand movements near distractors result in more interference than hand movements further away from distractors (Tipper et al., 1992). This observation indicates an action-centered representation of selective attention—action and target characteristics interact to influence attentional capture (Tipper et al., 1992). Furthermore, distractors interfered more when actions required sustained attentional processes compared to actions that did not require continuous flow of information (Welsh & Pratt, 2008). Lastly, an inability to focus attention to a point in time led to poorer temporal estimates of voluntary motor onsets (Haggard & Cole, 2007). Subjective reports of event onsets were most accurate if participants were informed in advance of which event time they would be required to report compared to retrospective reports. Advanced knowledge of the to-be-reported event enabled participants to direct attentional processes to a point in time so that temporal estimates of actions and perceptions were improved (Haggard & Cole, 2007).

Action and attention may also be linked on a neural level. As observed with electrophysiological data, performing motor movements at a specific location automatically directs attention to the same location (Gherri & Eimer, 2010). The ERP components associated with spatial attentional shifts and sustained attention were evoked when actions were performed at cued locations, but not when actions were performed at a location opposite to the cue. These findings implicate an obligatory link between spatial attention and response preparation and execution (Gherri & Eimer, 2010). Together with the behavioural evidence, an association between motor and attentional systems is further supported. Accordingly, it is possible that motor movements and attention may act in similar ways on perception. This issue is further addressed in Chapter 4.

### 1.9 The effects of Attention on Temporal Processing

Attentional mechanisms influence perception (Spence et al., 2001). According to the law of prior entry, attended events are perceived sooner than non-attended events and this is true for multisensory events—attending to one modality speeds up perception of that modality relative to a non-attended modality (Spence et al., 2001). Whether attention also influences temporal resolution remains disputed. Research investigating the role of attention on the ability to accurately judge order of two stimuli remains divided (Spence et al., 2001; Stelmach & Herdman, 1991; Yeshurun & Levy, 2003). If attention and action systems are related, then it is important to understand attentional influences on perception as a part of predicting the effects of action on perception.

The effect of spatial attention on temporal precision has produced mixed findings. Attention may enhance temporal resolution—Stelmach and Herdman (1991) demonstrated participants were better at determining order of visual targets at cued compared to uncued locations. In contrast, attention may diminish temporal resolution—Yeshurun and Levy (2003) showed that observers exhibited a degraded ability in detecting a temporal gap presented between two visual targets at attended locations compared to unattended ones. Alternatively, spatial attention may not impact temporal resolution at all. Spence et al. (2001) did not observe a difference in temporal precision for targets presented at attended compared to unattended locations. Differences in experimental designs may explain the conflicting findings. Attentional effects on temporal resolution appear to be contingent on the nature of the stimuli (Nicol, Watter, Gray, & Shore, 2009). In a visual TOJ task, exogenous attention enhanced temporal resolution based on target characteristics. For example, greater temporal resolution was revealed for stimuli that were distinct from one another and were presented at different locations. In contrast, stimulus characteristics that encouraged perceptual grouping (i.e., stimuli were viewed as one object), produced opposite effects of exogenous attention (i.e., diminished temporal resolution; Nicol et al., 2009). Although the direction in which attention affects temporal resolution is unclear, it is evident that spatial attention has an influence on temporal resolution. The question remains as to whether action will also demonstrate an influence on temporal resolution. Chapter 4 of the present thesis addresses this question.

### 1.10 Voluntary versus Involuntary Actions

The way in which we perceive our actions impacts how we perceive the world. The perception of control provides the observer with the ability to set goal oriented behaviours (c.f., Moore & Obhi, 2012). According to the causality hypothesis, events occurring nearby motor movements are perceived as being causal (Moore & Obhi, 2012; Obhi & Haggard, 2004). But is volition necessary to experience control? The way in which we experience control over our behaviours is poorly understood.

Early attempts to understand the mechanisms involved in the sense of motor control, investigated neural correlates evoked prior and/or during self-evoked actions. In one study, observers made voluntary hand movements while measuring EEG activity and reported one of three events: the point at which they experienced the intention to move, the point at which they initiated the motor movement, or the point at which they experienced the sensation of the movement (Libet, Gleason, Wright, & Pearl, 1983). The readiness potential (RP) (a negative potential that occurs about 1 second (or more) prior to a motor movement)—is an index of preparatory activity (Libet et al., 1983). Unexpectedly, Libet et al. (1983) observed that subjective intentions to act were reported as occurring over 300 ms *after* the RP. Those data implicated preparatory cerebral activity as a *cause* of intention to act, bringing the existence of free will into question (c.f., Obhi & Haggard, 2004).

Preparatory cerebral activity as a cause rather than effect of intention to act was disputed in later work (Haggard & Eimer, 1999). Haggard and Eimer (1999) followed Libet and colleagues' (1983) procedures while measuring an additional component, the lateralized readiness potential (LRP). The LRP develops in the hemisphere opposite to the action location, and is therefore a more specific and precise correlate of the intention to act. Haggard and Eimer (1999) also differentiated between actions that were voluntary (participants decided the hand to be used) or actions that were fixed (participants were instructed on the hand to be used). Consistent with Libet et al.'s (1983) findings, RP activity was observed prior to reports of intention to act. However, the LRP activity coincided with reported intention to act. Therefore, intention to act may be self-produced rather than a consequence of preceding brain activity. Secondly, no differences in cerebral activity were observed for free versus fixed actions—the type of action, whether free or fixed, might not affect subsequent perception in discrete manners (Haggard & Eimer, 1999).

Whether action type (voluntary or involuntary) impacts subsequent perception in different ways continues to be debated. Haggard et al. (2002) first reported the intentional binding effect between actions and tones as occurring only after self-produced (voluntary) actions, but not TMS-induced actions. The intentional binding effect has been replicated across the visual and tactile modalities since, but the mechanisms that govern the intentional binding effect remain disputed (Strother, House & Obhi, 2010; Engbert, Wohlschlager, Thomas, & Haggard, 2007; Engbert, Wohlschlager, & Haggard, 2008; Moore, Lognado, Deal, & Haggard, 2009). On one end of the argument, the feeling of agency, or feeling of control over the action, is a prerequisite for intentional binding (Haggard et al., 2002; Engbert et al., 2007; Engbert et al., 2008). For example, Engbert et al. (2007) found that the intentional binding effect was stronger (i.e., subject judged the interval between the action and consequence as being shorter) when motor movements were self-generated compared to observing motor movements as other-generated, or those generated with a rubber hand. The feeling of agency as a prerequisite of intentional binding was observed for both external stimuli (lights or sounds) and internal (tactile perception of own body) sensory consequences (Engbert et al., 2008). In contrast, the *intention* to act may be a sufficient condition for binding. No differences in binding effects were observed for self-generated actions compared to other-generated actions as long as the intention to act was present (Strother et al., 2010). The necessary conditions required for intentional binding of actions and consequences remain indeterminate.

Neuroimaging studies looking at differences in activity between free and forced actions have also failed to reach consensus. Distinct patterns of activity in the sensory cortices were revealed preceding chosen (free) button presses compared to fixed (forced) button presses (Kostelecki, Mei, Dominguez, & Velazaquez, 2012). On the other hand, no difference in prefrontal cortex (PFC) activity, associated with planning and attentional processes, was observed for the different action types (Kostelecki et al., 2012). Free and forced action types appear to involve some common and some distinct processes, which may be contingent on the stage of the motor activity. For example, the initiation process of the different motor movements may be distinct, but later planning stages may involve the same processes. In contrast, there was no observed difference in LRP correlates (associated with action initiation) for free compared to fixed actions (Haggard & Eimer, 1999). The discrepancies in the literature may be due to varying cross-experimental methodologies and neuroimaging techniques. It is unclear what discrete stage of motor movement is measured through each neuroimaging technique. The effects of free versus forced actions on subsequent perception clearly require further exploration. An attempt to differentiate between different action type effects on subsequent perception is explored in Chapters 2 and 3.

### 1.11 Temporal Order Judgment Task

The subjective nature of temporal perception makes it difficult to measure objectively. The temporal order judgment (TOJ) task is one method by which objective temporal judgments can be obtained. In this task, participants are typically presented with two stimuli, separated by varied stimulus onsets asynchronies (SOAs) and they must decide the order of stimulus presentation. The TOJ task can be performed with a variety of stimuli, including stimuli of different sensory modalities. An underlying theoretical assumption of the TOJ task is that it is a reliable measure of temporal perception of events. While other processes may govern TOJ performance (e.g., sensation, comparison, and decisional processes), the present work assumes that ultimately these processes represent perception. In Chapters 2, 3, and 4 I utilize a bimodal TOJ task to measure action effects on multisensory temporal processing. It is assumed that by comparing performance on the

TOJ task when a prior action is executed to when no action is performed, a reliable measure of differences in perceptual processing is obtained.

Two informative measures can be computed from a TOJ task—the just noticeable difference (JND) and the point of subjective simultaneity (PSS). The JND represents the smallest temporal interval required between the stimuli to accurately judge order on 75% of the trials (e.g., Shore & Spence, 2005). The PSS indicates the separation time required between the two stimuli to perceive them as occurring simultaneously. In other words, it represents the point in time at which observers equally report each modality as occurring first (Shore & Spence, 2005). The two measures provide independent indices of performance, and can be indicative of the impact of different variables of interest on temporal processing (Spence et al., 2001).

The JND represents temporal precision—higher accuracy in judging the order of two stimuli is reflected as smaller JND scores. On the other hand, increased difficulty in indicating the order of stimuli would require a larger temporal window between stimuli to achieve an accurate judgment, and would therefore be reflected as higher JND scores (Spence et al., 2001; Shore & Spence, 2005). The PSS score represents the time by which one stimulus must lead another to perceive them as concurrent (Shore & Spence, 2005). Varied travelling speeds and transduction rates across modalities lead to differences in processing rates of each modality (King, 2005; Shore & Spence, 2005). While this baseline difference may appear negligible in our daily interactions, in a TOJ task this difference is reflected in the PSS score. In Chapters 2, 3, and 4, PSS and JND measures were used to calculate how actions influence temporal processing rates of different modalities. Again, the PSS and JND measures are assumed to represent differences in processing rates.

### 1.12 Present Study: Goals

The main goal of this thesis is to explore how self-induced motor movements affect subsequent temporal perception of different sensory modalities. The idea of behaviours influencing our perceptions is relatively new. To the best of my knowledge, action effects on subsequent multisensory perception had yet to be explored prior to the studies reported here. A secondary goal of this thesis is to explore the role of agency of motor movements on temporal perception. Specifically, I aim to differentiate between actions that are voluntary (or chosen) from those that are involuntary (or predetermined).

In Chapter 2 I begin by investigating the effects of action on perceived onsets of visuotactile stimuli. In this chapter, I also attempt to distinguish between free and forced action types. Given the novelty of this research, Chapter 2 also serves as a tool to establish the methodology needed investigate the question of interest. In Chapter 3, I extend the investigation of action effects on the perception of onset of events with other bimodal pairs, including: visuotactile, audiovisual, and audiotactile. I also further investigate the different influences of action type based on pre-established methods of Chapter 2. Next, to obtain a more complete picture of action effects on temporal processing, in Chapter 4 I investigate the effect of action on temporal precision. Finally, in Chapter 5 I discuss the empirical groundwork laid out in the thesis, highlighting the dynamic interplay between motor movements and subsequent multisensory perception, and I consider limitations and future work that will contribute to this body of literature.

# Chapter 2: The Effects of Action on Perceived Visual and Tactile Onsets

## 2.1 Abstract

Voluntary motor movements speed up the perceived onset of single sensory stimuli. However, perception often involves the combination of multiple modalities. The current study examined how prior actions influenced the perceived onsets of subsequent visual and tactile events. In Experiment 1, participants performed a visuotactile temporal order judgment (TOJ) task to establish the baseline perception of visual and tactile stimuli. To observe action effects on subsequent perception, in Experiments 2-4, participants performed a left or right hand button press prior to the TOJ task. For these experiments, each sensory stimulus either appeared at the left hand or at the right hand location (always on opposite ends). This allowed the investigation of the effects of spatial relation between action and stimuli. In Experiment 2, participants selected the button press sides. In Experiment 3, the button presses were fixed and dictated via light commands. Lastly, Experiment 4 was used to clear up some observed uncertainties of Experiment 3 so button presses were again fixed, but dictated via voice commands.

Across all experiments, actions were shown to speed up perception of the sensory stimulus presented on the same side of the action. In other words, following an action, the sensory stimulus that appeared on the opposite side of the action needed to be presented sooner than in the baseline condition to be judged as occurring simultaneously with the same side stimulus. In addition, the same influences on perception were observed whether the preceding actions were chosen or fixed. Together, the findings indicate that prior actions speed up perception of proximate visual and tactile events.

## 2.2 Introduction

Successful interactions with our surroundings require the integration of relevant motor movements and sensory information. A trivial task such as picking up a cup of coffee involves careful coordination of motions and perceptions. Cognitive mechanisms integrate the planning and execution of a reaching and grasping motion toward the cup with the perception of the physical features of the cup, such as its location, size, texture and weight. Classically perception was viewed as a passive process that influences subsequent behaviours in a unidirectional manner. By this view, for example, an observer would perceive the physical characteristics of a ball flying toward him, and then react to that perception with an appropriate catching movement. However, an alternative view is that actions also influence subsequent perceptions. For example, making the catching movement influences the perception of the size of the ball (Witt, 2011), suggesting that mechanisms involved in motor control and perception are bidirectional. Current studies investigating action effects focus on subsequent perception of a single modality. However, perception of events is a multisensory experience. In the above examples, actions must be integrated with visual and tactile information. In this chapter, I investigated the effect of action on the relative timing of visual and tactile perception.

Planning and executing movements alters the perception of a single modality. Stimulus detection is facilitated if observers first prepare an action that matches the parameters of the stimulus (Fagioli, Hommel, & Schubotz, 2007). Contingencies are formed between actions and their effects; this process occurs is automatic and can take place for actions and events that appear unrelated (Hommel, 1996; Wykowska, Schubo &

Hommel, 2009). The simple act of pressing a button can alter the perceived temporal interval between two visual events (Park, Schlag-Rey, & Schlag, 2003); likewise, a voluntary button press, but not a TMS-induced button press, results in subjectively shorter time lags for a subsequent auditory stimulus (Haggard, Clark & Kalogeras, 2002). Together, these results imply that perception is a dynamic process, and that action can alter the perception of a single stimulus.

### 2.2.1 The Neural Link between Action and Perception

Shared neural links between actions and perceptions further supports the view that these two factors are related. Actions and their consequent perceptions are stored together as “event files” (Hommel, 2004). Event files include perceptual representations, motor representations and overall context. Encountering some features that are stored in the representation activates the overall event file. For example, a specified motor movement will activate stimuli that are represented together, resulting in faster perception of those stimuli, but slower perception of unexpected stimuli (Zmigrod, Spapé & Hommel, 2009). This observation further supports the existence a neural link between motor movements and perceptions.

### 2.2.2 Action and the Rules of Multisensory Integration

The association between action and perception may imply that actions follow the same multisensory integration rules. Sensory stimuli presented in spatial or temporal proximity are more likely to be interpreted as one percept, or bound together (e.g., Hommel, 1996; Spence, Shore, & Klein, 2001). The issue of whether actions presented in close spatial or temporal proximity to stimuli could display similar binding effects remains unresolved. Actions and sensory consequences are more likely to be interpreted as related or bound together for events presented close together in space and/or time (Moore & Obhi, 2012). For instance, an observer that notices a light shortly after a button press may assume the button press *caused* the light to appear. In this view, the button press and the light are bound together, suggesting actions follow the temporal law of multisensory integration. Accordingly, the effects of action on subsequent perception may depend on spatial and temporal constraints. However, it remains unclear in what way spatial and temporal relations between actions and stimuli influence perception.

Experimentally, actions have been shown to follow the temporal law of multisensory integration. Actions performed immediately before the presentation of auditory and visual stimuli speed up perception of the visual modality (Vallet & Shore, unpublished). Observers performed an action (key-press) prior to completing an audiovisual temporal order judgment (TOJ) task. Following the action, the first sensory stimulus appeared either with no delay, or after a 500 ms delay. When there was no delay, the visual stimulus was perceived as occurring sooner in time than when there was a delay between the button press and the first stimulus. Similarly, in prior work it was shown that participants estimated action that preceded tones as occurring later in time, and the tones as occurring earlier in time (Haggard et al., 2002). In both scenarios, actions appear to follow the temporal rule of multisensory integration—when presented in temporal proximity to sensory stimuli actions appear bound to the stimulus. Whether action can follow the spatial law has been less investigated. In the procedures described above, Vallet and Shore (unpublished) observed that the side of the sensory stimulus relative to the action did not influence TOJ performance. A temporal, but not spatial binding effect between actions and sensory stimuli suggests actions can only follow the temporal law of integration, but not the spatial law of integration. In the present chapter, I further investigate actions' ability to follow the multisensory laws of integration.

### 2.2.3 Free versus Forced Actions

Several factors influence the perceived binding between action and perception. The type of action, (whether it is voluntary or involuntary), parameters of the action, and the temporal window between actions and consequences all influence binding. Voluntary actions, but not TMS-induced (involuntary) actions produced an intentional binding effect (Haggard et al., 2002; Haggard & Clark, 2003). The sense of agency, or observer's feeling of control over the action and subsequent effect may be essential for the intentional binding effect (e.g., Moore & Obhi, 2012). In addition, binding is more likely to occur if the action's features match the subsequent stimulus features (Fagioli et al., 2007; Obhi & Haggard, 2004; Wykowska et al., 2009; Welsh & Pratt, 2008). Lastly, actions and stimuli occurring close together in time are more likely to be perceived as occurring together (Moore & Obhi, 2012). Thus, the intentional binding effect is contingent on the type of action performed along with the temporal properties of the action and stimuli.

It is possible that only free, but not forced actions result in a binding effect. For actions to be considered as free, a subjective feeling of intent to act must be present. Participants tend to associate agency with actions that result in immediate sensory effects

(Moore & Obhi, 2012; Obhi & Haggard, 2004). The mere illusion of agency demonstrates similar binding effects to actual intended actions (Strother, House, & Obhi, 2010). Neuroimaging studies implicate different brain region activations for free versus forced actions (Kostelecki, Mei, Dominguez &Velazquez, 2012). In particular, differential neural activity was observed prior to making a free motor movement compared to a forced motor movement, but no distinction was observed in the later stages of the action. Given that different action types influence intentional binding in distinct ways, a secondary question of interest in the present thesis was to examine whether free or forced action led to different types of binding effects.

### 2.2.4 Scope of the Present Study

The goal of this chapter was to investigate the effects of performing a prior action on multisensory perception. Specifically, I examined whether action preferentially bound to visual or tactile modalities, and whether the type of action (free versus forced) influenced the degree of binding. Most studies examining motor and perceptual binding focused on a single sensory modality. In reality, perception is rarely unimodal; motor information must be integrated with information from multiple modalities. In our daily activities, vision and touch guide our ability to define objects with which we interact. It is possible that actions will influence visuotactile stimuli in a different way than previously demonstrated with other sensory stimuli. A secondary question of interest was whether free compared to forced actions would demonstrate unique effects on perception. Based on the literature, it was speculated that free actions would bind to sensory stimuli with a greater magnitude than forced actions. No previous research has investigated how action binds to visual and/or tactile stimuli.

To explore the effects of action on perception, participants performed either a forced or free action type that preceded a visuotactile TOJ task. In a typical TOJ task, observers are presented with two stimuli separated by a variable amount of time, and are asked to judge which stimulus was perceived first. Two independent performance measurements are obtained from such tasks: just noticeable difference (JND) and point of subject simultaneity (PSS) (e.g., Zampini et al., 2005). The JND reflects the shortest time interval between the two sensory modalities for which observers can successfully judge the order of stimuli on 75% of trials. The PSS reflects the amount of time by which one stimulus needs to lead the other for the two to be perceived as simultaneous. The PSS is of particular interest in the present studies. A shift in PSS following an action relative to a no action condition would indicate that motor movements speeds up or slows down perception of one (or the other) modality. A theoretical assumption of the TOJ task is that performance reflects differences in perception. In other words, because the task requires participants to indicate which stimulus they perceived first, it is assumed that performance is a true reflection of perception.

Because this research is exploratory, it is unclear how action may affect visuotactile TOJ performance. First, based on the audiovisual TOJ task data presented by Vallet and Shore (unpublished), it is possible that action will not spatially bind to either sensory modality. In this scenario, following an action a unidirectional shift in PSS may be observed relative to baseline, regardless of the relative spatial location of the action and stimuli. On the other hand, actions are expected follow the temporal law. Based on Vallet and Shore's (unpublished) findings, actions performed close in time to the TOJ task may result in faster perception of the visual modality. Alternatively, different modality combinations may interact in different ways with action. In other words, actions preceding audiovisual pairings may speed up visual perception, but actions preceding visuotactile pairings may speed up tactile perception instead. Shifts in PSS would indicate the direction in which action affects perception. In addition, free and forced action types were manipulated across experiments. Consistent with previous findings, it is expected that free, but not forced actions would result in an intentional binding effect. If a difference in intentional binding exists between free and forced action types, this would be reflected in PSS shifts as a function of action type.

This chapter also served to develop and improve experimental methodology to investigate the questions of interest. In all experiments, participants held a wooden cube in each hand; each cube was equipped with a vibrator and a LED light. The action performed was a button press. Similar procedures to those of Spence et al. (2001) were followed. In their experiments, participants completed a visuotactile TOJ task with two cubes containing vibrations and LED lights. On some trials, the two stimuli appeared on the same cube and on other trials the two stimuli appeared on opposite cubes. Modalities presented in close proximity result in poorer temporal resolution because they are more likely to be bound as one percept (Spence et al., 2001). The intent of Experiment 1 was to replicate these baseline findings, and therefore no action was completed prior to the TOJ task. In Experiment 1, Spence et al.'s (2001) methods were followed and stimuli either both appeared on the same cube or on opposite cubes. This was in contrast to Experiments 2-4, in which stimuli always appeared on opposite cubes. In Experiments 2-4, free or forced button presses were performed prior to the TOJ task. The two modalities always appeared on opposite cubes because the primary interest was to investigate the effect of spatial proximity of action to each sensory modality.

The present study will provide a deeper understanding of whether action can behave as a sensory stimulus when it comes to following the spatial law of multisensory integration, whether free versus forced actions have different effects on subsequent perception, and whether actions influence visual and tactile stimuli in unique ways. Together, the findings will contribute to the development of a framework for understanding the dynamic relation between perception and motor movements.

## 2.3 Experiment 1: Baseline Visuotactile TOJ

Experiment 1 served as a baseline to establish the methods in the present study. We aimed to replicate methods introduced by Spence et al. (2001) to observe how visuotactile stimuli are integrated in the absence of action. A successful replication would then allow us to use this methodology to extend our research to issues related to integration of action and multisensory perception.

### 2.3.1 Methods

#### *Participants*

Sixteen McMaster University undergraduate students participated in the experiment in exchange for course credit. All participants were naïve to the goal of the study, and all reported normal or corrected-to-normal vision. Six were female and 10 were male. Fourteen participants reported being right-handed. Participants' ages ranged from 17 to 19 years old (M = 18.38, SD = 0.62). All participants signed a written consent form prior to participation. The study took about an hour to complete. All procedures were in accordance with the McMaster Research Ethics Board.

### ***Stimuli and Apparatus***

The experiment occurred in a black painted room with the lights off. Light entering underneath the door and the light emitting diodes (LED) stimuli were the only light sources. Participants were seated at an 81 cm high and 79.5 cm wide wooden table that stood against a wall. A piece of masking tape was placed vertically across the mid section of the table to guide the central position of participants. Participants held two, 8 cm long by 3.7 cm wide by 5.2 cm high wooden cubes, one in each hand. The cubes were held 24 cm to the left and 24 cm to the right of the central masking tape, at marked locations.

Each cube was equipped with an Oticon-A (100 Ohm) bone-conducting vibrator in the centre, driven by a 250-Hz sine wave, and a red LED mounted on top. The vibrator was situated beneath a circular button, 2 cm in diameter. The cubes were held with the thumbs on top of the buttons, and the fingers underneath the wooden cube. The vibrations and light stimuli were presented for 20 ms each, separated by variable stimulus onset asynchrony (±250, ±108, ±72, ±24 ms; negative SOA indicated that the visual stimulus was presented first, and positive SOAs indicated that the tactile stimulus was presented first).

A blue/yellow fixation LED was mounted at eye level on the wall in front of the participant. Two foot-pedals mounted to an adjustable Plexiglas frame were positioned to the right of the participant, underneath the table. The heel and the toes of the right foot were depressed over the two pedals; participants lifted their heel or toes to make responses. In order to mask the noise made by the vibrators, participants wore headphones that played continuous white noise. The Experiment was programmed and presented via MATLAB (R2011b) on a Dell dimension 8250, Pentium® 4 computer.

### *Design*

The factors in the design included relative stimulus side (same vs. different), and SOA (±250, ±108, ±72, ±24). This design resulted in 16 possible conditions (2 stimulus sides x 8 SOAs). Subjects completed 640 trials, divided into 8 blocks of 80 trials). All possible stimulus side combinations (left-left, right-right, left-right, right-left) along with SOAs were randomly distributed within the experiment.

### *Procedures*

Participants first completed 20 trials of a speeded discrimination task to become familiarized with stimuli to foot-pedal mappings. Participants were randomly presented with one stimulus for 20 ms (light or vibration) and were asked to respond as quickly as possible with the foot-pedal, lifting their toes for the light and heels for vibration. Most participants performed this task without difficulty. However, if participants responded incorrectly on more than 4 trials, they were asked to re-do the discrimination task until they performed with high accuracy.

The visuotactile TOJ task followed the discrimination task. In the visuotactile TOJ task, participants judged which of two modalities was presented first. Each trial began with a blue central fixation LED, that lit up for 250 ms. Following a 1000 ms delay, the first stimulus appeared either on the left or right cube for 20 ms. Following a varied SOA, the second stimulus appeared for the same amount of time, either on the same or opposite cube. Participants responded to the modality they perceived first with the foot-pedal. Accuracy was emphasized over speed, but if no response was recorded within 3000 ms, the central LED, cube's LED and the vibrators all lit up and vibrated for 500 ms. After a 250 ms delay, the next trial began.

### *Analysis*

Discrimination task data were not submitted for analysis. A repeated measures ANOVA was computed for the proportion "vibration first" responses on the main TOJ scores. JND and PSS scores were calculated for same versus different stimulus side trials. The proportion "vibration first" responses were converted into z-scores and the best-fit lines were computed for each participant using the eight SOAs. The slopes and intercepts were calculated and used to compute the PSS(-intercept/slope) and JND (0.675/slope). The resulting PSS and JND scores for same versus different side trials were compared using paired-sample t-tests.

Participants were removed from the analysis if they failed to meet one or more of the following criteria (Spence et al., 2001): 1. The average proportion "vibration first" across all the conditions at the extreme SOAs (±250 ms) was lower than 0.75 (at one or both extremes). 2. Participants whose PSS scores were greater than ±250 ms. 3. The correlation of the line of best fit for the z-transformed scores and SOAs was lower than 0.70.

### 2.3.2 Results

*ANOVA*

None of the participants were removed from the analysis as a result of the exclusion criteria, and therefore the results of sixteen observers were subjected to the analysis. Trials for which participants did not respond within 3000 ms were removed. This resulted in the removal of 0.5% of trials.

The proportion "vibration first" responses were subjected to a 2 (stimulus side: same vs. different) x 8 (SOA: ±250 ms, ±108 ms, ±72 ms and ±24 ms) repeated-measures ANOVA (represented in Figure 2.1). In the case of violation of Mauchly's test of sphericity, the Greenhouse-Geisser epsilon (ε) and non-adjusted degrees of freedom are reported. Proportion "vibration first" responses increased with increasing SOA [F (7,105)=134.70, p<0.001, ε=0.33]. Stimulus side had a significant effect on "vibration first" responses [F (1,15)=9.08, p=0.009]. Lastly, there was a significant interaction between SOA and stimulus side [F(7,105)=5.67, p<0.001].

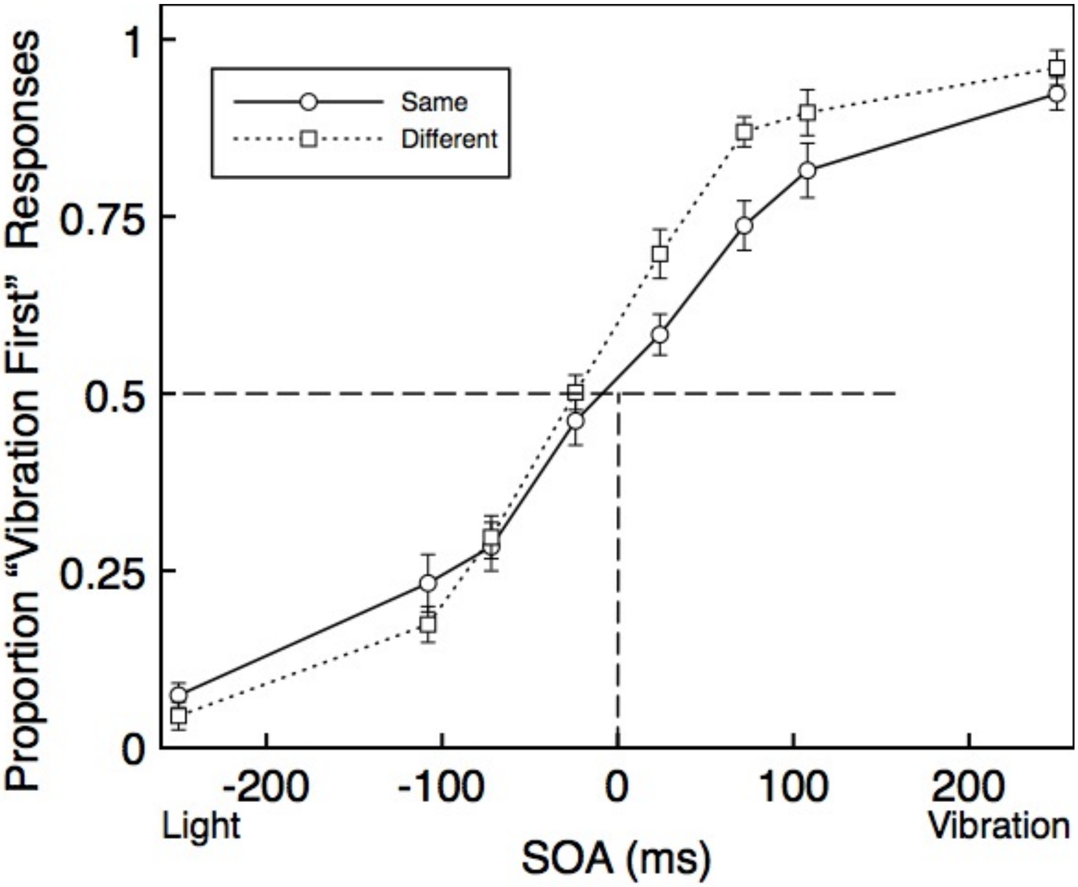


*Figure 2.1* Proportion "vibration first" responses as a function of SOA for targets that appeared on the same and different sides, for Experiment 1. Error bars represent standard error of the mean, corrected for within-participants comparisons.

### ***PSS and JND Analysis***

The computed JND and PSS scores were submitted to paired-sample t-tests to compare performance on same versus different side trials (Figure 2.2). No difference in PSS scores was observed for stimulus side [t(15)=1.88, p=0.08]. JND data revealed an overall worse performance for same (M=115.3 ms) compared to different (M=92.2 ms) side trials [t(15)=4.22, p=0.001]. Vision and vibration needed to be separated by a larger time interval on same side trials for correct order judgment on 75% of the trials.

The PSS data were also subjected to a one-sample t-test to determine whether each condition (same or different side) was different relative to a test statistic of 0 ms. A significant difference for different side trials [t(15)=-3.55, p=0.003] relative to a test statistic of 0 was observed. On the other hand, the PSS for same side trials did not differ significantly from 0 ms [t(15)=-0.95, p=0.357].

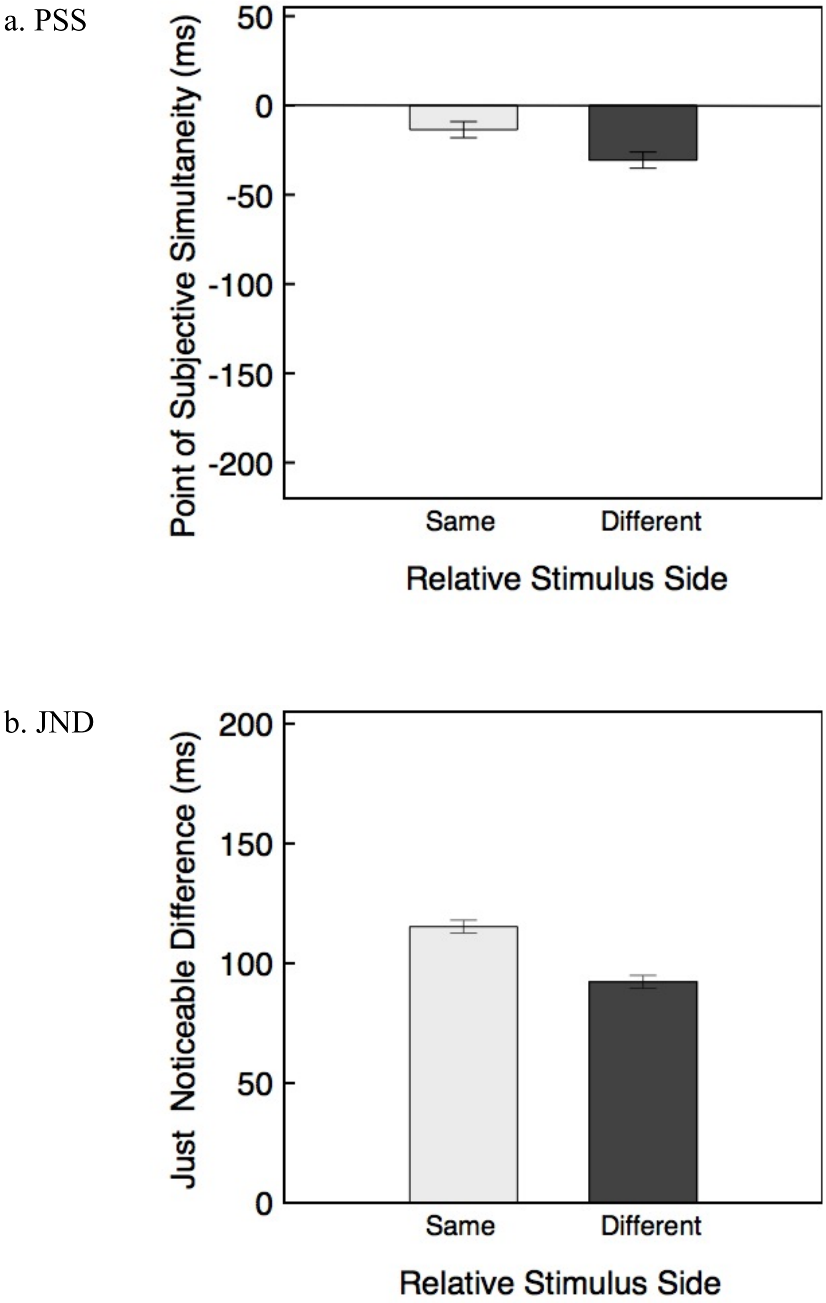


*Figure 2.2* Experiment 1: PSS (a) and JND (b) for same and different stimuli side trials. The PSS scores represent the amount of time visual stimuli needed to lead tactile stimuli (in ms) to be judged as simultaneous. The JND scores represent the smallest amount of time needed to separate the two stimuli to accurately judge the temporal order on 75% of trials. Error bars reflect standard error of the mean, corrected for within-participants comparisons.

### 2.3.3 Discussion

The primary aim of Experiment 1 was to establish a method that would replicate previous findings of visuotactile TOJ performance. This replication would then allow for the exploration of action's influence on visuotactile TOJ performance. As previously observed by Spence et al. (2001), vision needed be presented before vibration when modalities were presented from different spatial positions to achieve a simultaneous judgment. In contrast, when the two stimuli were presented at a single location, there was no difference from a standard of 0 ms. Spence et al. (2001) analyzed trials on which both modalities were presented on the left side separately from when both modalities were both presented on the right side. Interestingly, it was only for right side trials that they found vision needed to precede touch to achieve simultaneity. In the present study, the proportion of left side only trials were balanced with right side only trials, but those data were averaged together for the analysis. Averaging across sides could account for the lack of finding for same side trials in the present study.

Lastly, consistent with previous findings, poorer temporal resolution (higher JND) was observed for same side trials. Visual and tactile stimuli presented in close spatial proximity are more likely to be bound together as a single percept, making TOJ judgments more difficult. Having established this baseline set of measures, similar methodology was used in Experiment 2 with the addition of a free button prior to the visuotactile TOJ task to explore the effects of voluntary action on perception. In contrast to Experiment 1, in Experiments 2-4, participants were psychophysical observers who repeated the task over three sessions.

## 2.4 Experiment 2: Voluntary Action effects on Visuotactile Perception

### 2.4.1 Methods

#### *Participants*

Two McMaster University students volunteered to participate in the study, along with the author, A.F. Participants were experienced psychophysical observers. The volunteers were remunerated with 10$/session. With the exception of the author, participants were naïve to the goal of the study. All reported normal or corrected-to-normal vision. Two were female, and all were right-handed. The mean age was 23.33 and ranged from 22 to 25 years old. Participants signed a written consent form prior to participation. The study took place over three separate sessions, each about 45 minutes in length. All procedures were in accordance with the McMaster Research Ethics Board.

#### *Stimuli and Apparatus*

Stimuli and apparatus were identical to Experiment 1 with the exception that the central fixation LED lit up yellow (instead of blue) to indicate the start of a trial. The light signaled for observers to make a left or right button press. The TOJ task followed 10 ms after the button press. Unlike in Experiment 1, visual and tactile stimuli always appeared on opposite sides.

#### *Procedures*

Three experienced psychophysical observers completed the experiment over three 45-minute sessions. All sessions were completed within one week. Participants performed the exact same task over the three sessions. During the first session, participants completed 20 trials of a discrimination task (same as in Experiment 1) to become familiarized with stimuli to foot-pedal mappings. Following the discrimination task, participants completed 20 practice trials of the experimental task. The speeded discrimination task and practice trials were not completed during the second and third sessions.

As in Experiment 1, participants held one wooden cube in each hand, with their left and right thumbs over the buttons, and the fingers underneath the cube. A central yellow fixation LED lit up for 250 ms to indicate the start of the trial. Participants were instructed to maintain their gaze on the fixation light and to press either the left or right button on one of the cubes once the LED lit up. They were told they could choose which button to press, but to try to press each of the two buttons equally often over the course of the experiment. Participants made the button press at any point they felt ready, as there was no imposed time limit. Ten ms following the button press, the first stimulus appeared for 20 ms, either on the left or right cube. The second stimulus appeared at varying SOAs (same as in Experiment 1) always on the opposite cube. As in Experiment 1, participants responded by lifting their toes or heel from the foot-pedal to indicate which modality they perceived first. Subjects completed 12 blocks of 80 trials each (a total of 960 trials) during each session. The side on which the first stimulus appeared was random and counterbalanced across the experiment. The chosen actions could be performed either at the same spatial location as vibration (action near vibration condition) or at the same location as vision (action near light condition).

### 2.4.2 Results

Individual observer's proportion "vibration first" responses for each session along with each observer's average across the three sessions are displayed in Figure 2.3. Each observer's session averages are displayed again in Figure 2.4 along with one graph displaying the average of all participants across the sessions. Because the data depicted here is of psychophysical nature and no statistical analyses were performed, the individual data by day, individual averages across the three sessions, and overall average of all of the observers are presented to show variability. For each participant's session, the mean PSS and JND scores were calculated as described in Experiment 1. The PSS and JND averages are displayed in Figure 2.5.

Baseline data obtained in Experiment 1 were used as a comparison. The PSS and JND scores for different stimulus side trials of Experiment 1 were subjected to a bootstrapping procedure of 9,999 samples. Through this method, the estimated baseline PSS mean was -31 ms with a 95% confidence interval (CI) of -47 to -15. The estimated baseline JND mean was 92 ms with a 95% CI of 78 to 110. In Figure 1.5, a solid horizontal black line depicts the baseline mean estimate with the grey area representing the 95% CI estimate.

The average PSS and JND scores for Experiment 2 were compared with the obtained baseline CI. The PSS and JND means for actions performed near vibrations and actions performed near light were then compared to the baseline CI. Means that fall outside the CI indicate a significant difference from baseline. It should be noted that interpretation must be made with caution as the baseline means and action means were obtained between subjects and using slightly different methods.

As seen in Figure 2.5, the mean PSS for actions near vibration (M=-111 ms) falls well outside the baseline CI (-47 to -15 ms), indicating that light needed to be presented for a greater amount of time before vibration for simultaneity perception to be achieved. On the other hand, when action was near light, a perceptual shift in the opposite direction was observed (M= 8 ms), indicating vibration needed to be presented before light for PSS to be achieved. This bi-directional shift in PSS, depending on action location, was clearly seen with observers A.F. and D.M. across all three sessions. On the other hand, observer B.T. seemed to demonstrate a PSS shift in the same direction following a button press, regardless of its spatial position relative to the stimuli (Figure 2.3). The JND data indicate similar performance for actions that were near vibration (M = 110) versus near light (M = 104) and both fall within the baseline (M=92 ms ) CI (78 to 110). Summary statistics for individual participants and experiment averages are depicted in Table 2.1 and Table 2.2 respectively.

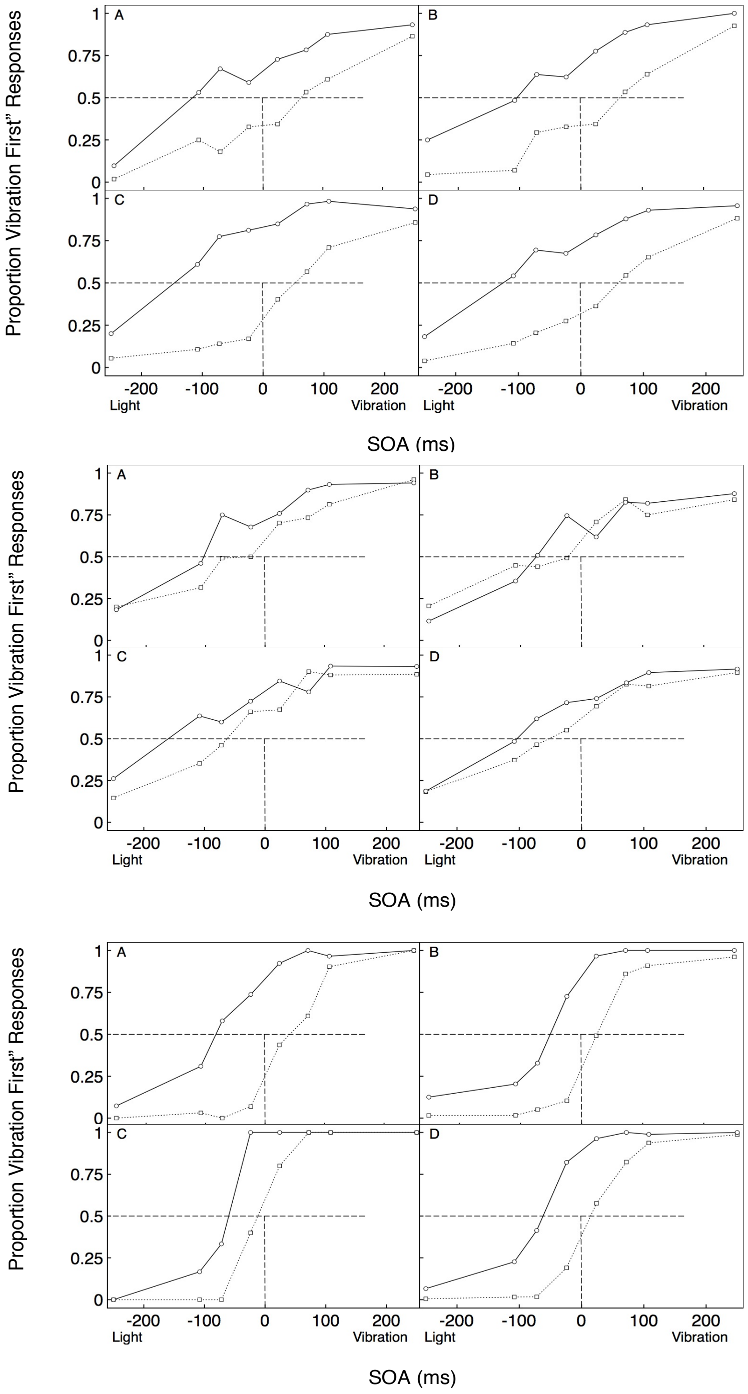


*Figure 2.3* Data from Experiment 2: Proportion "vibration first" responses for participants A.F., B.T., and D.M. in top, middle and bottom graphs respectively. The darker, solid line represents actions near vibration and the lighter, dashed line represents action near light. In each graph, Panels A, B, and C depict performance on the first, second and third sessions for each participant respectively and panel D represents each observer's average across the three sessions.

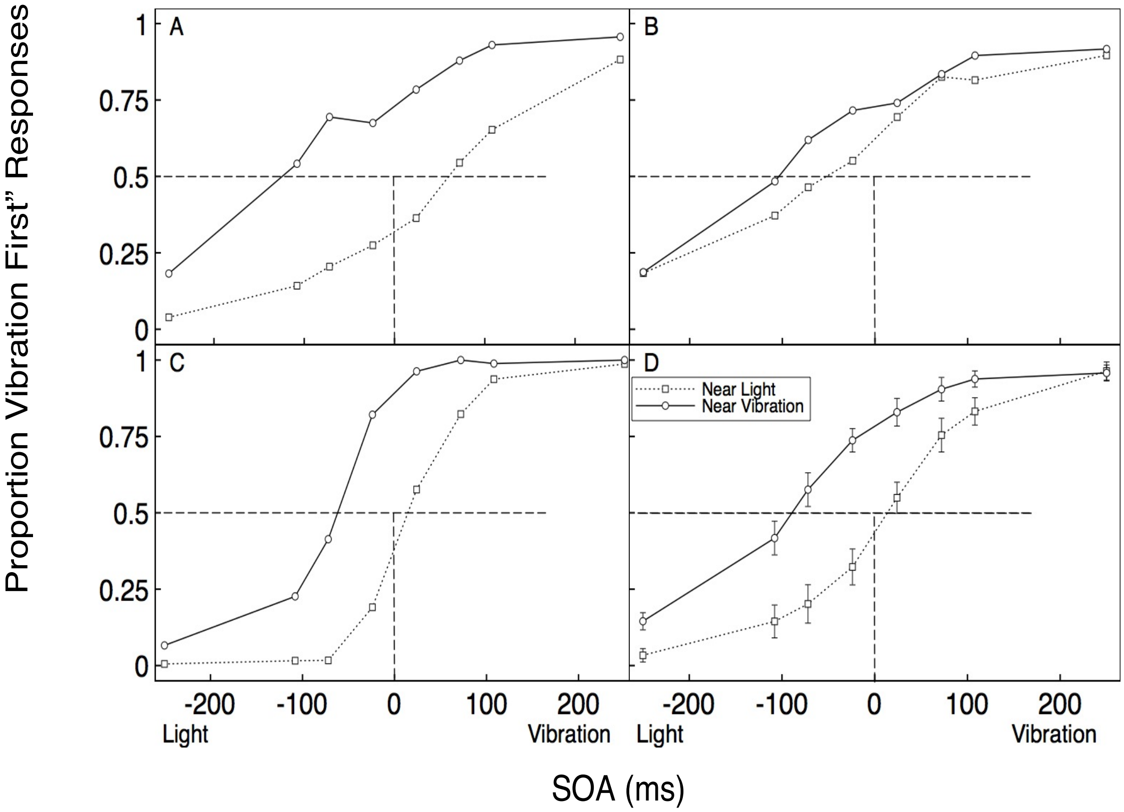
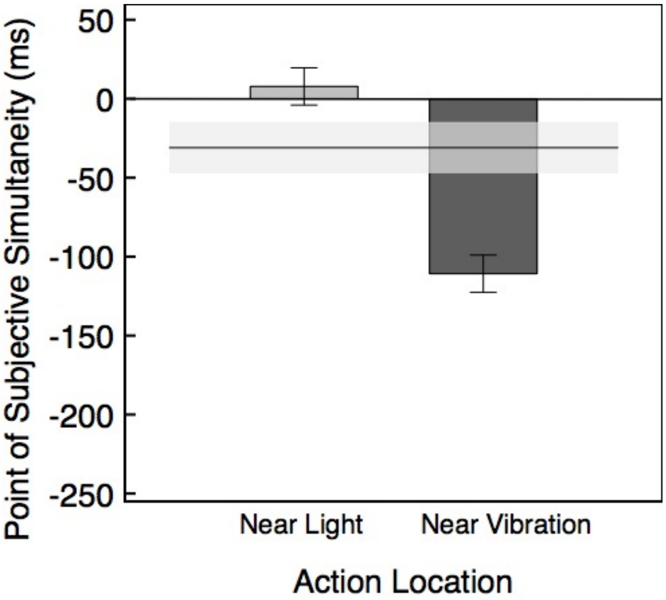


*Figure 2.4* Data from Experiment 2: Average proportion “vibration first” responses. Panels A, B and C represent averages across three sessions for participants A.F., B.T., and D.M. respectively. The darker, solid line represents action near vibration and the lighter, dashed line represents action near light. Panel D displays all participant averages. Error bars are within-subject standard error of the mean.

a. PSS



b. JND

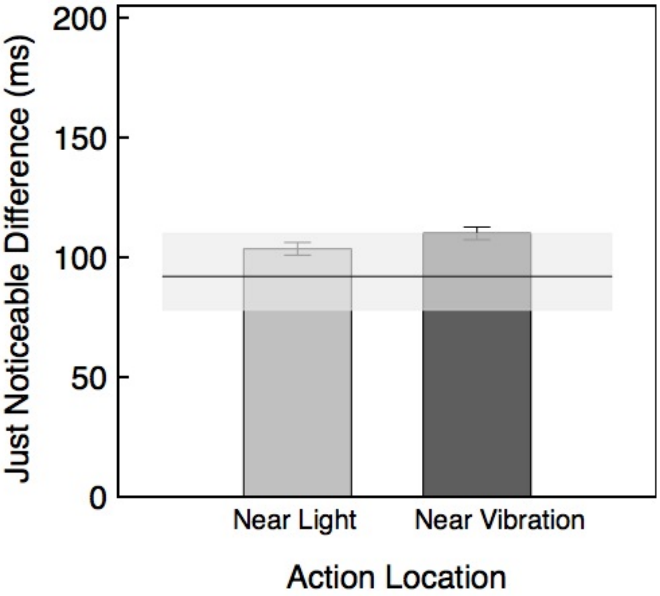


*Figure 2.5* Experiment 2: PSS (a) and JND (b) for action near light and action near vibration conditions. Negative PSS scores represent the amount of time visual stimuli needed to lead tactile stimuli (in ms) to be judged as simultaneous. The JND scores represent the smallest amount of time needed to separate the stimuli to accurately judge the temporal order on 75% of trials. Error bars indicate standard error of the mean, corrected for within-participants comparisons. In each graph, the horizontal black line represents Experiment 1 baseline mean estimate as predicted by a bootstrapping method. The shaded grey area represents the 95% estimated confidence interval.

### 2.4.3 Discussion

Action binds to whichever modality is presented in spatial proximity. When a vibration was presented on the same side immediately following a voluntary action, visual stimuli needed to lead by about 110 ms for perception of simultaneity to be achieved. This value is well outside the baseline CI and indicates that tactile stimuli are processed first and faster following an action on the same side. The opposite was true when light was presented on the same side immediately following the action; tactile stimuli needed to lead visual by about 8 ms for perception of simultaneity. Faster visual perception when action was near light is a reversal of the observed baseline condition. The ability to perceive visual or tactile stimuli quicker following an action depends on the spatial location of the action relative to each modality. This finding implies that actions can follow the spatial law of multisensory integration, binding to the nearest stimulus.

The magnitude of the effect of action following a vibration appeared numerically larger than the effect of action following a light. This could indicate that actions bind more strongly to vibrations than to light. However, it is difficult to obtain conclusive interpretations of these data due to their psychophysical nature (and lack of statistical analysis). In addition, the baseline comparison was obtained in a different experiment, which adds variability to the data.

Temporal precision on the TOJ task when action was near vibration was similar to when it was near light. This conclusion was supported by the similarity in JND scores for action near vibration and action near light conditions. Although overall perception of same side stimuli appeared faster after an action, it did not influence observers' thresholds for judging the temporal order of the two stimuli, and action did not appear to alter overall temporal precision relative to baseline.

In Experiment 2, the effects of a voluntary action on perception were explored. Participants chose which button to press. It is possible that the action type (whether voluntary or involuntary) influences the binding effect. To explore this possibility, Experiment 3 was designed to investigate the effects of directed or "forced" action on subsequent perception.

## 2.5 Experiment 3: Involuntary Action Effects on Visuotactile Perception I

### 2.5.1 Methods

***Participants***

Three experienced physiological observers, and the author A.F., volunteered to participate in the study. Participants were McMaster University students, and all but the author were naïve to the purpose of the study. They were compensated with 10$/ session to thank them for their time. All reported normal or corrected-to-normal vision. Three were female, one male, and all were right-handed. Participants ranged from 19 to 26 years old (M=23.75, SD=3.2). Participants signed a written consent form prior to participation. The study took place over three separate sessions, each about 45 minutes in length. All procedures were in accordance with the McMaster Research Ethics Board.

### *Stimuli and Apparatus*

Stimuli and apparatus were identical to Experiment 2 with the exception that the central fixation LED lit up yellow on half the trials and blue on the other half of the trials. The colour indicated the button press required by participants.

### *Procedures*

Procedures followed those of Experiment 2 with minor changes. As in Experiment 2, the experienced psychophysical observers completed the study over three-45 minute sessions within one week. The only change was that the action location was forced instead of free. Participants were instructed to press the left button if the central LED lit yellow and the right button if the central LED lit blue. Observers had an unlimited time to make a button press. In the case that an incorrect button was pressed, participants were given light and vibration feedback, and a new trial initiated 250 ms later. The forced side (central LED colour) was counterbalanced throughout the experiment.

### 2.5.2 Results

Individual observer's data for each session, along with each observer's data averaged across the three sessions are displayed in Figure 2.6. Figure 2.7 again displays each individual's data averaged across the three sessions, along with all the observers' data averaged together. As in Experiment 2, it was important to display individual data by day, individual averages, and all participants' averages to display variability. For each participant, the mean PSS and JND scores were calculated as in Experiment 2. The average PSS and JND scores for all participants are depicted in Figure 2.8.

The PSS and JND scores were compared to the baseline in the same manner as described in Experiment 2 (see Figure 2.8). The same bi-directional shift in PSS was observed in the present study as in Experiment 2. With the forced action, the effect appeared to be numerically more pronounced than the one observed with a free action (Experiment 2). When action was on the same side as the vibration, PSS was greatly numerically shifted to the left, indicating that light needed to be presented about 227 ms before vibration for perception of simultaneity (as opposed to 111 ms in Experiment 2). On the other hand, when action was near light, the vibration needed to lead light by about 26 ms for perception of simultaneity (as opposed to 8 ms in Experiment 2). Again, numerically the PSS shift indicates the possibility of action binding more strongly to tactile stimuli. As in Experiment 1, these data must be interpreted with caution because no actual statistical tests were performed and because the baseline condition was obtained in a separate experiment. These PSS shifts were consistent for all participants with the exception of M.T., who demonstrated a PSS score within the baseline CI (M=-22 ms) when action was near light. However, M.T. was consistent with other participants in demonstrating a pronounced perceptual shift toward vibration when action was near vibration.

The JND results indicated poorer precision in performance for action near vibration condition. When the vibration appeared on the same side as the action, participants had greater difficulty distinguishing the order of stimuli. The mean JND score for action near vibration condition (M=148 ms) was outside the baseline CI. On the other hand, the action near light condition did not appear to be different than baseline. All participants, with the exception of P.F. who seemed to perform equally well in both conditions, displayed this trend. The difficulty participants faced when action was near vibration challenges the true interpretation of JND scores. JND means are calculated by obtaining the z-transformed proportion "vibration first" responses at 25% and 75% proportions. However, on average participants were biased to perceive vibration as occurring first on trials where action was near vibration, so a measurement could not be obtained for 25% performance. This is further addressed in the Discussion section of Experiment 3.

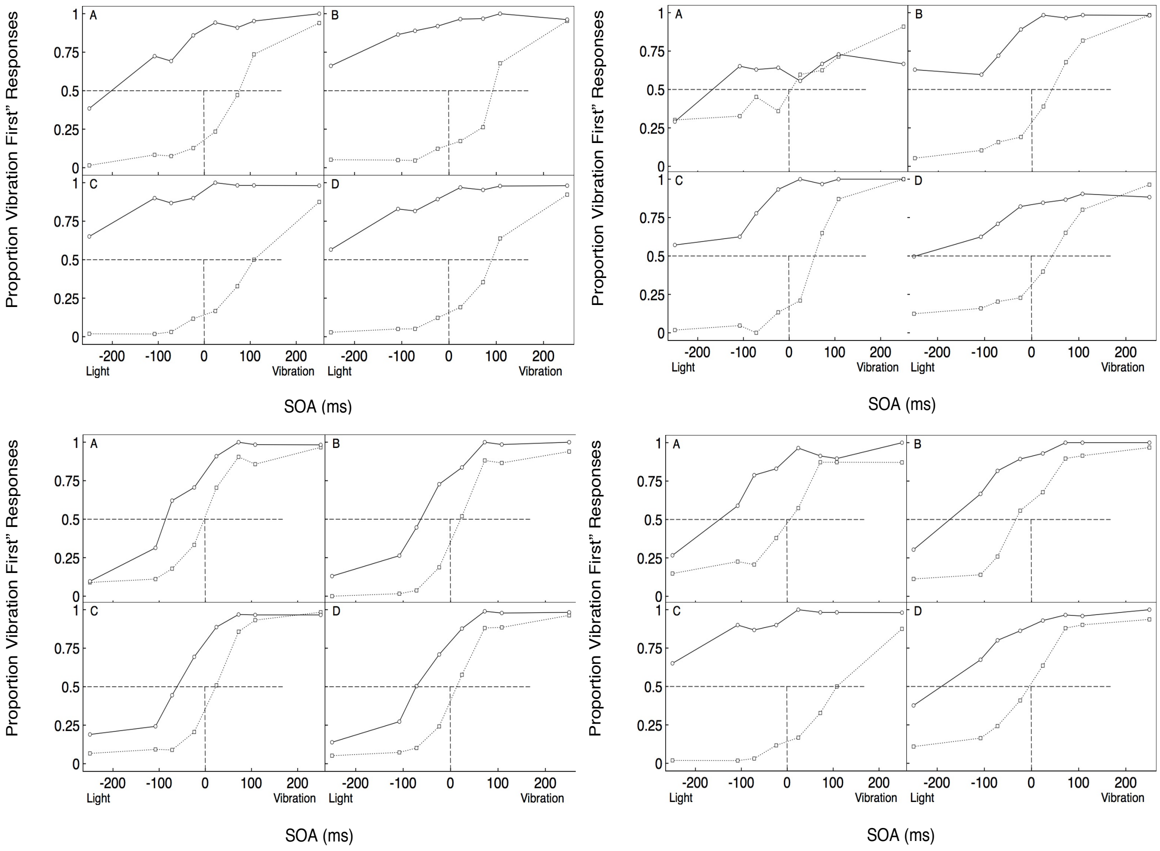


*Figure 2.6* Data from Experiment 3: Proportion "vibration first" responses for participants A.F., N.L., P.F., and M.T are displayed in top-left, top-right, bottom-left and bottom-right graphs respectively. The darker, solid line represents action near vibration and the lighter, dashed line represents action near light. In each graph, Panels A, B, and C depict performance on the first, second and third sessions for each participant respectively and panel D represents each observer's average across the three sessions.

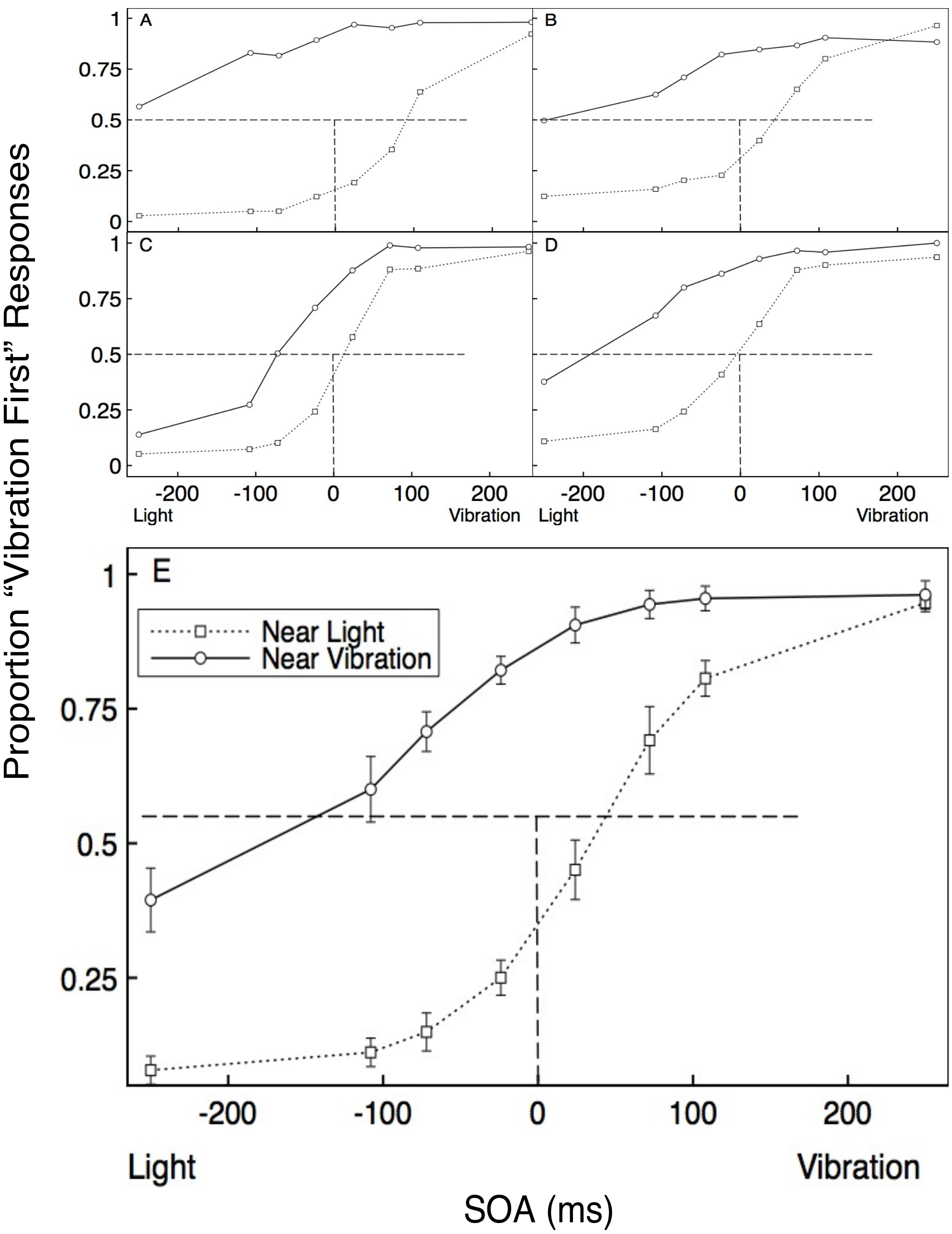
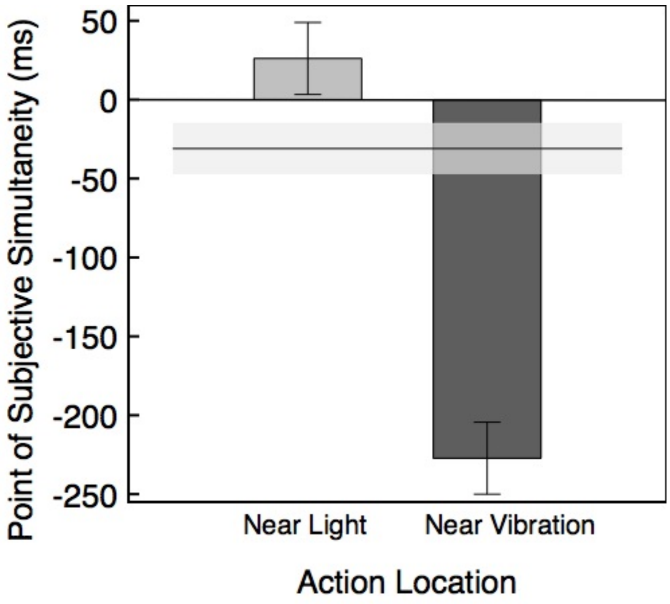


*Figure 2.7* Data from Experiment 3: Average proportion "vibration first" responses. Panels A, B, C and D represent averages across three sessions for participants A.F., N.L., P.F., and M.T. respectively. The darker, solid line represents action near vibration and the lighter, dashed line represents action near light. Panel E displays the data averaged across all sessions and all participants. Error bars reflect standard error of the mean, corrected for within-participants comparisons.

a. PSS



b. JND

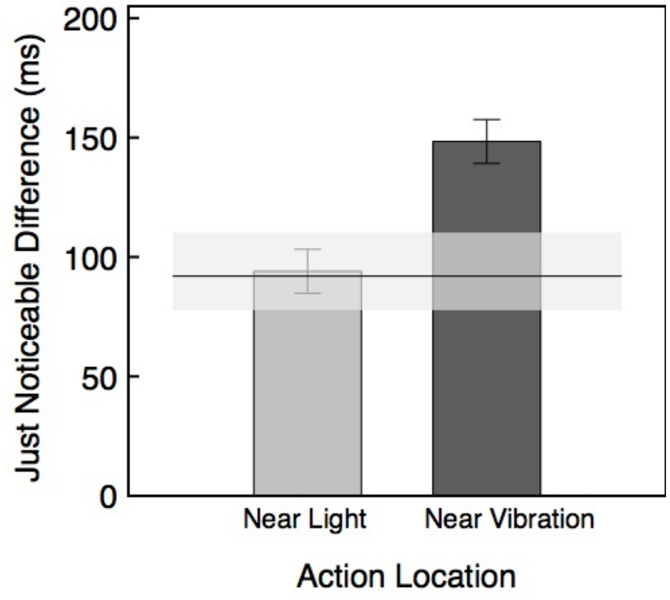


*Figure 2.8* Experiment 3: PSS (a) and JND (b) for action near vibration and action near light conditions. Negative PSS scores represent the amount of time visual stimuli needed to lead tactile stimuli (in ms) to be judged as simultaneous. The JND scores represent the smallest amount of time needed to separate the two stimuli to accurately judge temporal order on 75% of trials. Error bars reflect standard error of the mean, corrected for within-participants comparisons. In each graph, the horizontal black line represents Experiment 1 baseline mean estimate as predicted by a bootstrapping method and the shaded grey area represents the 95% estimated confidence interval.

### 2.5.3 Discussion

Binding of action to the most spatially and temporally proximate sensory stimulus is a robust effect. This effect was first demonstrated in Experiment 2, and replicated in Experiment 3. Interestingly, the type of action (free versus forced) appeared to modulate this effect. Contrary to the initial prediction, the effect seemed intensified for forced actions relative to free actions. Based on previous literature, it was postulated that forced actions would demonstrate the opposite of a binding effect, a repulsion type effect, where forced actions would be perceived to occur further away from a subsequent sensory stimulus (e.g., Haggard et al., 2002). This was not the case in the present study.

The apparent larger perceptual shifts following a forced compared to a free action may reflect uncertainty rather than a true effect. Participants expressed difficulty in performing the task. They were required to arbitrarily map LED colours to button presses, perform the TOJ task, and arbitrarily map modalities to foot-pedal responses. In fact, the higher JND scores in the action near vibration condition may reflect difficulty in performance. The JND scores are challenging to interpret because participants' responses for proportion "vibration first" responses never reached the lower end of the curve.

The goal of Experiment 4 was to address some of the uncertainty issues encountered in Experiment 3. Experiment 4 was designed to investigate further whether forced action truly intensifies perception of same side stimuli. To decipher whether the intensified forced action effect observed in Experiment 3 was a true effect, the procedure of Experiment 3 were repeated while reducing participants' uncertainty. In Experiment 4, forced actions were dictated by intuitive voice commands rather than arbitrary light commands. The goal was to reduce the difficulty of stimulus-response mappings, and thus obtain a more precise measure of the effect of interest.

## 2.6 Experiment 4: Involuntary Action Effects on Visuotactile Perception II

### Methods

#### *Participants*

Three experienced McMaster University psychophysical observers (2 female, 1 male) volunteered to partake in the study. All were naïve to the purpose of the study. One of the participants, N.L., also participated in Experiment 3, but was not debriefed at the time so was still naïve to the purpose. Participants were compensated with 10$/ session. All reported normal or corrected vision, and all reported to be right-handed. Participants ranged from 21 to 25 years old (M=22.67, SD=2.08). A written consent form was signed prior to participation. The study took place over three separate sessions, each about 45 minutes in length. All procedures were in accordance with the McMaster Research Ethics Board.

#### *Stimuli and Apparatus*

Stimuli and apparatus were identical to Experiment 3, with the addition of two Logitech LS11 speakers placed at the back of the table, directly in front of the two cubes. The speakers were used to deliver the forced instruction; a male-recorded voice specified “left” or “right” instructions, randomly selected and counterbalanced throughout the experiment. The fixation light only lit up yellow to indicate the start of the trial. The start signal was followed by the verbal forced action instruction, button press, and the TOJ task.

### *Procedures*

Procedures were identical to Experiment 3 with the exception that the forced action instructions were delivered verbally rather than by the colour in the LED lights. As in Experiment 3, participants had an unlimited time to make a button press following a verbal instruction, and were given feedback in the case of a wrong button press.

### 2.6.2 Results

Individual observer's data for each session along with each observer's overall average are displayed in Figure 2.9. Observer's averages across the three sessions along with the collapsed data for all participants are displayed in Figure 2.10. Mean PSS and JND scores calculated for each observer's session and averaged across sessions are displayed in Figure 2.11.

As in previous experiments, PSS and JND scores were compared to the Experiment 1 baseline. The same pattern of results was observed as in Experiments 2 and 3: when action was near vibration visual stimuli needed to lead tactile (M=-126 ms), and this was outside the baseline CI (-47 to -15 ms). On the other hand, when action was near light, the PSS scores flipped so that tactile information needed to lead visual information (M=6 ms).

Using voice commands (Experiment 4) instead of light commands (Experiment 3) appeared to reduce some of the uncertainty observed in Experiment 3 to produce results comparable to those observed in Experiment 2. Table 2.2 displays summary statistics for all of the experiments. As seen in Table 2.2, the average JND scores were reduced in Experiment 4 and were now comparable between the action near vibration and action near light conditions. In particular, for Experiment 4 the action near vibration condition JND mean was within the baseline CI (unlike in Experiment 3).

The binding effect between actions and same side modalities in the present experiment appeared within the range of Experiment 2 (free condition) rather than Experiment 3 (forced condition, light commands). These results suggest that free and forced action types may not differ after all. As seen in Figure 2.11, In Experiment 4 only N.L. produced a large PSS shift like those observed for all participants in Experiment 3. Interestingly, observer J.W. demonstrated a PSS within the baseline CI for actions that were near light and observer D.C demonstrated a PSS within the baseline CI for actions that were near vibration.  Granted the individual differences, the effect of action binding to stimuli presented on the same side appears to be a robust one and was replicated within this experiment. Table 2.1 displays mean PSS and JND scores for each participant for all the experiments.

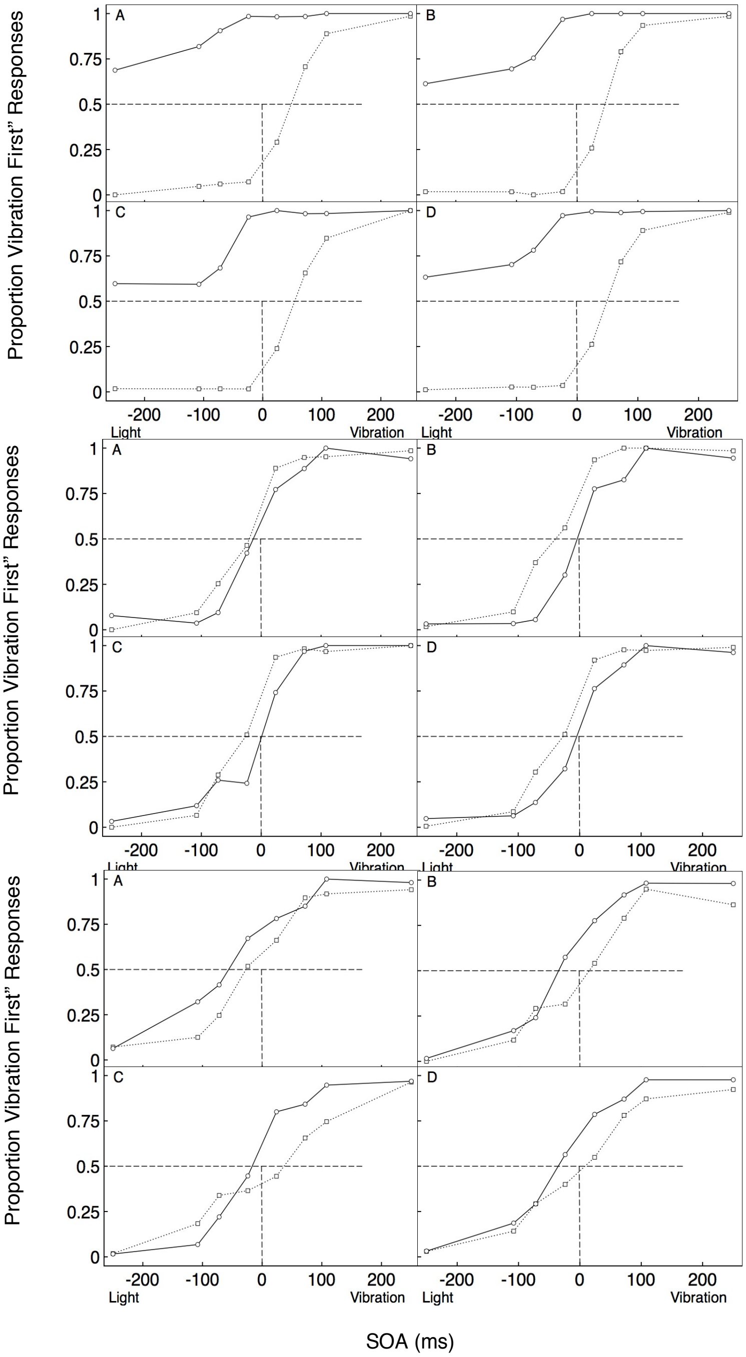


*Figure 2.9* Data from Experiment 4: Proportion "vibration first" responses for participants N.L., J.W., and D.C respectively. The darker, solid line represents action near vibration and the lighter, dashed line represents action near light. Panels A, B, and C depict performance on the first, second and third sessions for each participant respectively and panel D represents each observer's average across the three sessions.

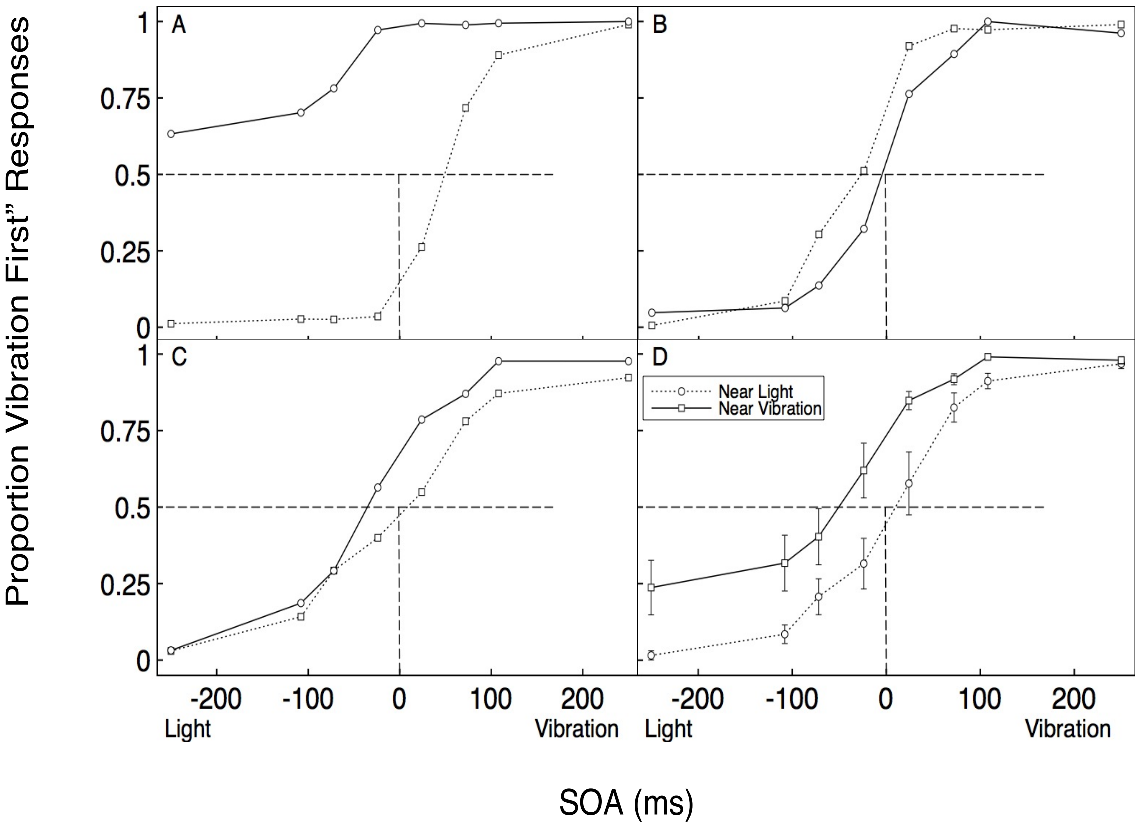
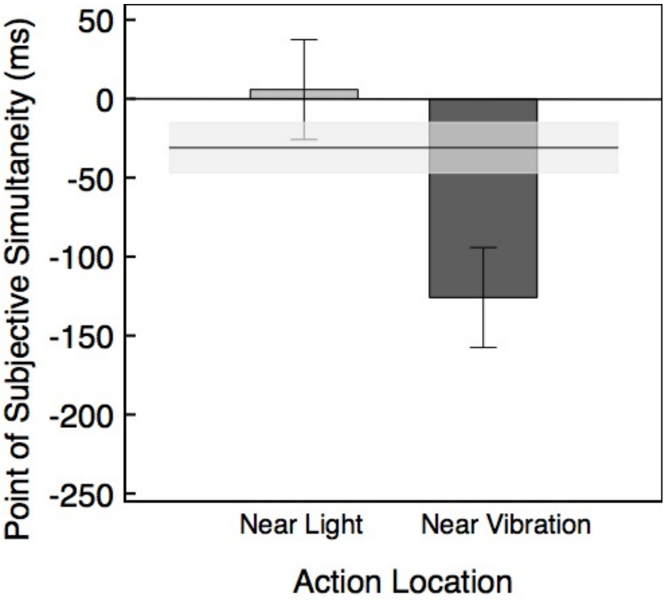


*Figure 2.10* Data from Experiment 4: Average proportion "vibration first" responses. Panels A, B and C represent averages across three sessions for participants N.L., J.W., and D.C. respectively. The darker, solid line represents action near vibration and the lighter, dashed line represents action near light. Panel D displays all participant averages. Error bars represent within-subject standard error of the mean.

a. PSS



b. JND

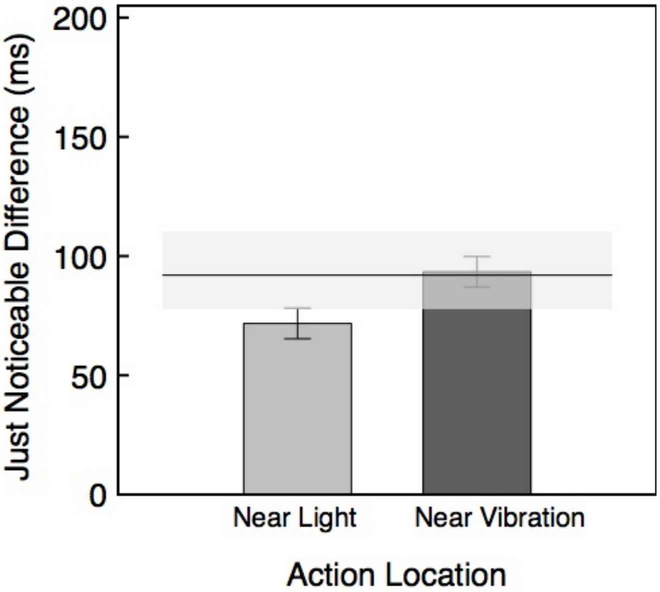


*Figure 2.11* Experiment 4: PSS (a) and JND (b) for action near vibration and near light conditions. Negative PSS scores represent the amount of time visual stimuli needed to lead tactile stimuli (in ms) to be judged as simultaneous. The JND scores represent the smallest interval needed between the two stimuli to accurately judge the temporal order on 75% of trials. Error bars reflect standard error of the mean, corrected for within-participants comparisons. In each graph, the horizontal black line represents Experiment 1 baseline mean estimate as predicted by a bootstrapping method and the shaded grey area represents the 95% estimated confidence interval.

Table 2.1

*Mean PSS and JND Scores for Individual Participants for Experiments 2-4*

| Experiment | M PSS[1] | | M JND[2] | |
|---|---|---|---|---|
| | Near Vibration | Near Light | Near Vibration | Near Light |
| Experiment 2: (Free Action) | | | | |
| AF | -123.6 | 61.2 | 119.4 | 108.9 |
| BT | -112.0 | -65.1 | 139.7 | 141.3 |
| DM | -98.6 | 27.2 | 70.8 | 60.4 |
| Experiment 3: (Forced Action, light commands) | | | | |
| AF | -357.7 | 101.6 | 168.5 | 91.8 |
| MT | -214.9 | -22.1 | 117.9 | 98.8 |
| NL | -235.1 | 14.1 | 221.0 | 107.8 |
| PF | -101.2 | 10.9 | 86.1 | 77.8 |
| Experiment 4: (Forced Action, voice commands) | | | | |
| NL | -322.4 | 55.4 | 134.4 | 64.2 |
| JW | -16.9 | -40.9 | 70.8 | 62.9 |
| DC | -38.2 | 2.9 | 74.9 | 88.1 |

[1] PSS values are in ms and were computed by averaging the lines of best fit for each participant, for each session, and then obtaining each participant's average across the sessions. Negative values indicate that light needed to be presented before vibration for PSS to be achieved, and positive values indicate that vibration needed to be presented before light for PSS to be achieved.

[2] JND values are in ms and were calculated by subtracting the SOA value at 0.75 proportion "vibration first" response form the SOA value at 0.25 proportion "vibration first" response on the line of best fit, for each participant session. The JND scores were then averaged across all session for each participant. Once transforming the proportions into z-scores, algebraically, JND = 0.675/ slope.

Table 2.2
*Summary statistics for Experiments 1-4*

| Experiment | Measure | PSS[1] | | JND[2] | |
|---|---|---|---|---|---|
| | | Same[3]<br>Near Vibration[3] | Different[3]<br>Near Light[3] | Same[3]<br>Near Vibration[3] | Different[3]<br>Near Light[3] |
| Experiment 1: Baseline | M | -13.6 | -30.6 | 115.3 | 92.2 |
| | SEM[4] | 4.6 | 4.6 | 2.8 | 2.8 |
| Experiment 2: Free Action | M | -110.8 | 7.7 | 110 | 103.5 |
| | SEM[4] | 11.8 | 11.8 | 2.7 | 2.7 |
| Experiment 3: Forced Action (Light commands) | M | -227.2 | 26.1 | 148.4 | 94.03 |
| | SEM[4] | 22.8 | 22.8 | 9.2 | 9.2 |
| Experiment 4: Forced Action (Voice commands) | M | -125.9 | 5.8 | 93.4 | 71.8 |
| | SEM[4] | 31.6 | 31.6 | 6.4 | 6.4 |

[1] PSS values are in ms and were computed by averaging the lines of best fit for each participant, for each session, and then obtaining the overall average of all participants. Negative values indicate that light needed to be presented before vibration for PSS to be achieved, and positive values indicate that vibration needed to be presented before light for PSS to be achieved.

[2] JND values are in ms and were calculated by subtracting the SOA value at 0.75 proportion "vibration first" response form the SOA value at 0.25 proportion "vibration first" response on the line of best fit, for each participant session. The JND scores were then averaged across all participants. Once transforming the proportions into z-scores, algebraically, JND = 0.675/ slope.

[3] For Experiment 1, "same" and "different" refers to relative stimulus side. For Experiment 2-4, actions were performed either near vibration stimulus or near light stimulus.

[4] SEM represents within-subject standard error of the mean

### 2.6.3 Discussion

The type of action, free or forced, does not appear to influence binding. Although the data from Experiment 3 appeared to demonstrate an increased binding effect between forced actions and same side stimuli, the present findings suggest that this effect could have been an artifact associated with task difficulty. Changing the forced action commands to more intuitive verbal instructions produced scores that were in line with those of Experiment 2. Voice commands also resulted in more precise performance overall—this was reflected in the near vibration condition JND scores, which were comparable to the baseline in Experiment 4 but outside of the baseline CI in Experiment 3. One observer, N.L., still demonstrated difficulty in judging order when action was near vibration. For this participant, the JND scores were difficult to interpret because a JND calculation requires a measure for the lower end of the curve (at 25% proportion "vibration first" response). Overall, the data indicate a robust binding effect of action to same side stimuli, but variability amongst participants. The effects of action on temporal precision are explored further in the next data chapter.

## 2.7 General Discussion

### 2.7.1 Summary

The effect of action on subsequent visual and tactile perception was investigated. Whether the type of action influenced subsequent perception was also of interest. Two major findings were obtained from the present study. First, action spatially binds to whichever sensory modality is presented in close spatial and temporal proximity, leading to faster perception of that modality. When action was performed near vibration, light needed to lead vibration for PSS to be achieved. On the other hand, when action was performed near light, vibrations needed to lead light for PSS to be achieved. The latter finding is a reversal of classic visuotactile TOJ task performance (Experiment 1; Spence et al., 2001). The bi-directional PSS shift was a robust effect, observed across all experiments.

Interestingly, across the experiments the effect appeared to be numerically larger for actions that preceded vibration compared to actions that preceded light, suggesting a stronger binding between motor movements and tactile stimuli. However, as discussed earlier, these findings must be interpreted with caution due to the current experimental design: the data was of psychophysical nature, thus lacking statistical analysis, only a small number of observers participated, and the baseline was obtained in a separate experiment. These issues were corrected for in Chapter 3.

A second major finding was that the type of action, whether free or forced, did not appear to influence binding. This implies that it is not the sense of agency or intention that leads to binding, but rather, the act of performing the action itself. The present findings and their implications are discussed in greater detail below.

### 2.7.2 Action and Laws of Multisensory Integration

Action can behave as a sensory stimulus when it comes to the laws of multisensory integration. This finding may be unique to visuotactile pairs. Past research on audiovisual pairs demonstrated that actions preceding stimuli resulted in perceptual shifts only toward the visual modality (Vallet & Shore, unpublished). Regardless of the spatial location of action and stimuli, audition needed to lead vision for PSS to be achieved. The present findings imply that it is not solely temporal proximity that influences binding between action and perception, but spatial proximity can also impact binding between action and visual and tactile targets. These are the first known to date findings that demonstrate action's ability to follow the same temporal and spatial integration laws, thus behaving a sensory stimulus.

Relevant stimuli rarely occur at the exact same moment; the brain requires a mechanism to ensure related stimuli are processed together. The intentional binding effect (e.g., Haggard et al., 2002; Haggard & Clark, 2003) is one mechanism by which the brain perceives actions and relevant consequences as occurring together; actions appear to shift forward in time and their sensory consequences appear to shift backward in time. This effect has never been examined across sensory modalities. Action binding to the modality presented in close spatial proximity is consistent with the causality hypothesis. The causality hypothesis suggests that effects occurring near the action must be relevant and thus increasing the chance of a binding effect (Moore & Obhi, 2012). However, it must be noted that the degree of binding appeared to be larger for proximate tactile stimuli. In nature, tactile stimulation following a motor movement may occur more often and serve more value to the observer, thus increasing the association between action and tactile targets (Gregory, 1967).

### 2.7.3 Mechanisms Involved in Action-Modality Binding Effect

The mechanisms involved in the binding effect remain unresolved. One possibility is that prior contingencies between actions and perceptions allow for predictions of sensory consequences before they occur; the anticipation of the consequences leads to faster perception (Haggard & Clark, 2003). Due to the more informative nature of tactile targets (Gregory, 1967), there is potential reason to believe that observers would anticipate vibration over light. Indeed, it was observed that binding between action and tactile stimuli occurred at a greater magnitude than with visual stimuli. An alternate possibility is that conscious awareness of the action and its consequences occur after the fact, as a reconstruction by our brain to explain what has already happened (Haggard & Clark, 2003). In other words, conscious awareness of actions and consequences are attributed post hoc. The present design cannot rule out either possibility.

Subjective time estimates depend on the internal pacemaker—a centralized, amodal timekeeper that counts the number of ticks per unit of time (Hodinott-Hill, Thilo, Cowey, & Walsh, 2002). Initiating or executing an action may alter the number of units counted by the internal pace maker. For example, the effect of chronostasis—time seems to freeze for a moment when first glancing at an analog clock, was first attributed to the brain's compensation for lost time during a saccade. However, more recent findings demonstrate that performing a motor movement may also alter temporal estimates (Park et al., 2003). Performing an action increases levels of arousal, leading to more units of time being counted by the internal pacemaker. This increase in units of time being counted could lead to an overestimation of the time it takes to complete the action.

Consequently, the action may appear closer in time to the stimulus that follows. This account would also explain the lack of difference between free and forced actions. Under the assumption of an internal clock, the sense of intention should play no role in binding, but rather the mere act of executing an action alters temporal perception. The exact mechanism involved in binding need to be further investigated.

### 2.7.4 Voluntary versus Involuntary Actions

Only voluntary actions were expected to influence perception. Past studies demonstrated the opposite of a binding effect for involuntary motor movements; actions and sensory stimuli were perceived further apart (e.g., Haggard et al., 2002). The sense of agency, or the feeling of control over action and consequences, is implicated in the intentional binding effect (Moore & Obhi, 2012). In Experiment 2, participants chose which button to press, thus experiencing a sense of agency for the action and the sensory consequence. On the other hand, when subjects were instructed which button to press (Experiment 3), no feeling of agency was expected. As such, it was surprising to find that the binding effect appeared to be even larger in that scenario. With a more intuitive stimulus-response mapping for the forced action, the apparently larger binding effect for forced actions and sensory modalities was not observed in Experiment 4. In fact, the effect in Experiment 4 (forced) resembled the size of the effect in Experiment 2 (free). This result suggests that there may be no difference in performance on visuotactile TOJ task for free and forced action types. The present findings indicate that perhaps it is not the type of action that influences perception, but rather the execution of the action itself. Alternatively, the current methods may have failed to truly distinguish between free and forced actions. The distinction between forced and free action types will be further discussed after Chapter 3 where the two action types are more carefully controlled.

It should be acknowledged that the current experimental design and methods might have failed to truly distinguish between free and forced actions. First, given the small number of participants and the variability between participants, it is difficult to make conclusive interpretations. In addition, the subjective sense of intent distinguishes free actions from forced ones. Intent is subjective, and may be an illusion (Strother et al., 2010). It is impossible to distinguish in which trials observers may have felt a sense of agency. Instructing participants to "choose" may be equivalent to instructing participants to press a specified button. Because it is possible for feeling of agency to develop post hoc, even in the forced condition participants may have felt as if they caused the consequence. On the other hand, being told to "choose" may have led to lack of feeling of intent. This prevents the formation of a clear distinction between voluntary and involuntary processes. Haggard et al. (2002) induced forced action via TMS. In this case, participants truly lacked any control over their action.

As such, it may be that the current design does not clearly differentiate between free and forced actions. In one view, free actions are self-generated, not triggered by external cues (Passingham, Bengtsson, & Lau, 2010). According to this definition, the criterion for free action was not met because the central fixation acted as an external cue for a button press. However, as mentioned above, if observers felt control over the button press and/or outcome, this can give rise to the illusion of agency (Obhi & Haggard, 2004).

Neuroimaging studies implicate different brain regions for free and forced actions. In one study, MEG activity was monitored as participants made free or forced actions. Observers either memorized a series of instructions for left or right key-presses (forced condition), or were told to choose left or right key-presses. A distinct pattern of activity was observed in the sensory cortices and temporal cortex prior to the execution of the action (Kostelecki et al, 2012). This result implies a true distinction between free and forced processes. The methods in the described study resemble the action type distinction in the present study. However, it is unknown how the differential patterns in activity translate in terms of perception. In summary, it remains unclear whether the lack of difference between free and forced action in the present study truly reflects no difference between action types, or rather reflects an absence of a clear distinction between action type in the present methodology. Lastly, the comparison of free versus forced actions was done cross-experimentally. It is important to investigate this in a more controlled way, within one experiment—Chapter 3 addresses this issue.

### 2.7.5 Conclusion

Action's ability to spatially bind to sensory modalities has not been previously observed. Vallet and Shore (unpublished) failed to demonstrate spatial binding for actions preceding audiovisual pairs, and as such, this effect may be unique to visuotactile combinations. Our daily interactions often rely on visual and tactile cues to orient ourselves in space. Our experiences with actions and visuotactile pairings may be more common than with audiovisual pairings. Most interactions with objects require visual and tactile information. Therefore, the need to spatially locate audiovisual stimuli following an action may be less usual. Based on the present findings and past research, it is reasonable to believe that actions may have different effects on other sensory modality pairings. In Chapter 3, I continue the exploration of the relation between action and sensory perception. The current established methodology was applied to investigate the effects of action on competing audiovisual, audiotactile and visuotactile pairings.

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# 3.0 Chapter 3: The Idiosyncratic Effects of Action on Multisensory Perception

## 3.1 Abstract

Voluntary motor movements performed in close proximity to sensory stimuli speed up perception of those stimuli. Specifically, this was shown to be the case for action preceding visuotactile events (Finkelshtein, unpublished; Chapter 2). In the present study I extended the research regarding the effects of action on subsequent multisensory perception to visuotactile (Experiment 1), audiovisual (Experiment 2), and audiotactile (Experiment 3) stimuli.

In this study, participants executed a chosen (left or right) button press (free condition), a fixed button press (forced condition), or no button press (wait condition) prior to a bimodal TOJ task. The sensory stimuli appeared on opposite ends to each other (either on the left, or on the right) to assess the spatial effects between action and sensory stimuli. The study concluded that actions behave in idiosyncratic ways on subsequent bimodal perception. Perception of visual or tactile stimuli was faster for stimuli that appeared on the same side as the action. This appeared to be the case for audiotactile stimuli as well. On the other hand, actions preceding audiovisual stimuli always led to faster visual perception, regardless of relative stimulus side. In addition, the type of action, whether free or forced, did not demonstrate differential effects. These findings imply that actions have dynamic influences on subsequent multisensory events, regardless of whether the action is chosen or fixed.

## 3.2 Introduction

Contrary to classic beliefs, perception is not a passive process independent of our behaviours—our motor movements influence how we view the world (c.f., Witt, 2011). Perception is dynamic, requiring synchronization of motor movements and sensory information across multiple modalities (Hommel, 2004; Vatakis & Spence, 2007; Harrar & Harris, 2008; King, 2005). The simple act of walking up a flight of stairs involves coordinating leg movements with tactile information (texture and sturdiness of the stairs) and visual information (steepness and location). A failure to coordinate these signals could cause one to trip. Not only does perception of the stairs impact the observer's motor movements, but also the motor movements and one's abilities can alter subsequent perception (Finkelshtein, unpublished; Chapter 2; Haggard Clark, & Kalogeras, 2002; Haggard & Cole, 2007; Fagioli, Hommel, & Schubotz, 2007; Park, Schlag-Rey, & Schlag, 2003). For example, a less fit observer may perceive a flight of stairs as steeper than an athletic counterpart (Witt, 2011), demonstrating that actions and perceptions interact in a dynamic manner. The current literature offers no consensus on how actions influence subsequent multisensory perception. The goal of this chapter is to explore temporal and spatial factors involved in the effects of action on perception of competing bimodal stimuli.

Actions speed up perception of some sensory modalities, but it is unclear which ones and to what extent (Haggard et al., 2002; Vallet & Shore, unpublished; Finkelshtein, unpublished; chapter 2). Cross-experimental findings on action effects are inconsistent. For example, voluntary actions led to faster perception of a tone (Haggard et al., 2002;

Haggard & Clark, 2003; Haggard & Cole, 2007). Similarly, hand configurations made prior to presentation of visual stimuli sped up perception of stimuli with matching dimensions (Fagioli et al., 2007; Wykowaska, Schubo, & Hommel, 2009). However, executing an action prior to the presentation of both auditory and visual information sped up perception of only visual stimuli (Vallet & Shore, unpublished). On the other hand, actions performed prior to the presentation of visual and tactile stimuli sped up perception of the sensory stimulus presented closest to the motor movement (Finkelshtein, unpublished; chapter 2). The cross-experimental discrepancies do not allow forming of general conclusions concerning the effect of action on perception. It is evident that action effects on perception are manifold and may vary depending on the sensory stimuli that follow.

### 3.2.1 Point of Subjective Simultaneity as a Measure of Processing Rates

The processing rates of each sensory modalities differs—varying travel speeds of signals and varying transduction rates by sensory organs lead to faster perception of some modalities over others (King, 2005; Harrar & Harris, 2008; Vroomen, Keetels, de Gelder, & Bertelson, 2004; Spence, Shore, & Klein, 2001; Zampini, Shore, & Spence, 2003). However, mechanisms exist to allow for perception of simultaneity—for instance, we perceive lip movements to coincide with voices despite the different processing times of auditory and visual signals (Jackson, 1953; Vatakis & Spence, 2007; King, 2005). The point of subjective simultaneity (PSS) represents the amount of time one modality must lead another to be judged as occurring concurrently (Shore & Spence, 2005).

The point of subjective simultaneity (PSS) is one measure to assess action's effects on subsequent perception. The PSS measures, established through previous literature, are assumed to represent different processing rates across modalities (Spence et al., 2001; Zampini et al., 2003; Zampini et al., 2005; Vroomen et al., 2004; King, 2005). In visuotactile and audiovisual temporal order judgment (TOJ) tasks, visual modalities must lead tactile and auditory modalities to achieve simultaneous perception; tactile and auditory stimuli are processed sooner than the visual (Spence et al., 2001; Zampini, et al., 2003; Vroomen et al., 2004; King, 2005). For audiotactile TOJ tasks, tactile stimuli must lead auditory stimuli to achieve simultaneous perception; the auditory modality is processed sooner (Zampini et al., 2005). Following an action, any changes in the established baseline processing rates of each multimodal pair will determine actions' influence on perception—the magnitude and direction of PSS shifts after a motor movement will determine the degree by which actions alter the perceived speed of one (or more) sensory target.

Perception of simultaneity for different bimodal combinations is modulated by unique mechanisms (Harrar & Harris, 2008). PSS judgments can be recalibrated through experience (Vroomen et al., 2004; Navarra, Vatakis, Zampini, Soto-Faraco, Humphreys, & Spence, 2005; Navarra, Soto-Faraco, & Spence, 2007). Although auditory information is typically processed before visual, repeated exposure to lights that preceded sounds after a fixed stimulus onset asynchrony (SOA) resulted in a perceptual shift so that visual information was perceived before auditory in a following audiovisual TOJ task (Vroomen et al., 2004; Harrar & Harris, 2008). Audiovisual pairs appear more flexible than other bimodal combinations—no recalibration was observed following the same exposure for audiotactile and visuotactile pairs (Harrar & Harris, 2008). In nature, audiotactile stimuli are most often experienced in internal space, and are therefore less likely to be separated by a large amount of time relative to audiovisual stimuli (Navarra et al., 2007). However, audiotactile pairs required a larger window of separation for integration after repeated exposure to asynchronous audiotactile stimuli (Navarra et al., 2007). These findings further implicate flexibility in the perception of simultaneity across modalities. Actions could impact perception of bimodal pairs in unique ways depending on the bimodal stimuli.

Recalibrations post repeated exposure of action-stimulus combinations have also been demonstrated (Stenson, Cui, Montague, & Eagleman, 2006). When participants repeatedly executed an action that followed a light after a fixed SOA, presentation of a light immediately after the motor movement led to the illusion that the light was presented before the action (Stenson et al., 2006). Recalibration of perceived order is not unique to sensory modalities, indicating action's ability to behave as sensory stimuli.

### 3.2.2. Perception of Multisensory Events

Spatial and temporal relation between stimuli impact perception of simultaneity (Vatakis & Spence, 2007; Spence et al., 2001). According to the unity assumption, stimuli presented in spatial and/or temporal proximity are likely to be perceived as a single percept; this is true for multisensory stimuli (Vatakis & Spence, 2007; Spence et al., 2001; Jackson, 1953). In bimodal TOJ tasks, visuotactile and audiovisual pairs presented near each other in external space were more likely to be perceived as concurrent—spatial proximity led to multisensory binding (Spence, Shore, & Klein, 2001; Zampini, Shore, & Spence, 2003). On the contrary, auditory and tactile stimuli presented near each other in external space do not exhibit a binding effect—the spatial relation does not influence perception when stimuli are presented in external space (Zampini et al., 2005). However, presentation of audiotactile stimuli close to the head (in internal space) exhibits the same effects as in other bimodal pairings, where auditory and tactile stimuli presented near each other are more likely to be perceived as concurrent (Kitagawa, Zampini, & Spence, 2005).

Actions may follow the unity assumption so that motor movements are bound to spatially and/or temporally proximate modalities. Executing an action shortly before the presentation of an auditory stimulus resulted in faster perception of that stimulus (Haggard et al., 2002; Haggard & Cole, 2007; Haggard & Clark, 2003). This effect, known as intentional binding, implicates the role of temporal proximity between actions and sensory consequences in binding. Similarly, audiovisual stimuli that followed immediately after an action, but not after a short delay, resulted in binding between the action and the visual modality (Vallet & Shore, unpublished). The spatial influences on binding of motor movements and sensory stimuli remain indeterminate. The spatial relation between motor movements and auditory or visual stimuli did not influence binding (Vallet & Shore, unpublished). Actions' ability to follow the spatial and temporal law needs to be further investigated.

### 3.2.3 Voluntary versus Involuntary Actions

Different types of motor movements influence subsequent perception in distinct ways (Haggard et al., 2002; Engbert, Wohlschlager, Thomas, & Haggard, 2007; Engbert, Wohlschlager, & Haggard, 2008; Moore, Lognado, Deal, & Haggard, 2009). Only voluntary (self-generated) actions, but not involuntary (other-generated) actions lead to an intentional binding effect—the action is "pulled" toward the stimulus so that they are perceived to occur closer together (Haggard et al., 2002; Engbert et al., 2007; Engbert et al., 2008). No intentional binding between motor movements and stimuli were exhibited if actions were TMS-induced (Haggard et al., 2002) or observed while generated by others (Engbert et al., 2007; Engbert et al., 2008). Following a self-induced motor movement, observers perceived stimuli to occur as a consequence of the action; the perception of agency modulates the binding effect between actions and modalities (Strother, House, & Obhi, 2010). The perception of agency is unlikely to occur for TMS-induced (forced) actions or other-induced actions. However, observing other-generated actions led to intentional binding when the intention to act was present within the observer (Strother et al., 2010). The perception of agency governs the intentional binding effect, but the intention to act may be sufficient to produce feelings of agency (Strother et al., 2010).

To establish whether different action types influence binding in distinct ways, voluntary and involuntary actions must be defined. In the present thesis, previous examination of free and forced actions concluded that binding effects are independent of the action type (Finkelshtein, unpublished; Chapter 2). Free actions were characterized by a choice of button press sides whereas forced actions were characterized by fixed button press sides (Finkelshtein, unpublished; Chapter 2). In this case, voluntary and involuntary actions were determined by the ability to make a decision. This is different than the ability to exert physical control over the action such as with TMS-induced or other-generated actions, where no physical control can be exerted (Haggard et al., 2002; Engbert et al., 2007; Engbert et al., 2008; Strother et al., 2010). If observing consequences following a motor movement is sufficient to establish a feeling of agency (Hommel, 1996; Storther et al., 2010), then dictating action location may not be sufficient to produce a forced action type condition. The way in which different action types influence perception was further explored in the present study.

### 3.2.4 Scope of the Present Study

The goal of the present study was to investigate action effects on subsequent perception of competing bimodal pairs: visuotactile, audiovisual and audiotactile. Secondly, the present research also investigated whether different action types (free or forced) impact perception in distinct ways. To examine action effects on subsequent multisensory perception, participants completed either free or forced button presses that followed either a visuotactile, audiovisual or audiotactile TOJ task. Each type of modality pairing was presented in separate experiments, while the action types (free or forced) were presented in all experiments, divided between blocks. To examine the role of spatial proximity on binding of actions and stimuli, each modality was presented on different sides of participants' external space so that on a given trial, the button press was executed near one modality and far from the other modality. A baseline no action "wait" condition, which served as a comparison, was intermixed within action type blocks.

### 3.2.5 Predictions and Contribution

Given the exploratory nature of this research, there are several possible outcomes. First, if making a decision is essential for sensation of agency, then binding effects may be enhanced when the actions are voluntary (Haggard et al., 2002; Strother et al., 2010). On the contrary, an inability to form a decision in the forced action condition may fail to evoke a feeling of agency so that no binding may occur. Second, because each bimodal pair influences perception differently (Harrar & Harris, 2008; Vroomen et al., 2004; Navarra et al., 2007; Zampini et al., 2005), it was expected that action would exhibit idiosyncratic binding effects on subsequent bimodal perception.

Actions preceding visuotactile stimuli were expected to bind to the most proximate modality. This prediction was based on my previous findings in which actions that preceded a visuotactile TOJ task sped up perception of the sensory stimulus presented near the action (Finkelshtein, unpublished; Chapter 2). I expected to replicate this finding in the present experiment—this would be observed as a perceptual shift in the direction of the modality closest to the action.

Actions do not spatially bind to audiovisual modalities. Instead, actions preceding an audiovisual TOJ task led to faster visual perception regardless of spatial properties (Vallet & Shore, unpublished). If action effects on audiovisual perception are robust, the same effect was anticipated with the current design. That is, in the present study, actions would bind to the visual modality regardless of spatial properties. A unidirectional perceptual shift toward vision was expected relative to the baseline.

Alternatively, the effect reported by Vallet and Shore (unpublished) could have been unique to their experimental design. In their study, the audiovisual TOJ was computer based. In the present design, participants held two wooden cubes that contained buttons for the motor movements. The cubes were held directly in front of the speakers that delivered sounds, and contained the light emitting diodes that delivered the lights. The visual bias observed by Vallet and Shore (unpublished) could have been a consequence of the computer apparatus. Amongst computer users, non-directional visual feedback (letters) is common following keyboard presses, whereas auditory feedback is less frequent. The preferential and non-directional binding to visual stimuli may be unique to computer-based tasks.

Action effects on audiotactile stimuli have not been previously explored. With visuotactile pairs, tactile stimuli that appeared close to the action were processed sooner. Conversely, audiovisual pairs displayed a lack of spatial binding to actions. Therefore, no clear predictions can be made regarding action effects on audiotactile perception. One possibility is that actions will preferentially bind to proximate tactile stimuli only. On the contrary, as observed with visuotactile pairs, actions may bind to either the auditory or tactile modality depending on spatial proximity. It is also important to note that audiotactile pairs are unique when it comes to the spatial law; audiotactile stimuli appear to be less spatial (Zampini et al., 2005). Unlike with other bimodal pairs, audiotactile pairs presented in external space do not demonstrate a binding effect for spatially proximate stimuli (Zampini et al., 2005), but do demonstrate binding between proximate auditory and tactile modalities that are presented in internal space (Kitagawa et al., 2005). Therefore, it will be interesting to observe how proximate actions affect these modalities.

The present research will provide a framework to explain how actions interact with competing modalities. Multisensory binding is ubiquitous in perceptions of daily events, but little is known about how actions influence binding of multiple modalities. The present methodology was utilized to investigate action effects on different competing bimodal pairs in a controlled way. Additionally, replication of previous findings would further establish the robustness of action effects. Exhibiting distinct effects dependent on the multimodal combination will provide further evidence of the dynamic processes involved in perception.

## 3.3 Experiment 1: Action Effects on Perceived Visual and Tactile Onsets

### 3.3.1 Methods

#### *Participants*

Twenty-one undergraduate McMaster University students (twelve female) participated in exchange for course credit. All participants were naïve to the goal of the study, and all reported normal or corrected vision. Participants ranged from 17 to 26 years old (M = 19.62, SD = 2.89), and all were right-handed. Participants signed a written consent form prior to participation. The study took about an hour to complete. All procedures were in accordance with the McMaster Research Ethics Board.

### *Stimuli and Apparatus*

The experiment took place in a black painted room with the lights off. The only light sources were the light emitting diodes (LED) stimuli and light entering underneath the door. Participants were seated facing a wall at a 81 cm high and 79.5 cm wide wooden table and faced a wall just behind the table. Two wooden cubes (8 cm L * 3.7 cm W * 5.2 cm H) were held in each hand at a position marked on the table, 24 cm to the left and 24 cm to the right of a centrally positioned vertical piece of masking tape. Two Logitech LS11 speakers were placed against the wall in front of the wooden cubes to deliver voice commands. A blue/yellow LED fixation was centrally mounted at the observers' eye level on the back wall.

Each cube was equipped with a red LED mounted on top and an Oticon-A (100 Ohm) bone-conducting vibrator situated underneath central circular buttons (2 cm in diameter). The LED lights were presented as visual stimuli and the vibrations (driven by a 250-Hz sine wave) were presented as the tactile stimuli. The cubes were held with the thumbs on top of the buttons, and the fingers underneath the wooden cube. Figure 3.7 pictures the stimuli used and the overall experimental set-up of Experiments 1, 2 and 3.

Two foot-pedals affixed to an adjustable Plexiglas frame were placed on the right side beneath the table. The heel and the toes of the right foot were depressed over the two pedals; participants lifted their heel or toes to make TOJ responses. Continuous white noise was played through headphones to mask out external noises produced by the equipment. The Experiment was programmed and presented via MATLAB (R2011b), on a Dell dimension 8250, Pentium® 4 computer.

### *Design*

The factors of interest were: action type (free vs. forced), action location (near vibration, near light, or wait) and SOA (±250 ms, ±108 ms, ±72 ms or ±24 ms, negative SOAs indicated light stimuli preceded vibrations and positive SOAs indicate vibrations preceded light). This design resulted in 48 possible conditions (2 action types x 3 action locations x 8 SOAs). Subjects completed 10 blocks of 72 trials each (a total of 720 trials). Action type was presented in alternating blocks and action location (including the wait condition) and SOAs were randomly intermixed within-blocks. Within each block, there were 48 trials in the action condition (24 left action and 24 right action, or 48 free actions) and 24 trials in the no action condition (wait trials). The first stimulus appeared on each side in equal proportions across all conditions.

While the effect of action type was of interest, action type did not reach significance and did not interact with any other factors for all the experiments. As a result, action type was removed as a factor from the analysis for all experiments. This issue is further addressed in the General Discussion section.

### *Procedures*

Participants were familiarized with the foot-pedal mappings by completing 20 trials of a speeded discrimination task. On each trial, a light or vibration was presented for 20 ms and participants lifted their heel for vibration and toes for light as quickly as possible. Most participants performed this task without difficulty. However, if they responded incorrectly for more than 4 trials, the task was repeated. Following the discrimination task, 10 practice trials of the experimental TOJ task (5 free trials; 5 forced trials) were completed. Participants were given the opportunity to do more practice trials until they felt comfortable with the task.

Following the practice trials, participants completed a visuotactile TOJ task by indicating which modality they perceived first. Each trial began when the central yellow fixation LED lit up for 250 ms. Participants maintained gaze on the fixation light throughout the experiment. Following the fixation light, a male-recorded voice command from the speakers instructed participants on the action type: “left”, “right”, “choose” or “wait”. The baseline condition (“wait”) was intermixed within all blocks, while the forced (“left” or “right”) and free (“choose”) action types were separated by blocks. In the free condition, participants chose the button side, but were instructed to press both buttons in approximately equal proportions throughout the experiment. There was no time limit for the button press. For the “wait” condition, participants were instructed not to make a button press. In the case that a button was pushed on a “wait” trial, or the wrong button was pushed in a forced trial (e.g., left instead of right) participants were given feedback and those trials were disposed. Feedback consisted of a yellow central LED, the vibrators of both cubes, and green LEDs on the cubes, all of which simultaneously lit up and vibrated for 500 ms. Participants made a foot-pedal response to restart a new trial when wrong response feedback was received.

The first modality was presented for 20 ms either 10 ms following a button press or 500 ms later in the “wait” condition. The 500 ms delay was chosen based on previous literature that demonstrated no binding between actions and consequences after a 500 ms delay (Vallet and Shore, unpublished). After a varied SOA, the second modality appeared for 20 ms always on the opposite cube. Participants lifted their toes or heel to indicate which modality they perceived first. Accuracy was emphasized over speed, but if no response was made within 3000 ms, participants received the same feedback as for wrong button press.

### 3.3.2 Results

#### ***Removal Criteria***

Speeded discrimination and practice trials data were not subjected to analysis. Trials on which the wrong button was pressed or responses that exceeded 3000 ms were also excluded from the analysis. This exclusion procedure resulted in the removal of 1.3% of trials. Because action type was removed from the analysis, the proportion "vibration first" responses were collapsed across free and forced conditions. The collapsed proportion "vibration first" responses of the TOJ were transformed into z-scores. The transformed z-scores and the eight SOAs were used to calculate slopes and intercepts for each participant. The obtained lines of best fit were then used to compute the PSS, JND and correlation coefficient of each participant. Participants were excluded from the analysis of variance if they met one or more of following criteria: A. average proportion modality first responses across all the conditions at one or both extreme SOAs (±250 ms) was below 0.75, B. PSS scores higher than 250 ms, C. correlation of best-fit lines was lower than 0.70. Application of these criteria resulted in the removal data from three participants. The data from the remaining 17 participants were subjected to the analysis. In the "choose" action type condition, the right and left buttons were pushed in approximately equal proportion (49% and 51% respectively).

### ***ANOVA on Proportion "Vibration First" Responses***

The proportion "vibration first" responses were subjected to a repeated-measures ANOVA with the factors action location (near light, near vibration, or wait) and SOA (±250 ms, ±108 ms, ±72 ms or ±24 ms, where negative SOAs indicated light stimuli preceded vibrations and positive SOAs indicate vibrations preceded light). The proportion "vibration first" responses as a function of SOA, collapsed across action type are represented in Figure 3.1. In the case of violation of Mauchly's test of sphericity, the Greenhouse-Geisser epsilon (ε) and non-adjusted degrees of freedom are reported. Not surprisingly, there were more "vibration first" responses with increasing SOAs [F (7,112)=201.4, $p<0.001$, $\varepsilon=0.25$]. The average proportion "vibration first" responses were influenced by action locations relative to each sensory stimulus (action location) [F (2,32)=48.67, $p<0.001$, $\varepsilon=0.66$], with the least amount of "vibration first" responses when action was near light. The effect of action location interacted significantly with SOA [F(14,224)=13.73, $p<0.001$, $\varepsilon=0.39$], indicating that the proportion of "vibration first" responses as a function SOAs depended on the action location (near vibration or near light) and/or whether the action was performed at all (wait condition).

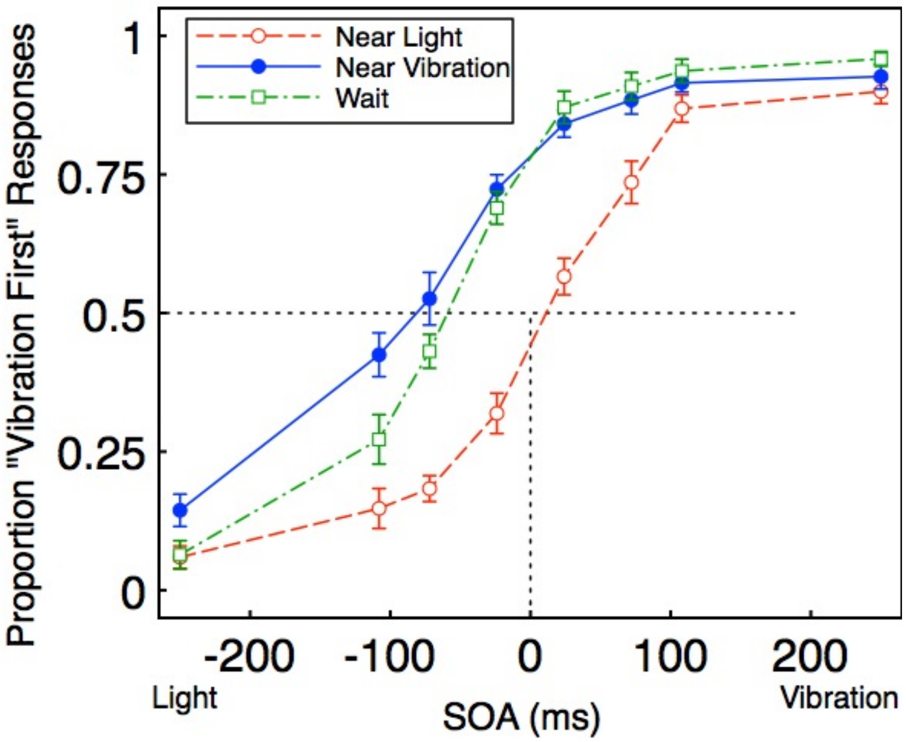


*Figure 3.1* Proportion “vibration first” responses as a function of SOA collapsed across action type, for Experiment 1. Error bars reflect standard error of the mean, corrected for within-participants comparisons.

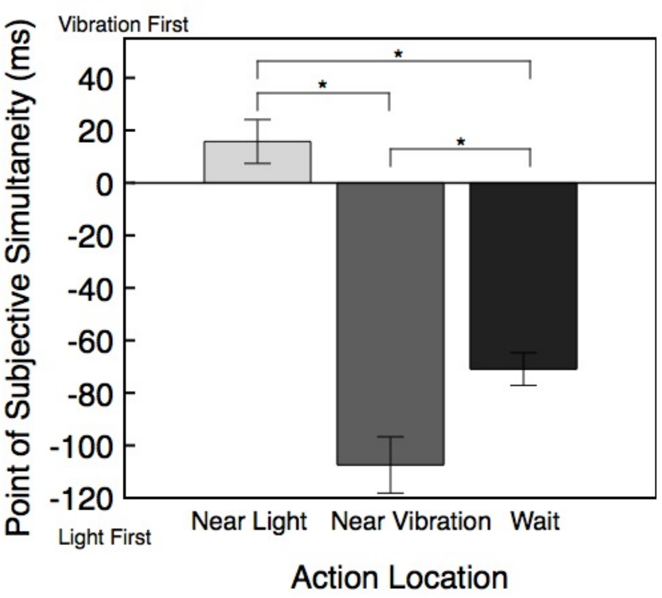
### ***ANOVA on PSS and JND***

The slopes and intercepts obtained from the z-transformed data were used to compute the PSS (-intercept/slope) and JND (0.675/slope). PSS and JND scores were collapsed across action type condition (free and forced) and paired-sample t-tests were computed to compare performance between each of the three action location pairs (action near vibration – action near light, action near vibration – wait, and action near light– wait). The PSS analysis revealed a significant difference between each of the three pairs [$t(16)=6.76$, $p<0.001$)], [$t(16)= -2.37$, $p=0.031$)] and [$t(16)=8.6$, $p<0.001$] respectively. In the baseline wait condition (when no action was made), light needed to lead vibration by about 71 ms for PSS to be achieved, this was significantly different than a 0 ms PSS [$t(16)=-9.73$ , $p<0.001$]. Compared to the baseline, the amount of time required for light to lead vibration increased significantly to 107 ms when action was performed near vibration. On the other hand, when an action was performed near light, the PSS scores flipped so that vibration needed to lead light by about 16 ms. The data indicate earlier perception of the stimulus that appears on the same side as the action.

To obtain a measurement of the binding effect size, the difference in PSS scores between each of the action conditions and the baseline wait condition were compared. The action near light condition produced a larger binding effect ($M=86.7$ ms) compared to the action near vibration condition ($M=36.5$ ms), [$t(16)=2.70$, $p=0.016$]. This indicates that while action bound to whichever sensory stimulus appeared on the same side, vibrations needed to lead light by a significantly greater amount of time when action was near light compared to the amount of time that lights needed to lead vibration in the action near vibration condition. In other words, actions appear to preferentially bind to the visual modality over the tactile modality.

The paired t-test comparisons on JND scores revealed a significant difference between the action near vibration condition and the wait condition [t(16)=2.38, p=0.015] and a marginal difference between the action near vibration compared to action near light conditions [t(16)=-1.79, p=0.09]. Performance was worst for the action near vibration trials.

a. PSS



b. JND

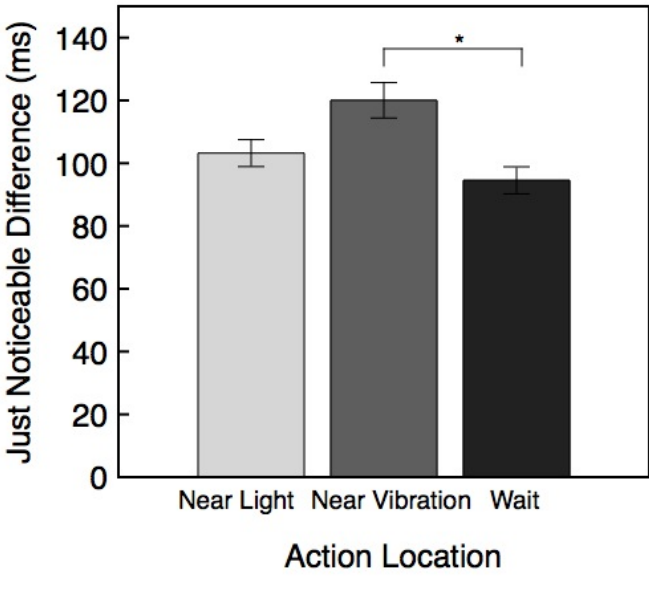


*Figure 3.2* Experiment 1: PSS (a) and JND (b) for action near vibration, action near light, and wait conditions. The PSS scores represent the amount of time one stimulus needed to lead another stimulus (ms) to be judged as simultaneous. Negative PSS scores indicate visual stimuli led tactile stimuli. The JND scores represent the smallest required interval between the two stimuli to accurately judge the temporal order on 75% of trials. Error bars reflect standard error of the mean, corrected for within-participants comparisons.

### 3.3.3 Discussion

Consistent with the previous chapter's findings, the current findings demonstrated that actions bound to subsequent proximate sensory stimuli (Finkelshtein, unpublished; chapter 2). In other words, the stimulus that appeared near the action was processed sooner than the stimulus that appeared far from the action. The effect was clearly evident when comparing each action condition to the baseline. Actions bind to relevant stimuli, and proximity could be an indicator of relevance.

Surprisingly, it was also observed that actions preferentially bound to the visual modality over the tactile. The difference in the binding effect between the baseline wait condition and the action near light condition was greater than the difference between the baseline wait condition and action near vibration condition. These findings constitute the first demonstration that action binds with preference to the visual modality over the tactile modality. While actions sped up the perception of either nearby sensory modality, this effect of faster perception was enhanced for visual stimuli following an action compared to tactile stimuli following an action.

The finding of greater binding to the visual modality following an action contrasts with the results of Chapter 2, in which actions were numerically demonstrated to preferentially bind to touch. It is important to note that no actual statistical analyses were computed in Chapter 2, and the methods of Chapter 2 were different and more ambiguous. First, the free and forced action conditions were split into separate studies in Chapter 2, as opposed to blocked within one study as in the present experiment. Second, in the forced condition in Chapter 2, participants were required to arbitrarily map blue and yellow fixation light colours to left or right button presses—this introduced a difficulty that was observed by the greater JND scores of participants. Third, the baseline condition was obtained in a separate experiment that had different methods and different participants, the baseline as was used as an estimated comparison. Lastly, fewer participants were enrolled in the studies of Chapter 2, which introduced greater variability. These differences make it difficult to draw true conclusion from Chapter 2 data. On the other hand, in the present study the statistically larger binding effect size strongly implicates a preferential binding to vision.

Lastly, as indicated by the JND scores, temporal resolution was overall the worst after vibration followed nearby actions. Executing an action that followed nearby vibrations impaired the ability to accurately differentiate the order of sensory targets. Temporal resolution was significantly lowered following an action and nearby vibration compared to a baseline wait condition, and was marginally worse than when visual stimuli appeared near the action.

## 3.4 Experiment 2: Action Effects on Perceived Auditory and Visual Onsets

### 3.4.1 Methods

#### *Participants*

Twenty-eight McMaster University students (23 females) participated in exchange for course credit. All participants were naïve to the goal of the study, and all reported normal or corrected to normal vision. Participants ranged from the age of 17 to 21 years old (M = 18.57, SD = 0.92), and 26 were right-handed. All participants signed a written consent form prior to participation.  The study took about an hour to complete. All procedures were in accordance with the McMaster Research Ethics Board.

### *Stimuli and Apparatus*

The same stimuli and apparatus were used as described in Experiment 1. An additional pair of Dell AX210 speakers was positioned directly in front of the cubes to deliver the auditory stimuli. The auditory stimuli were1000 Hz tones, presented at a 44100 Hz sampling frequency for 20 ms.

### *Design*

The design was the same as in Experiment 1 with minor changes. The factors were: action type (free vs. forced), action location (near light, near sound, and wait) and SOA (±250 ms, ±108 ms, ±72 ms or ±24 ms, negative SOAs indicated auditory stimuli were presented first and positive SOAs indicated visual stimuli were presented first). All other aspects of the design were identical to Experiment 1. As in Experiment 1, the data were collapsed across action type, and this factor was not included in the data analysis (see Appendix A).

### *Procedures*

Procedures were identical to those described in Experiment 1 with the exception that participants performed an audiovisual TOJ. The light stimuli were LEDs on top of the cubes (as in Experiment 1), and the sound stimuli were tones presented from the speakers directly in front of the cubes (Figure 3.7). Observers lifted their heel to indicate light first responses, and their toes to indicate sound first responses. Participants received the same tactile and light feedback for wrong button presses or responses exceeding 3000 ms.

### 3.4.2 Results

The data were analyzed in the same manner as described in Experiment 1. The same exclusion criteria were applied. The data from five participants were removed in accordance to the exclusion criteria, and the data from six participants were removed due to technical errors. Data from the remaining 17 participants were subjected to analyses of variance. Removal of wrong button responses and responses exceeding 3000 ms accounted for 2.3% of trials. In the "choose" action type, participants pushed left and right buttons in equal proportion (49.6% and 50.4% respectively).

#### ***ANOVA on Proportion "Light First" Responses***

The proportion "light first" responses were subjected to a 2 (action type: free vs. forced) x 3 (action location: near light, near tone, wait) x 8 (SOA: ±250 ms ±108 ms, ±72 ms and ±24 ms) repeated-measures ANOVA. In the case that Mauchly's test of sphericity was violated, the Greenhouse Geisser epsilon values are reported with the non-corrected degrees of freedom and p-values. Figure 3.3 represents the proportion "light first" responses as a function of SOA collapsed across action type.

Unsurprisingly, as the SOA increased, there was an increase in the proportion of "light first" response [$F\ (7,112)=178.74$, $p<0.001$, $\varepsilon=0.27$]. Also, the proportion of "light first" responses differed across the action location conditions [F (2,32)=10.63, p<0.001, ε=0.75]. Critically, these action location and SOA entered into a significant interaction with each other [F (14, 224)=5.32, p<0.001, ε=0.47] indicating that the impact of SOA was different across the three different action location conditions.

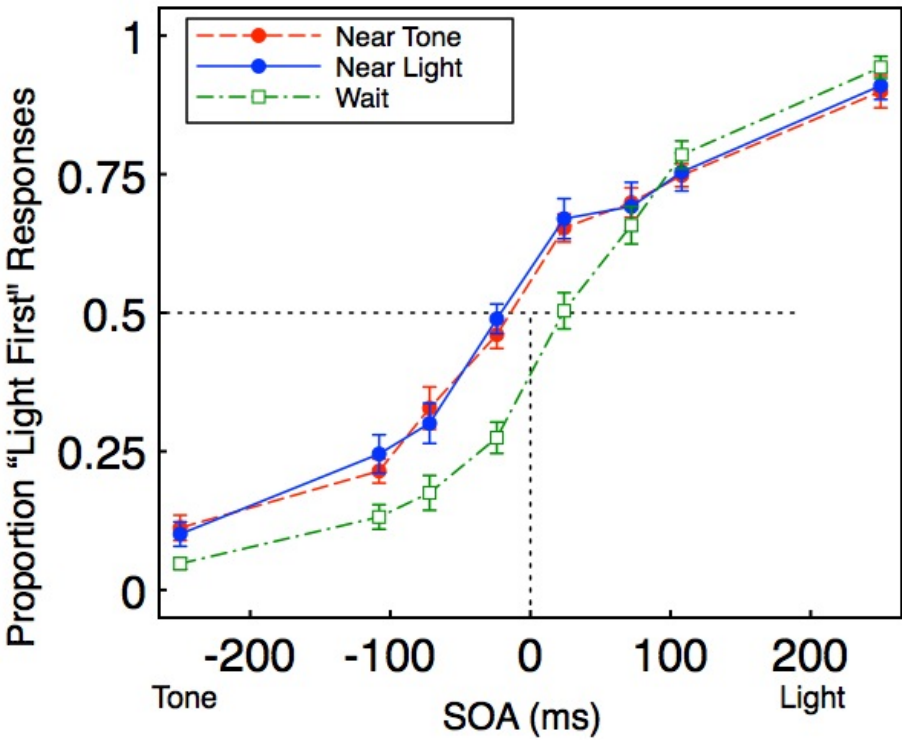


*Figure 3.3* Proportion "light first" responses as a function of SOA collapsed across action type, for Experiment 2. Error bars reflect standard error of the mean, corrected for within-participants comparisons.

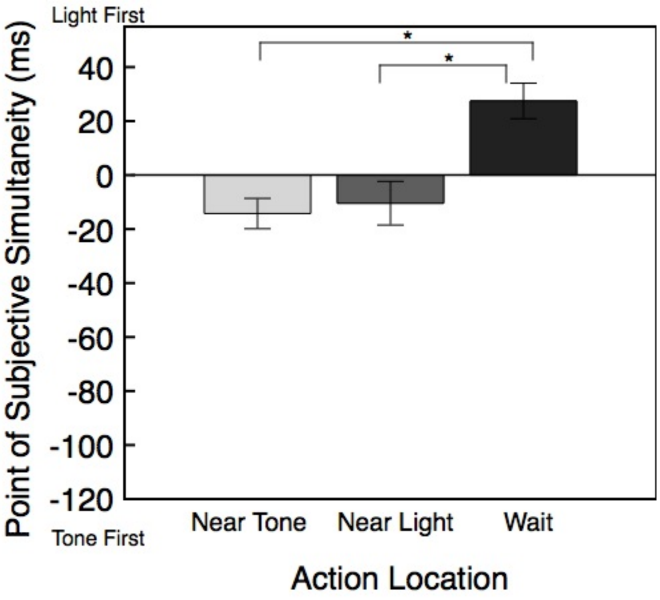
### *ANOVA on PSS and JND*

As in Experiment 1, the proportion “light first” scores were converted into z-scores and the slopes and intercepts were computed to calculate the best-fit lines for each participant, using the eight SOAs. Again, the PSS and JND scores were collapsed across action type and subjected to three, paired-sample t-tests (near light–near tone, near light–wait and near tone–wait). Interestingly, the PSS analysis revealed no significant difference between the two action locations (near light–near tone), but each action location was significantly different from the wait condition [$t(16)=-4.53$, $p<0.001$ for near tone–wait, and $t(16)=-2.78$, $p=0.013$ for near light–wait]. When a button press was performed, auditory stimuli needed to precede visual stimuli by about 14 ms (action near tone) and 10 ms (near light) compared to baseline wait condition where visual stimuli needed to precede auditory stimuli by 27 ms. Secondly the baseline wait condition significantly differed from 0 ms, indicating auditory information was processed before tactile [$t(16)=3.21$, $p=0.005$].

The binding effect for action near light condition ($M=37.9$ ms) did not significantly differ from the binding effect for action near tone condition ($M=41.7$ ms) [$t(16)=0.311$, $p=0.76$]. Regardless of the relative action location, the binding to vision is of the same magnitude.

The JND data followed the same pattern. In the wait condition, temporal precision was better ($M=94$ ms) than in each of the action conditions ($M=130$ ms for action near tone and $M=132$ ms for action near light).

a. PSS



b. JND

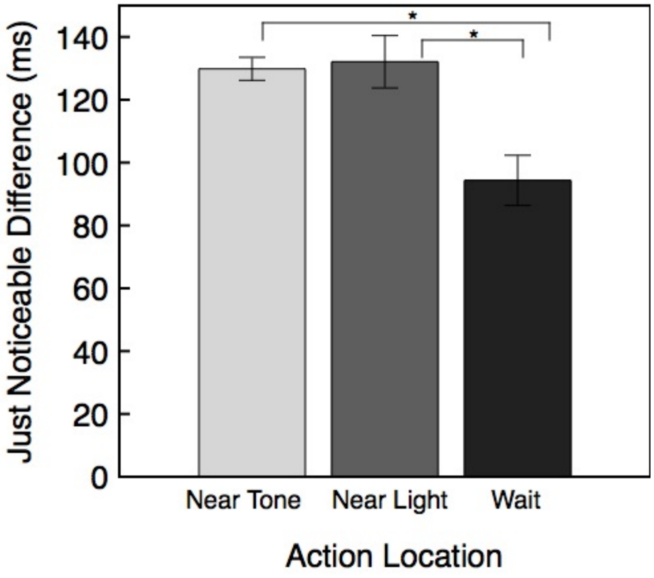


*Figure 3.4* Experiment 2: PSS (a) and JND (b) for action near tone, action near light, and wait conditions. The PSS scores represent the amount of time one stimulus needed to lead another stimulus (in ms) to be judged as simultaneous. Negative PSS scores indicate auditory stimuli led visual stimuli. The JND scores represent the smallest interval required between the two stimuli to accurately judge the temporal order on 75% of trials. Error bars reflect standard error of the mean, corrected for within-participants comparisons.

### 3.4.3 Discussion

Action affects audiovisual modalities differently than visuotactile modalities. Unlike with visuotactile modalities, action does not bind to spatially proximate sensory stimuli. Instead, action preferentially binds to the visual modality regardless of spatial location. When an action was performed, auditory stimuli needed to lead visual stimuli for PSS to be achieved. This result is in contrast with the baseline condition in which auditory stimuli were processed before visual stimuli. This effect is in line with Vallet and Shore's (unpublished) finding, which also concluded actions preferentially bind to the visual targets, while utilizing a computer-based equipment. In their study, participants made keyboard presses that followed either an auditory tone presented from the speakers and a circle that flashed on the computer monitor (Vallet & Shore, unpublished). These methods are inherently different than the cube equipment used in the present design. For one, computers are commonly used in everyday activities and thus may have resulted in different binding effects. The present findings further implicate preferential binding of action to visual stimuli over auditory stimuli, indicating the robust effect of action on subsequent audiovisual perception.

Similar to Experiment 1 in which temporal precision was the lowest following an action near vibration, the current JND scores indicated an overall better ability to detect order of sensory stimuli when no action was executed compared to both action near light and action near tone conditions. This result indicates that performing a motor movement may interfere with detection of order of stimuli.

## 3.5 Experiment 3: Action Effects on Perceived Auditory and Tactile Onsets

### 3.5.1 Methods

#### ***Participants***

Twenty undergraduate McMaster University students (14 female) participated in exchange for course credit. All participants were naïve to the goal of the study, and all reported normal or corrected to normal vision. Participants ranged from 17 to 20 years old (M = 18.4, SD = 0.88), and 18 were right-handed. All participants signed a written consent form prior to participation. The study took about an hour to complete. All procedures were in accordance with the McMaster Research Ethics Board.

#### ***Stimuli and Apparatus***

Stimuli and apparatus were identical to Experiment 2. The audiotactile TOJ task involved vibrations presented from the cube for 20 ms and tones presented from the speakers directly in front of the cubes for 20 ms. Because there were no LED stimuli (except the fixation LED), a dim lamp was situated behind the participant to allow for some visibility. The experimental stimuli and the overall set-up of Experiments 1, 2 and 3 are depicted in Figure 3.7.

#### ***Design***

The design was identical to Experiment 2, with the exception that subjects responded to auditory tones and vibrations. Negative SOAs indicated audition was presented first; positive SOAs indicated vibrations were presented first. Action location was either near vibration, near tone, or wait. Participants lifted their heel for vibration first responses, and their toes for tone first responses. Again, action type (free versus forced) was excluded as a factor in the analysis.

#### *Procedures*

Procedures followed those of Experiment 2, but an audiotactile TOJ task was performed instead of an audiovisual one.

### 3.5.2 Results

The same removal criteria were applied as described for Experiments 1. This procedure resulted in the removal of data from three observers; data from the remaining 17 observers were subjected to the data analysis. An additional 1% of trials were removed due to the wrong button being pushed, or response times greater than 3000. As in previous experiments, approximately an equal proportion of left and right actions were made in the "choose" condition (49% left, 51% right).

#### *ANOVA on Proportion "Vibration First" Responses*

The proportion "vibration first" responses collapsed across action type for the three action locations are displayed in Figure 3.5. Unsurprisingly, the proportion "vibration first" responses increased with increasing SOA [$F(7,112)=215.79$, $p<0.001$, $\varepsilon=0.28$]. In addition, the proportion of "vibration first" responses depended on action location [$F(2,32)=7.94$, $p=0.002$], and this effect of action location interacted with SOA [$F(14,224)=11.12$, $p<0.001$, $\varepsilon=0.41$].

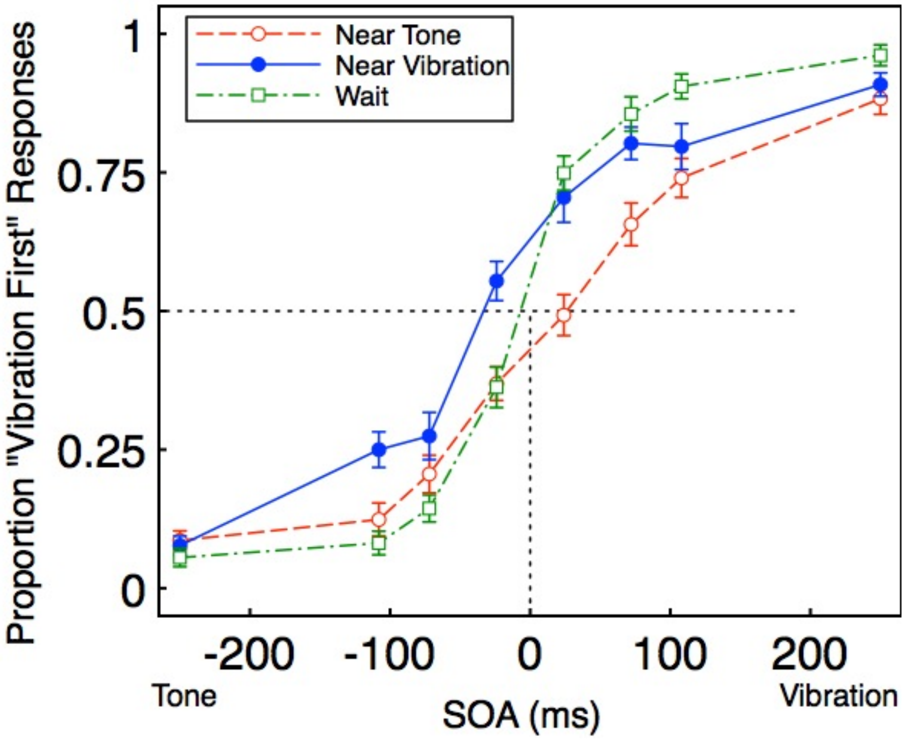


*Figure 3.5* Proportion “vibration first” responses as a function of SOA for (N=17) collapsed across action type, for Experiment 3. Error bars reflect standard error of the mean, corrected for within-participants comparisons.

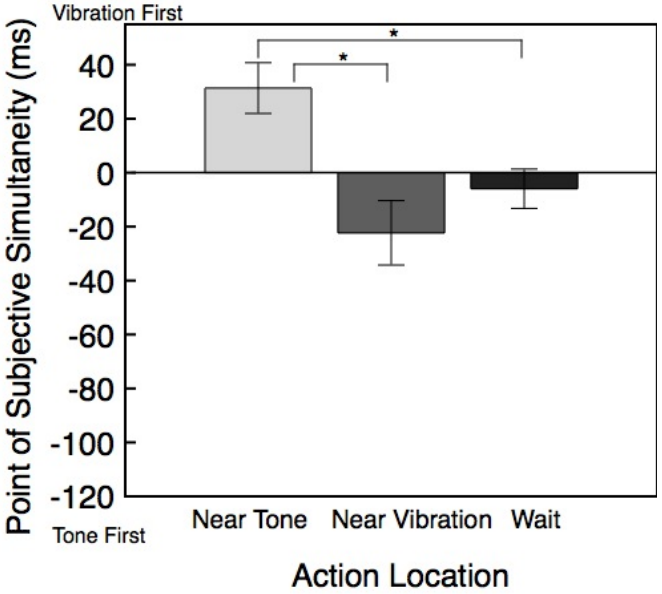
### ***ANOVA on PSS and JND***

PSS and JND scores were collapsed across action types and calculated in the same manner as described in Experiment 1. The average collapsed JND and PSS scores are presented in Figure 3.6. Paired-sample t-tests were computed to compare PSS scores between the three action locations. In the baseline condition, the tactile modality was processed before the auditory modality—tones needed to lead vibration by about 6 ms for PSS to be achieved, however this was not significantly different from 0 ms PSS [t(16)=-0.77, p=0.453]. This baseline wait PSS estimate was not significantly different from the 22 ms that tones needed to lead vibrations for perception of simultaneity in the action near vibration condition, [t(16)=-0.94, p=0.36]. On the other hand, when actions were performed near the tone, tactile stimuli had to be presented about 31 ms before auditory stimuli for perception of simultaneity. The action near tone PSS score significantly differed from that for both the action near vibration condition [t(16)=2.65, p=0.017] and the wait condition [t(16)=3.15, p=0.006].

As in Experiments 1 and 2, the effect sizes for each action condition were compared. A paired-sampled t-test revealed no significant difference for the action near tone condition (M=37.3 ms) from the binding effect size for the action near the vibration condition (M=16.4 ms) [t(16)=0.96, p=0.35], indicating a binding effect of a similar magnitude degree for each action location condition.

As with the previous experiments, the JND t-tests revealed overall better temporal resolution for the wait condition (M=81 ms) compared to the action near vibration (M=112 ms), [t(16)=4.11, p=0.001] and action near tone (M=124 ms) conditions, [t(16)=3.22, p=0.005]. The descriptive statistics for the JND and PSS scores for Experiments 1, 2 and 3 are presented in Table 3.1.

a. PSS



b. JND

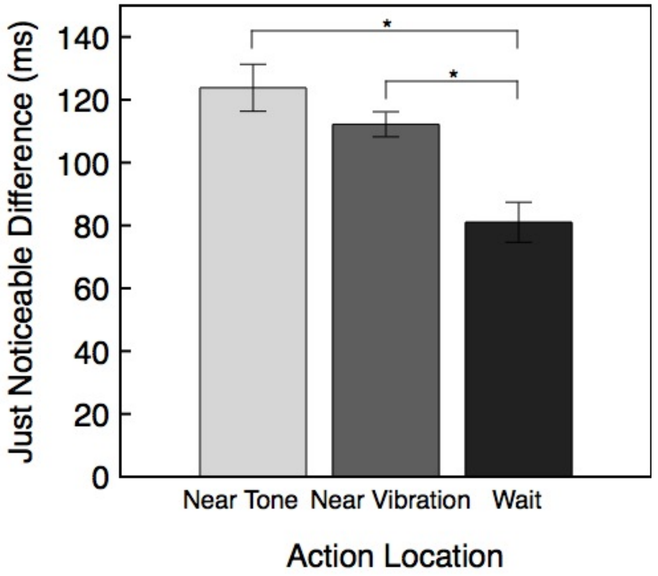


*Figure 3.6* Experiment 3: PSS (a) and JND (b) for action near tone, action near vibration, and wait conditions. The PSS scores represent the amount of time one stimulus needed to lead another stimulus (in ms) to be judged as simultaneous. Negative PSS scores indicate auditory stimuli led tactile stimuli. The JND scores represent the smallest interval required between the two stimuli to accurately judge the temporal order on 75% of trials. Error bars reflect standard error of the mean, corrected for within-participants comparisons.

Table 3.1

*Summary statistics for Experiments 1-3*

| Experiment | Action location | PSS[1] |  | JND[2] |  |
|---|---|---|---|---|---|
|  |  | M | SEM[3] | M | SEM[3] |
| 1 – Visuotactile | Near Vibration | -107.43 | 16.32 | 116.51 | 10.71 |
|  | Near Light | 15.70 | 9.49 | 99.13 | 10.73 |
|  | Wait | -70.90 | 7.29 | 90.38 | 9.43 |
| 2 – Audiovisual | Near Light | -10.42 | 11.97 | 132.10 | 18.97 |
|  | Near Tone | -14.24 | 11.05 | 129.85 | 12.80 |
|  | Wait | 27.47 | 8.56 | 94.36 | 5.63 |
| 3 - Audiotactile | Near Vibration | -22.30 | 17.63 | 112.20 | 10.21 |
|  | Near Tone | 31.37 | 13.99 | 123.83 | 16.53 |
|  | Wait | -5.94 | 7.73 | 81.01 | 4.47 |

[1] PSS values are in ms and were computed by averaging the lines of best fit for each participant. In Experiment 2, positive values indicate visual stimuli were presented first, and negative values indicate auditory stimuli were presented first. In Experiments 1 and 3 positive values indicate tactile stimuli were presented first. Negative values indicate light was presented first in Experiment 1, and audition was presented first in Experiment 3.

[2] JND values are in ms and were calculated by subtracting the SOA value at 0.75 proportion first response form the SOA value at 0.25 proportion first response on the line of best fit, for each participant. Once transforming the proportions into z-scores, algebraically, JND = 0.675/ slope.

[3] SEM represents standard-error of the mean as used in the ANOVA calculations.

a). Stimuli

b). Experimental Set-up

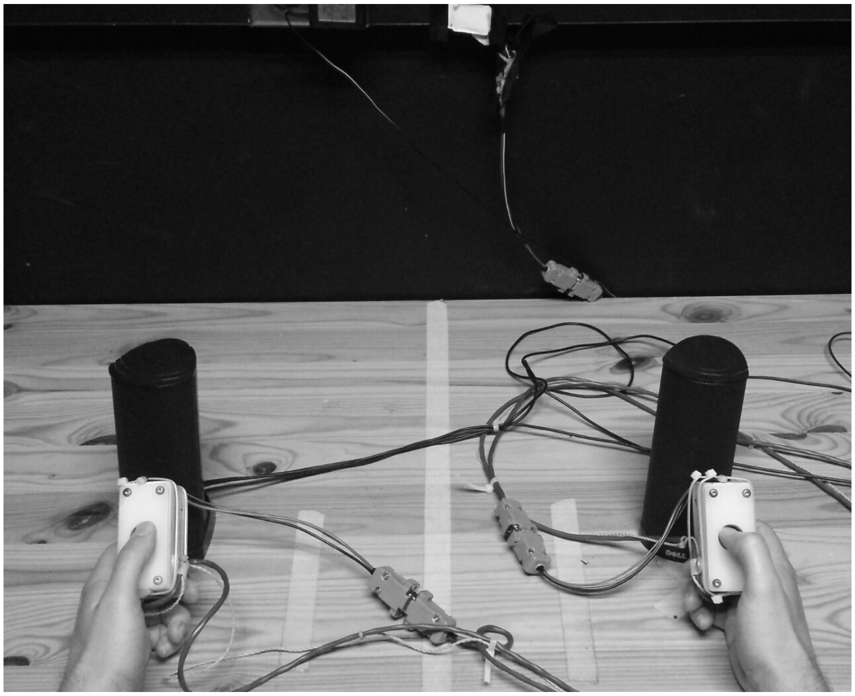


*Figure 3.7* a) A photograph of the experimental equipment for Experiments 1-3. Participants' thumbs were placed over the vibrations on a cube. Directly above the vibration, an LED light was mounted to the cube, the hand was positioned directly in front of a speaker. b) Participants sat in front of a central fixation mounted to the wall and placed their hands at marked positions of the table.

### 3.5.3 Discussion

The effects of actions preceding audiotactile stimuli remain inconclusive. As observed with visuotactile pairs, actions executed prior to an audiotactile TOJ task were numerically shown to bind to the nearest sensory stimulus, however the difference between action near vibration condition was not statistically different than the baseline. When action was performed near the tone, vibrations were required to lead auditory stimuli to achieve PSS, indicating faster perception of auditory stimuli. This result is in contrast to the baseline condition in which the PSS score did not differ from 0 ms. On the other hand, when actions were performed near vibration a numerical PSS shift was observed so that tone needed to lead vibration to achieve PSS, but this was not significant from baseline.

Secondly, there was no difference in the binding effect size between each of the action near stimulus conditions. This finding indicates that the degree of binding after a motor movement to each sensory stimulus is of the same magnitude. In other words, action can bind to tones and vibrations equally. These differences in statistical tests make audiotactile pairs somewhat difficult to interpret.

## 3.6 General Discussion

### 3.6.1 Summary

The present study examined action effects on subsequent perception of competing bimodal pairs. It was observed that binding of action to spatially and temporally proximate stimuli and that the degree of binding to each sensory stimulus is dependent on the bimodal pair. Motor movements that preceded visuotactile pairs bound to the closest sensory modality, but to a greater degree to the visual modality. On the other hand, actions that preceded audiovisual pairs preferentially bound to the visual modality, regardless of the spatial proximity of either modality to the action. Lastly, actions that led audiotactile pairs also appeared to bind to the nearest sensory modality. For the first time, the effect of action on multisensory perception was explored in a controlled experimental design that allowed for comparisons across multisensory combinations.

Three main conclusions can be drawn from the current findings. First, perception is not a passive process; the mere act of a button press alters subsequent perception for all sensory stimuli. Second, action can follow the conventional laws of multisensory integration in the same way as multiple sensory stimuli. According to these laws, sensory stimuli presented in close spatial or temporal proximity are likely to be bound as one percept (e.g., Spence et al., 2001). In specified cases, actions are bound to sensory targets presented close in space and/or time. For all bimodal combinations, actions executed directly prior to stimuli presentation led to faster perception of at least one sensory stimulus. However, spatial binding was only observed for visuotactile and audiotactile combinations. Accordingly, the most crucial finding of the present study is that action acts in idiosyncratic ways on bimodal perception. The present research provides a novel framework to illustrate the interaction of action with multiple sensory modalities.

The effect of action type (voluntary versus involuntary) on binding was also investigated. Previous research implicated distinct binding patterns for voluntary versus involuntary actions (e.g., Haggard et al., 2002; Kostelecki, Mei, Dominguez, & Velazaquez, 2012). On the contrary, the present findings fail to distinguish binding effects for free (chosen button press) versus forced (dictated button press) actions. Actions leading sensory stimuli result in faster perception for some modalities, independent of the action type.

The current experimental design could be one possible explanation for the lack of effect of action type on binding. It is possible that the present methods failed to distinguish between action types. The free and forced conditions may have been analogous. For free actions, participants were required to make a button press despite the ability to choose the location of the action. The requirement for a button press in the free condition may be interpreted as a forced condition. Similarly, for the forced actions participants still had control over when to execute the button press. Lastly, in both action type conditions the same sensory consequences followed. Because the anticipation of sensory consequences is sufficient for intentional binding (Haggard & Clark, 2003), in the forced action condition observers may have associated the action with the consequence in a similar way as in the free action condition.

Interestingly, brain-imaging studies have revealed distinct activations for free and forced actions in a design that resembled the current one. Discrete neural patterns were observed in related sensory cortices for chosen button presses (free) compared to predetermined button presses (forced), but no differences were observed in the prefrontal cortex (PFC), which is involved in planning and attentional resources (Kostelecki et al., 2012). These findings imply distinct mechanisms may be involved in the earlier stages of the action, such as during initiation, but later stages may involve more similar processes (Kostelecki et al., 2012) thus leading to the same perceptual consequences.

Cross-experimental discrepancies in action type effects may depend on how action types are defined. In the current study, the ability to *decide* the action location differentiated free actions from forced. For both action types, participants maintained physical control whilst completing the action. In this scenario, a similar amount of planning is required for task completion. This idea is consistent with the lack of differences observed in the PFC, which is thought to be involved in planning and attentional processes (Kostelecki et al., 2012). On the other hand, absence of intentional binding effects following TMS-induced actions (forced) were revealed when participants had no control over the execution of the motor movement (Haggard et al., 2002). TMS-induced actions may involve different processes than forced actions as defined by the current study—mainly TMS-induced actions may lack any planning or decisional processes.

### 3.6.2 Action Effects on Visuotactile Pairs

Actions that precede visuotactile stimuli bind to spatially proximate modalities. When no action was performed, visual stimuli needed to lead tactile stimuli to achieve a simultaneity judgment—this result is consistent with previous visuotactile TOJ task findings (Spence et al., 2001). The amount of time by which visual stimuli were required to lead tactile stimuli was significantly increased after executing an action near vibration. A complete reversal of the effect was observed when action preceded near light; in this case, vibrations needed to lead lights for PSS to be achieved. Following an action, the amount of time by which tactile stimuli needed to lead visual stimuli for nearby visual targets was greater than the amount of time by which visual stimuli needed to lead tactile stimuli for nearby tactile targets, indicating a relatively larger binding effect to vision than touch following an action. The finding in Experiment 1 that action binds to nearby sensory stimuli was consistent with the results observed in Chapter 2, implicating the robustness of action effects on visuotactile pairs (Finkelshtein, unpublished; chapter 2).

### 3.6.3 Action Effects on Audiovisual Pairs

Unlike with visuotactile pairs, action does not spatially bind to audiovisual modalities. Performance on an audiovisual TOJ task after a button press indicated overall faster perception of visual stimuli relative to baseline. This effect was independent of the spatial location of stimuli relative to the action. The unidirectional shift in PSS indicated preferential binding of actions to the visual modality. Interestingly, without an action auditory information is generally processed faster than visual information (Zampini et al., 2003; King, 2005). The tendency for action to speed up visual perception has been previously demonstrated with a computer-based audiovisual TOJ task (Vallet and Shore, unpublished). The replication of this effect using different equipment and stimuli further demonstrates the robustness of this particular action effect.

The results with audiovisual stimuli appeared especially unique due to the tendency for a prior action to speed up processing of visual stimuli regardless of spatial proximity. Faster visual perception for an audiovisual TOJ task has been previously reported following exposure to visuotactile stimuli (Harrar & Harris, 2008) and audiovisual stimuli (Voormen et al., 2004; Navarra et al., 2005; Harrar & Harris, 2008) separated by a fixed SOA. Exposure to bimodal stimuli separated by a fixed SOA did not influence perception of any other bimodal combinations (Harrar & Harris, 2008).

Together, the findings implicate a unique system for auditory and visual perceptual comparisons.

### 3.6.4 Action Effects on Audiotactile Pairs

Action followed by audiotactile pairs produced inconclusive findings. Actions appeared to bind to the most proximate sensory stimulus. In the baseline condition, audition and vibration reached subjective simultaneity when presented at the same rate (indicated by a lack of difference from a 0 ms PSS). When actions were on the same side as audition, tactile stimuli needed to lead auditory stimuli for perception of simultaneity—indicating faster perception of tones than vibrations. On the other hand, when actions were performed near tactile stimuli, auditory stimuli needed to lead tactile to achieve simultaneity. However, the latter was a numerical difference, not statistically significant. The size of the binding effect (measured as the difference in PSS shift following an action from the baseline wait condition) was not different for each action type, thus further supporting the notion that actions may bind to whichever sensory stimulus is on the same side as the action.

### 3.6.5 Visual Dominance Hypothesis

Perception is biased toward the visual modality (c.f., Posner, Nissen, & Klein, 1976). In an auditory/visual discrimination task, observers tend to respond only to the visual stimulus when presented concurrently with an auditory stimulus (Colavita, 1974). According to one account, visual information is less alerting by nature than vibrations or tones, and therefore requires additional resources to successfully perceive. Allocation of increased attentional resources toward vision leads to a visual bias (Posner, Nissen, & Klein, 1976). The bias is especially pronounced when modalities are competing. The visual dominance account can explain the visual bias observed when actions precede visuotactile and audiovisual pairs. A button press may direct attentional resources toward the less alerting visual stimulus.

Actions and subsequent recurring effects become contingent and stored together (Hommel, 1996). Our daily experiences dictate the strength of association between actions and each sensory stimulus. The different degrees of contingencies may account for the different degrees of binding observed across in the present study. Executing an action activates previously stored associations to allow for faster perception of stimuli (Haggard & Clark, 2003). An alternate explanation for the observed visual bias could be due to a stronger association between motor movements and visual stimuli. Executing an action such as a key or button press often results in immediate visual feedback (such as typing letters on a computer). However, this explanation is unlikely as tactile stimuli should hypothetically form stronger associations—a motor movement such as a button press results in immediate tactile feedback at all times, and may have more value to the observer. It is therefore somewhat surprising to observe preferential binding to the visual modality over the tactile modality.

### 3.6.6 Conclusions

Successful interaction with our environment requires the integration of self-produced motor movements with related sensory consequences. However, relatively few studies have investigated how actions bind with relevant modalities. Previous research investigating action effects on perception often focused on unimodal stimuli. The current experimental design allowed for clear comparisons and conclusions to be made on the effects of action on different competing bimodal pairs. For the first time, the idiosyncratic effects of motor movements on subsequent bimodal perception have been documented. This work lays the groundwork for further study of the robust effects of actions on subsequent bimodal perception.

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# 4.0 Chapter 4: Action Effects on Temporal Resolution of Multisensory Events

## 4.1 Abstract

Actions affect the perceived timing of events. It is evident that following an action some sensory stimuli are perceived quicker. Previous work (Chapter 3) provided insight on the perceived onsets of stimuli that followed an action. The present study focused on other aspects of temporal processing after a motor movement. Specifically, this research investigated whether nearby actions affect the temporal resolution of bimodal stimuli.

Participants chose a button press side (left or right), were told a button press side, or did not execute a button press prior to a bimodal TOJ task. The bimodal stimuli (visuotactile, audiovisual, or audiotactile) were presented in three separate experiments. In each of the experiments, the two stimuli that followed the action always appeared on one side, either on the same side or different side of the action.

It was concluded that regardless of stimulus location relative to the action, temporal resolution is generally worse after executing a button press compared to baseline. Additionally, the type of action, chosen or fixed, did not influence this effect. The findings suggest that actions, regardless of their nature, degrade temporal resolution of bimodal stimuli.

## 4.2 Introduction

To optimally interact with our environment we must incorporate motor movements with their related events. Perception of events is not a passive process and is influenced by our movements. For example, an auditory stimulus is perceived faster after a voluntary button press, and a hand configuration that matches stimulus dimensions speeds up the perception of that stimulus (Haggard, Clark, & Kalogeras, 2002; Fagioli, Hommel, & Schubotz, 2007). Understanding the relative timing of events and actions is essential for survival. For instance, if upon stepping onto a road one hears an ambulance siren, this would signal the observer to wait before taking further steps. In Chapter 3, it was established that actions affect the perceived onsets of bimodal stimuli in idiosyncratic ways (Finkelshtein, unpublished; chapter 3). Actions that precede visuotactile and audiovisual stimuli preferentially bind to the visual modality, whereas actions that precede audiotactile stimuli bind to the most proximate modality (Finkelshtein, unpublished; chapter 3). It is evident that motor movements influence how fast modalities are perceived. However, a clear understanding of action effects on temporal perception of events is yet to be established. Specifically, whether actions also influences observers' ability to correctly judge order of two consecutive events remains poorly understood. In the present chapter I investigated whether motor movements influence subsequent temporal precision of bimodal stimuli.

### 4.2.1 The Role of Attention on Temporal Resolution

Temporal precision may be influenced by attention. Past studies investigating the role of attention on temporal precision have produced mixed findings. Presenting targets at cued locations compared to uncued ones may enhance (Stelmach & Herdman, 1991), diminish (Yeshurun & Levy, 2003) or have no impact (Spence et al., 2001) on temporal resolution. In fact, the effect of attention on temporal resolution may vary depending on the experimental design; the nature of the cues and targets impact whether temporal precision is enhanced or diminished at cued locations (c.f., Nicol, Watter, Gray, & Shore, 2009). While the influence of attention on temporal resolution remains disputed, cuing attention to spatially proximate targets appears to impact temporal sensitivity.

### 4.2.2 The Link between Action and Attention

Voluntary actions and attention may be related. EEG evidence suggests an obligatory link between attentional and motor mechanisms (Gherri & Eimer, 2010) and behavioural observations support the existence of such a link. Motor movements impact attentional capture (Tipper, Lortie, & Baylis, 1992; Welsh & Pratt, 2008). For example, more interference was observed when hand movements were made near distractors compared to hand movements made further away from distractors (Tipper et al., 1992). In addition, when participants attended to a point in time they produced more accurate temporal estimates of self-produced action onsets than if asked to estimate onsets of actions retrospectively, so that they were unable to attend to a point in time (Haggard &

Cole, 2007). The existence of a link between action and attention indicates that, like attention, actions may also influence temporal precision.

### 4.2.3 Action Effects on Perceived Onsets

As discussed above, actions performed in close proximity to some sensory stimuli speed up perception of those stimuli (Finkelshtein, unpublished; chapter 3). For example, button presses performed before visuotactile presentation bind to either modality (with a greater degree to vision), depending on which was presented near the action. Similarly, actions preceding audiotactile pairs bind to the most proximate sensory stimulus (Finkelshtein, unpublished; chapter 3). In chapter 3, observers performed a button press prior to a bimodal temporal order judgment (TOJ) task. One sensory stimulus was presented near the button press, while the second sensory stimulus was presented further away. Although it was concluded that actions speed up the perceived onsets of some sensory stimuli, a possible criticism of this conclusion relates to response bias—an inability to reliably distinguish order of modality presentation may have led observers simply to choose the modality most proximate to the button press. Although this account seems an unlikely explanation of the results and it was not always the case that participants observed the most proximate stimulus as occurring first, the current design addressed the response bias account directly. In the present design, both sensory stimuli were presented at a single location, either on the same or different side of the action. An observation of preferential modality binding following an action would eliminate a proximate response bias account.

### 4.2.4 Present Study: Rationale and Predictions

In the present study, the effect of action on temporal resolution was investigated. The experience of time is highly subjective and can be difficult to measure. One method by which temporal resolution can be objectively measured is with use of the temporal order judgment (TOJ) task. In a typical TOJ task, observers are presented with two stimuli separated by varied SOAs and must judge which stimulus they perceived first. Two main measures are obtained from such tasks: the point of subjective simultaneity (PSS) and the just noticeable difference (JND). The PSS indicates a point in time at which two modalities are subjectively perceived to occur simultaneously. In other words, it indicates by how much time one modality must lead another for the two modalities to be judged as occurring first on 50% of the trials (Shore & Spence, 2005). On the other hand, JND, a hypothetically separate measure (Spence et al., 2001) represents the smallest temporal interval by which two modalities must be separated for participants to accurately judge order on 75% of the trials (Shore & Spence, 2005). JND is a measure of temporal precision; less precise, or larger JND scores indicate a greater difficulty in performing the task.

Participants performed a button press that was followed by a bimodal TOJ task. The two sensory stimuli were always presented at one spatial location, and either at the same or different spatial location relative to the action. Presenting stimuli either at the same or different side as the action allowed the exploration of spatial compatibility between actions and stimuli on temporal precision. A control no action TOJ condition acted as a baseline comparison. Visuotactile, audiovisual and audiotactile bimodal pairs were presented in three separate experiments. To maintain consistent methodology with previous data chapters, button presses were either forced (participants were told to press the left or right button) or freely chosen (participants were told that they could select which side to press). Based on the findings in Chapter 3, it was not expected that action type (forced or free) would influence performance (see Finkelshtein, unpublished; chapter 3, General Discussion).

It was hypothesized that performing a motor movement near the two sensory stimuli would enhance temporal resolution. Because perceived onsets of some stimuli are faster following an action (Finkelshtein, unpublished; chapter 3), it was possible that temporal precision would also be better at the action location compared to a location different from the action. Secondly, according to the action-centered representation account, attentional capture is influenced by our actions and affects subsequent perception (Tipper et al., 2002). Accordingly, the hand position may influence perception of nearby stimuli by enhancing temporal resolution of those stimuli. Because action effects on temporal precision have not been previously explored, these predictions were speculative.

Most of our interactions with the external world require coordination of motor movements with sensory stimuli. Seemingly trivial activities such as sitting down in a chair, walking down the street, or having a conversation with a friend, all require coordination of motor movements with multiple senses. As such, the ability to understand timing between events is crucial. To the best of my knowledge, the influence of action on the ability to accurately distinguish the order of bimodal stimuli has not been previously investigated. Understanding the effects of action on temporal sensitivity of multisensory signals will provide a deeper understanding of the dynamic relation between action and perception.

## 4.3 Experiment 1: Action Effects on Visuotactile Temporal Resolution

### 4.3.1 Methods

***Participants***

Twenty-one undergraduate McMaster University students (15 female) participated in exchange for course credit. All participants were naïve to the goal of the study, and all reported normal or corrected vision. Participants ranged from 18 to 21 years old (M =18.76, SD =0.89), and 19 were right-handed. Participants signed a written consent form prior to participation. The study took about an hour to complete. All procedures were in accordance with the McMaster Research Ethics Board.

***Stimuli and Apparatus***

The experiment was conducted in a black painted room with the lights turned off. Dim light was provided through light entering underneath the door and the light emitting diodes (LED) stimuli. Observers sat facing a wall at a wooden table that was 81 cm in height and 79.5 cm in width. In each hand, observers held a wooden cube equipped with an Oticon-A (100 Ohm) bone-conducting vibrator situated beneath centrally placed circular buttons (2 cm in diameter). The vibrators were driven by a 250-Hz sine wave and were used to present the tactile stimulus. A red LED was mounted on top of each cube were used to present the light stimulus. Participants were instructed to hold the cubes with their thumbs over the circular buttons and their fingers placed underneath the wooden cube. The cubes were 8 cm in length, 3.7 cm in width and 5.2 cm in height.

On the wall that observers were facing, a blue/yellow LED fixation was centrally mounted at the observers' eye level. The central position of observers was marked with a vertical piece of masking tape. Observers held the cubes 24 cm to the left and 24 cm to the right of centre; the positions were also marked with tape. The stimuli and apparatus were the same as the ones described in Chapter 3. Figure 3.7 pictures the stimuli and experimental set-up for Experiments 1-3.

Participants depressed their heel and toes of their right foot over two foot-pedals situated underneath the table, on the right side of the body. The foot-pedals were attached to an adjustable Plexiglas frame. The heel and the toes were lifted to make temporal order judgment (TOJ) task responses. Continuous white noise was presented through headphones to mask out external noises produced by the equipment. From the same headphone, male-recorded voice commands presented button press commands. The experiment was programmed and presented via MATLAB (R2011b), on a Dell dimension 8250, Pentium® 4 computer.

***Design***

The design included three factors: action type (free or forced), stimulus location relative to the action (same, different or wait) and SOA (±250 ms, ±108 ms, ±72 ms or ±24 ms, negative SOAs indicated light stimuli preceded vibrations and positive SOAs indicate vibrations preceded light). There were a total of 48 possible conditions (2 action types x 3 stimulus locations x 8 SOAs). Participants completed a total of 720 trials divided into 10 blocks of 72 trials each. Action type was presented in alternating blocks and stimulus location relative to action and SOAs were mixed randomly within-blocks. Each block consisted of 48 action condition trials (24 left action and 24 right action, or 48 free actions) and 24 no action condition trials (wait trials). All possible conditions were counterbalanced.

### ***Procedures***

Observers first completed a speeded discrimination task to familiarize themselves with the foot-pedal responses. Participants were presented with a stimulus from one modality for 20 ms on any given trial and were required to respond with a corresponding foot-pedal lift as quickly as possible. Heel lift indicated vibration was perceived and toe lift indicated light was perceived. Most participants performed this task without difficulty. Participants completed 20 trials but the series of trials was repeated if more than 4 incorrect responses were made. After the discrimination task, observers completed 10 practice trials of the experimental TOJ task (5 free trials; 5 forced trials). Participants who needed additional practice to feel comfortable with the task completed additional practice trials.

The experiment began following the practice trials. A central yellow fixation LED lit up for 250 ms to indicate the start of a trial. Observers were instructed to maintain gaze on the central light. After the light turned off, a male-recorded voice presented from the same headphones that played the white noise provided instructions for the button press. In a free block, the instructions were either “choose” or “wait”. Participants were told to select either the left or right button press when they heard the word “choose”, but to try to press both buttons in approximately equal proportions. In the baseline ("wait") condition, participants were instructed not to make a button press. The forced block consisted of the baseline condition and instructions that indicated the location of a button press in the action condition ("left" or "right"). There was no time limit imposed to make the button presses. Feedback was received in the case that a button was pressed in the wait condition, or the wrong button was pressed in the forced condition. The feedback consisted of the central yellow LED, the vibrators of both cubes, and green LEDs on the cubes, which all lit up and vibrated simultaneously for 500 ms.

Ten ms after the button press, or after a 500 ms delay for the wait condition, the first sensory stimulus was presented for 20 ms either on the same or opposite side of the action. Following a variable SOA, the second sensory stimulus appeared for 20 ms always on the same cube as the first sensory stimulus. Participants' task was to decide which sensory stimulus they perceived first; they lifted their heel or toe for light or vibration first responses respectively. Accuracy was emphasized over speed, but in the case that no response was registered within 3000 ms, the same feedback as described above was delivered.

### 4.3.2 Results

#### *Removal Criteria*

Data from the initial speeded discrimination and practice trial sessions were not included in analyses. In addition, experimental trials on which an incorrect button press was made or the response time that exceeded 3000 ms were not analyzed. Exclusion of incorrect button presses and overtime responses resulted in the removal of 1.3% of trials from the analyses. The proportion "vibration first" responses were submitted to a repeated-measures analysis of variance (ANOVA) with three factors: action type (free or forced), stimulus location relative to action (same or different side), and the eight different SOAs. Based on previous data, action type was not expected to produce any significant effects (see Finkelshtein, unpublished; chapter 3). The effect of action type on proportion "vibration first" responses was indeed non-significant, and did not interact with any other factor, and so the data were collapsed across action type in all of the analyses reported here.

The collapsed proportion "vibration first" responses were transformed into z-scores and used to calculate the lines of best-fit across the eight SOAs for each participant. Correlation coefficient, PSS and JND scores were calculated from the obtained slopes and intercept. Individuals' data were excluded if one or more of the following criteria were met: A. average proportion modality first responses across all the conditions at one or both extreme SOAs (±250 ms) was below 0.75, B. PSS scores higher than 250 ms, C. correlation of best-fit lines was lower than 0.70. Four participants were removed according to these criteria and one due to technical error. Data from the remaining 16 participants were subjected to the analysis. In the "choose" action type condition, the right and left buttons were pushed in approximately equal proportion (47.5% and 52.5% respectively).

### *ANOVA on Proportion "Vibration First" Responses*

Figure 4.1 depicts the proportion "vibration first" responses as a function of SOA, collapsed across action type. For the ANOVA, if Mauchly's test of sphericity was violated, the Greenhouse-Geisser epsilon (ε) and non-adjusted degrees of freedom are reported. The proportion “vibration first” responses increased across SOA [F (1,105)=161.8, $p<0.001$, $\varepsilon=0.41$]. The proportion “vibration first” responses also depended on stimulus location relative to action [F (2,30)=7.65, $p=0.002$]. Importantly, stimulus location relative to action also interacted significantly with SOA [F(14,210)=4.0, $p<0.001$, $\varepsilon=0.43$].

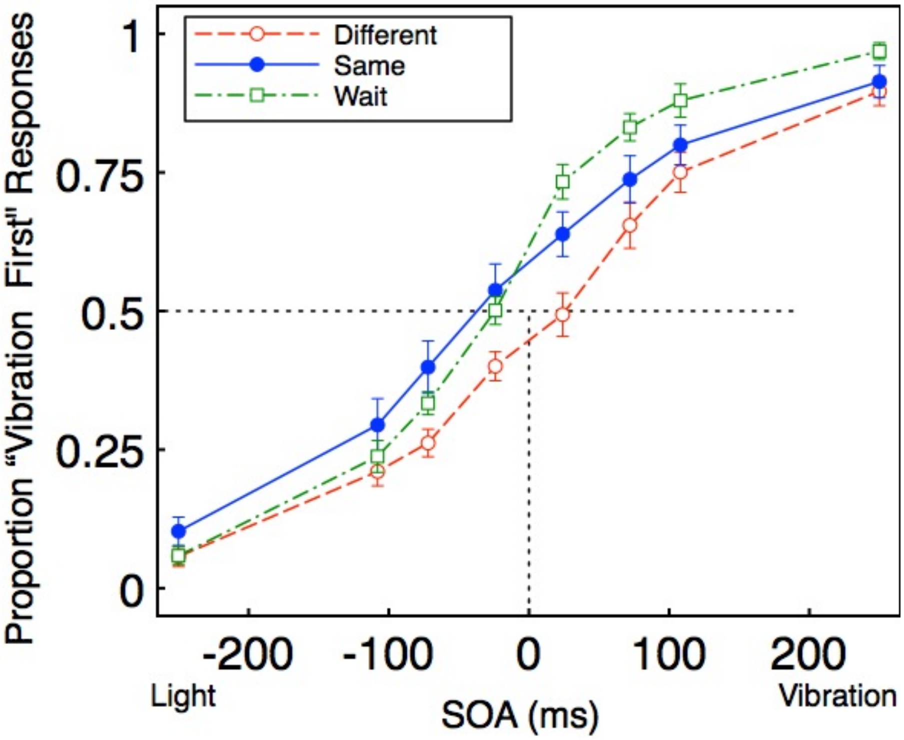


*Figure 4.1* Proportion “vibration first” responses as a function of SOA collapsed across action type, for Experiment 1. Error bars represent standard error of the mean, corrected for within-participants comparisons.

### *ANOVA on PSS and JND*

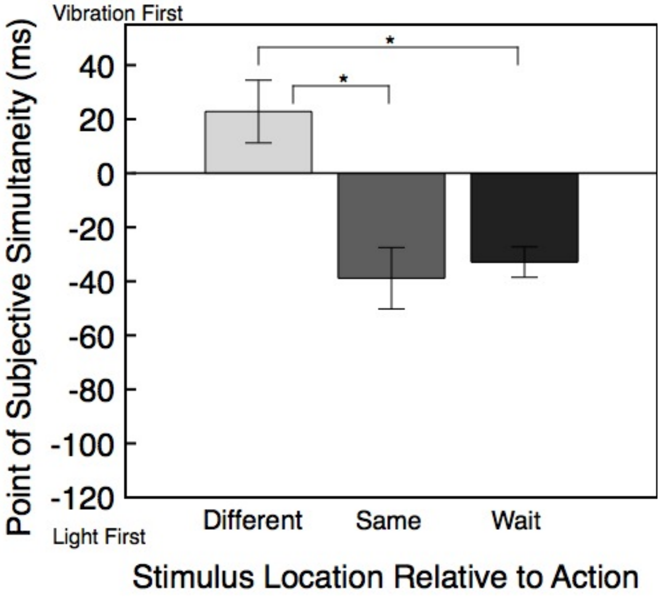
The computed z-transformed lines of best fit were used to calculate the PSS (-intercept/slope) and JND (0.675/slope). The PSS and JND scores were submitted to paired-sampled t-tests to further investigate differences among the stimulus location relative to action conditions. As such, for both PSS and JND three comparisons were made (different–same, different–wait, same–wait). Figure 4.2 presents the mean PSS and JND scores for each stimulus location relative to action, collapsed across action type and participants.

When stimuli were presented at a different location relative to the action location, tactile information had to lead visual information by about 23 ms to achieve simultaneity. The opposite was true when actions were completed on the same side as the stimuli. In this case, visual information had to lead tactile by about 39 ms for perception of simultaneity. The difference in PSS scored between same side and different side stimulus location conditions was significant [t(15)=2.8, p=0.014]. In the wait condition, visual stimuli also needed to lead tactile stimuli (M=32 ms), this was significantly different than a 0 ms [t(15)=-4.04, p=0.001]. The difference between the PSS scores for stimuli on the same side as action and the baseline wait condition was not significant. However, the PSS score for the different stimulus location from action condition differed significantly from that for the baseline condition [t(15)=3.9, p=0.001].

The binding effect for different side as action condition (M=56 ms) was larger than the binding effect for the same side as action condition (M=6 ms), [t(15)=2.94, p=0.01], indicating a stronger binding of action to vision when action was preformed away from the stimuli.

Stimulus location (different versus same) relative to action did not have a significantly affect on JND scores [t(15)=-1.5, p=0.16]. However, in both action conditions, temporal resolution was worse (M=112 ms for different and M=126 ms for same) than when no action (M=91 ms) was performed [t(15)=3.6, p=0.003 for different–wait, [t(15)=2.9, p=0.011 for same–wait].

a. PSS



b. JND

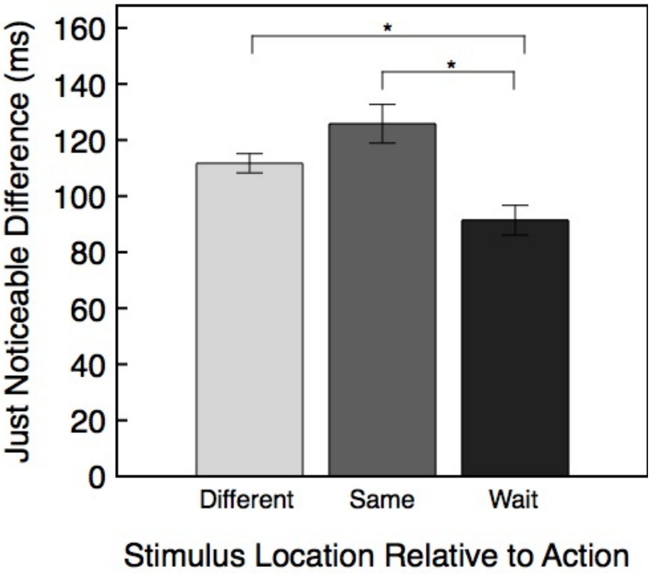


*Figure 4.2* Experiment 1: PSS (a) and JND (b) for different side stimulus location, same side stimulus location, and wait conditions. The PSS scores represent the amount of time one stimulus needed to lead another stimulus (ms) to be judged as simultaneous. Negative PSS scores indicate visual stimuli led tactile stimuli. The JND scores represent the smallest interval required between the two stimuli to accurately judge the temporal order on 75% of trials. Error bars represent standard error of the mean, corrected for within-participants comparisons.

### 4.3.3 Discussion

In contrast to the initial predictions, the data revealed that the proximity of the stimulus relative to the action did not impact observer's ability to judge the order of presentation. However, when an action was performed, stimuli required a larger temporal gap between them for accurate order judgments compared to when no action was performed.

The data also revealed that simultaneity judgment differed for button presses performed near or far from the stimulus presentation. For stimuli presented at locations different from action, tactile stimuli had to be presented prior to visual stimuli for perception of simultaneity to be achieved. This result contrasts with the baseline condition in which visual stimulus had to lead tactile stimuli for perception of simultaneity, and suggests that visual perception is speeded in this condition. In contrast, for stimuli presented at the same location as action, the PSS score was similar to that in the baseline condition, with visual stimuli having to lead tactile stimuli for simultaneity of perception to be achieved. All told, the results suggest that actions directed to a different location than visuotactile stimulus presentation bind to the visual modality.

## 4.4 Experiment 2: Action Effects on Audiovisual Temporal Resolution

### 4.4.1 Methods

***Participants***

Twenty-five McMaster University students (17 females) participated in exchange for course credit. Observers ranged from 18 to 22 years old (M = 18.84, SD = 1,07), and

23 were right-handed. All participants reported normal or corrected to normal vision. They were naïve to the goal of the study and signed a written consent form prior to participation. The study took about an hour to complete. All procedures were in accordance with the McMaster Research Ethics Board.

### *Stimuli and Apparatus*

The same stimuli and apparatus were used as described in Experiment 1, with the addition of a pair of Dell AX210 speakers to deliver auditory tone stimuli. The speakers were placed directly in front of the hands at a marked position. Tones were presented for 20 ms at 1000 Hz and a 44100 Hz sampling frequency.

### *Design*

The same design was followed as in Experiment 1 with the exception that negative SOAs indicated that auditory stimuli were presented first while positive SOAs indicated that visual stimuli were presented first.

### *Procedures*

Participants completed the same procedures as described in Experiment 1 with the exception that the TOJ task utilized audiovisual stimuli. The light stimuli were the same as described in Experiment 1 (red LEDs on top of each cube). The sound stimuli consisted of tones played from the speakers. Participants responded by lifting their heel for “light first” responses and toes for “sound first” responses. Each stimulus was presented for 20 ms. The same feedback was delivered for incorrect button presses or responses that exceeded 3000 ms.

### 4.4.2 Results

The same analysis and exclusion criteria were applied to data as described in Experiment 1. The exclusion criteria resulted in the removal of seven participants and the data from an additional two participants were removed due to technical errors. Data from the remaining16 participants were subjected to the analyses. Incorrect button responses and responses exceeding 3000 ms accounted for 0.62% of trials. In the "choose" action type, participants pressed the left and right buttons in approximate equal proportion (47.2% and 52.8% respectively).

#### *ANOVA on Proportion "Light First" Responses*

A repeated-measured ANOVA was computed on the proportion "light first" responses with action type (free or forced), stimulus side relative to action (same, different, or wait and the eight SOAs (±250 ms ±108 ms, ±72 ms and ±24 ms) as factors. The Greenhouse Geisser epsilon values along with the non-corrected degrees of freedom and p-values are reported in the case of Mauchly's test of sphericity violation. Figure 4.3 presents the proportion "light first" responses as a function of SOA for each stimulus location relative to action, collapsed across action type and participants.

Again, action type did not significantly affect proportion "light first" responses and did not significantly interact with the other factors. Not surprisingly, the proportion "light first" responses significantly increased with increasing SOA [F (7,105)=123.50,

$p<0.001$, $\varepsilon=0.25$]. The stimulus location relative to action (same or different) significantly affected the proportion “light first” responses [$F\,(2,30)=11.77$, $p<0.001$]. Importantly, stimulus side relative to action also interacted significantly with [$F\,(14, 210)=3.35$, $p<0.001$].

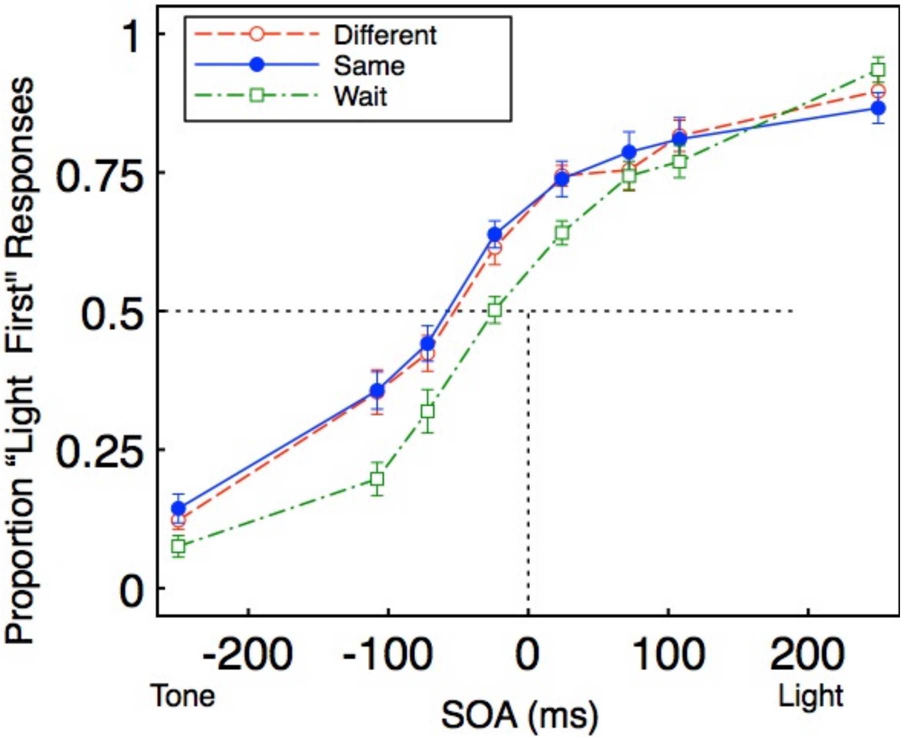


*Figure 4.3* Proportion "light first" responses as a function of SOA collapsed across action type, for Experiment 2. Error bars represent standard error of the mean, corrected for within-participants comparisons.

### *ANOVA on PSS and JND*

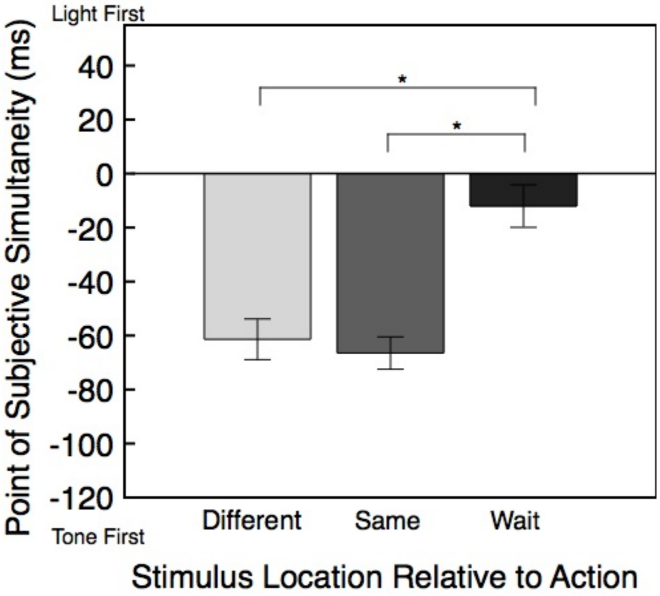
The proportion “light first” scores were collapsed across action type and converted into z-scores. The SOAs were used to compute lines of best fit for each participant. The PSS, JND, and correlation were calculated as described in Experiment 1. Figure 4.4 depicts PSS and JND averages for stimulus sides relative to action, collapsed across action type.

In the baseline condition, the tone appeared to need to lead the light by about 12 ms for PSS to be achieved. However, this PSS score did not significantly differ from 0 ms, as revealed by a one-sample t-test [t(15)=-1.135, p=0.274]. A paired-sample t-test comparing the baseline to different stimulus location relative to action and to same stimulus location relative to action indicated that the tone had to lead the light by a significantly larger amount of time (M=61 ms) when the stimuli were presented on different side [t(15)=-3.47, p<0.001], and when the stimuli were presented on the same side as the action (M=66 ms) [t(15)=-4.61, p<0.001]. PSS judgments for same compared to different stimulus location relative to action conditions did not significantly differ from each other [t(15)=0.46, p=0.65] .

A comparison of the binding effect size revealed no difference for the same side stimulus location (M=54 ms) compared to different side stimulus location (M= 49 ms). This further supports a PSS shift of the same degree following an action, regardless of the stimulus location.

Temporal resolution was overall better in the baseline condition compared to different stimulus location relative to action [t(15)=2.48, p=0.026], and same stimulus location relative to action [$t(15)=3.78$, $p<0.001$] conditions. Performance did not differ between the two stimulus location relative to action conditions [$t(15)=-0.40$, $p=0.69$].

a. PSS



b. JND

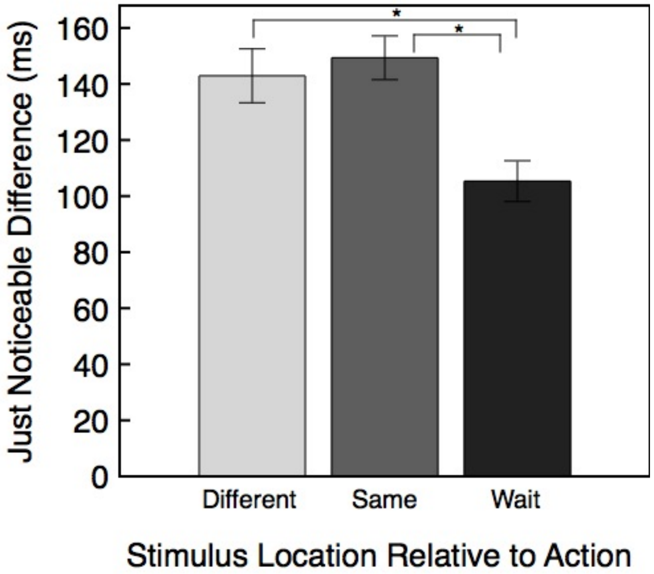


*Figure 4.4* Experiment 2: PSS (a) and JND (b) for different side stimulus location, same side stimulus location, and wait conditions. The PSS scores represent the amount of time one stimulus needed to lead another stimulus (in ms) to be judged as simultaneous. Negative PSS scores indicate auditory stimuli led visual stimuli. The JND scores represent the smallest required interval between the two stimuli to accurately judge the temporal order on 75% of trials. Error bars represent standard error of the mean, corrected for within-participants comparisons.

### 4.4.3 Discussion

In the baseline condition, when no action was performed, auditory and visual stimuli needed to be presented at the same time for PSS to be achieved. This finding was surprising and contradictory to the typical audiovisual TOJ findings in which auditory information is generally processed first, and therefore visual information typically needs to lead auditory to achieve PSS (c.f. King, 2005; Zampini et al., 2003). This unexpected finding is discussed further in the General Discussion section.

Crucially, the amount of time by which auditory information had to lead visual to achieve PSS increased significantly with the performance of a button press, regardless of its location relative to the sensory stimuli. Previously, I demonstrated that performing an action prior to an audiovisual TOJ task led to faster visual perception, however, the button press was always near one sensory stimulus (Finkelshtein, unpublished; chapter 3). It is now evident that this effect can be observed even if the action was performed away from both sensory stimuli. Perception of audiovisual modalities following an action appear to be spatially independent—regardless of the stimulus location following an action, the visual modality was perceived first.

Stimulus location relative to the action did not impact temporal resolution. Instead, the act of the button press diminished temporal sensitivity relative to baseline. The lack of difference in JND scores between same and different stimulus sides relative to action was surprising, but is consistent with the observation using visuotactile pairs (Experiment 1).

## 4.5 Experiment 3: Action Effects on Audiotactile Temporal Resolution

### 4.5.1 Methods

***Participants***

Twenty undergraduate McMaster University students (14 female) partook in the experiment in exchange for course credit. All participants reported normal or corrected to normal vision and were naïve to the purpose of the study. Participants' ages ranged from 18 to 26 years old (M=18.65, SD =1.85), and 19 were right-handed. The experiment took approximately 60 minutes to complete. Observers signed a written consent form prior to participation. All procedures were in accordance with the McMaster Research Ethics Board.

***Stimuli and Apparatus***

The same stimuli and apparatus were used as described in the previous experiments. The TOJ task was audiotactile; vibrations were presented for 20 ms from underneath the central buttons on the cubes, and the tones were presented for 20 ms from the speakers placed directly in front of the cubes. A dim lamp was placed behind the participants to allow minimal light as visual stimuli were not presented (with the exception of the central fixation LED).

### *Design*

The same design as described in Experiment 1 was implemented but the main task involved auditory and tactile stimuli. Negative SOAs indicated audition was presented first and positive SOAs indicated vibrations were presented first.

### *Procedures*

All procedures matched the ones described in Experiment 1 with the exception that the TOJ task was audiotactile. Participants lifted their toes or heels to indicate that they perceived first the auditory or tactile modality, respectively.

## 4.5.2 Results

The same removal criteria were applied as described for Experiments 1. This procedure resulted in the removal of data from three observers; data from the remaining 17 observers were subjected to analysis. Removal of trials that exceeded 3000 ms or that had incorrect button presses accounted for 2% of trials. Again, left and right button presses were selected in approximately equal proportions for the "choose" condition (47.1% left, 52.9% right).

### *ANOVA on Proportion "Vibration First" Responses*

The proportion "vibration first" responses were submitted to a repeated measures ANOVA. As observed with previous experiments, the effect of action type (free or forced) was not significant and action type did not interact with any other factor, so it was removed from further analyses. Figure 4.5 displays the proportion "vibration first" responses as a function of SOA, collapsed across action type. Both factors, stimulus location relative to action and SOA had significant effects on proportion “vibration first” responses, [F(2,32)=14.63, p<0.001] and [F(7,112)=232.58, p<0.001]. In addition, stimulus location relative to action interacted with SOA [F(14,224)=6.87 p<0.001].

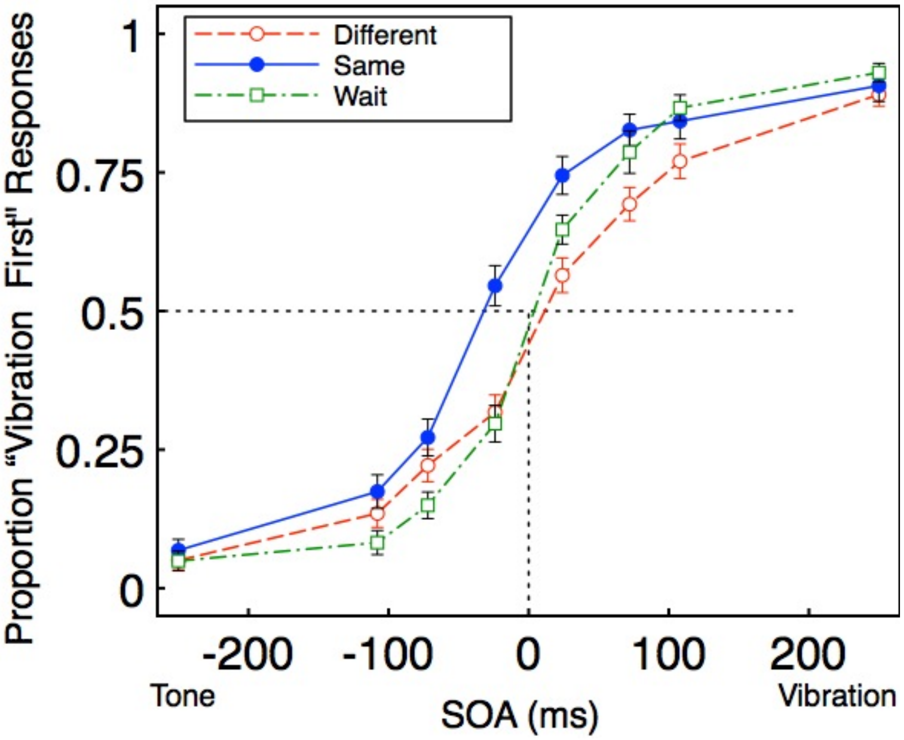


*Figure 4.5* Proportion “vibration first” responses as a function of SOA for collapsed across action type, for Experiment 3. Error bars represent standard error of the mean, corrected for within-participants comparisons.

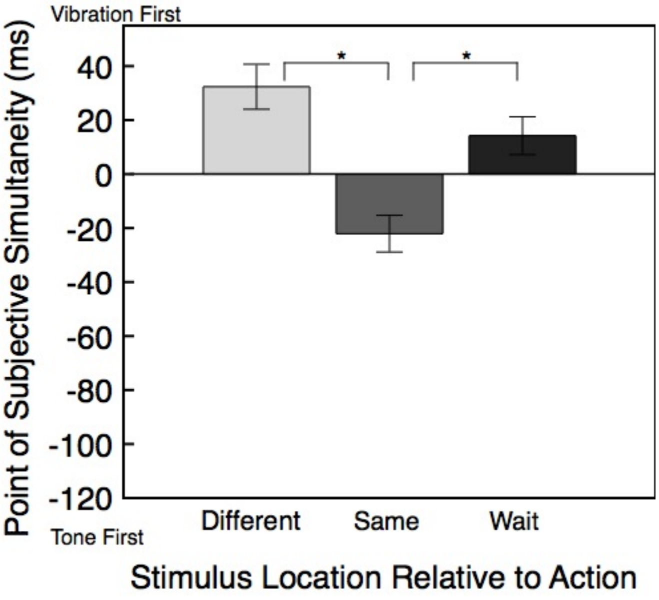
### ***ANOVA on PSS and JND***

Average PSS and JND scores collapsed across condition are presented in Figure 4.6. In the baseline condition, tactile stimuli had to lead auditory stimuli (M=14 ms) to achieve perception of simultaneity, however this value was not significantly different from a 0 [t(16)=1.59, p=0.132]. The PSS score in the baseline condition did not significantly differ from that in the condition in which stimulus location was different than action. In the different stimulus location scenario, tactile stimuli needed to lead by about 32 ms. On the other hand, when stimulus location was the same as action, auditory stimuli needed to lead tactile by about 22 ms to achieve perception of simultaneity. This same side stimulus location condition significantly differed from both the different stimulus location condition [t(16)=4.15, p=0.001], and the baseline condition [t(16)=-3.40, p=0.004].

The size of the binding effect for the same stimulus location condition (M=36 ms) did not differ from the different stimulus location condition (M=18 ms). This indicates that regardless of the stimulus location following an action, the degree of binding to a sensory stimulus remained the same.

As indicated by t-tests on JND scores, temporal resolution was yet again best when no action was performed relative to either action location [t(16)=2.49, p=0.024 for different–wait, t(16)=3.21, p=0.006 for same–wait]. On the other hand, no difference was observed in temporal resolution for same versus different stimulus locations relative to action [t(16)=0.26, p=0.802]. The descriptive statistics for the JND and PSS scores for Experiments 1, 2 and 3 are presented in Table 4.1.

a. PSS



b. JND

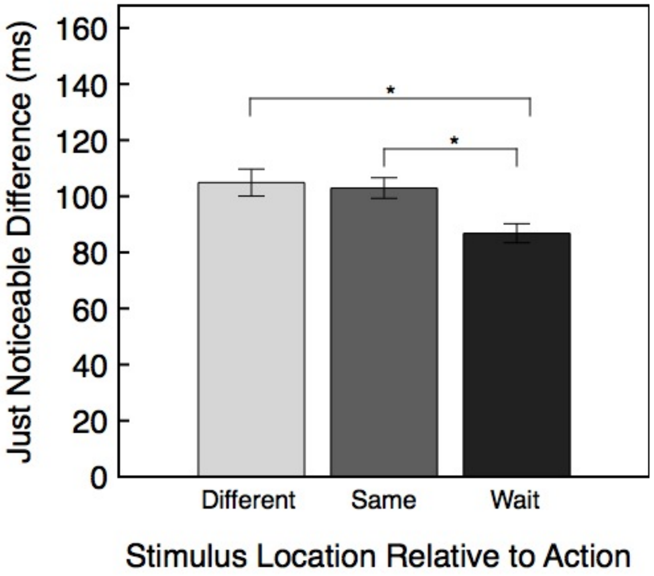


*Figure 4.6* Experiment 3: PSS (a) and JND (b) for different side stimulus location, same side stimulus location, and wait conditions. The PSS scores represent the amount of time one stimulus needed to lead another stimulus (in ms) to be judged as simultaneous. Negative PSS scores indicate auditory stimuli led tactile stimuli. The JND scores represent the smallest interval required between the two stimuli to accurately judge the temporal order on 75% of trials. Error bars represent standard error of the mean, corrected for within-participants comparisons.

### 4.5.3 Discussion

The perceived onsets of auditory and tactile stimuli were contingent on the stimulus location relative to the action. Actions executed at the same stimulus location bound with the tactile modality, whereas actions that were executed at a different stimulus location appeared to bind to audition. However, the PSS score in the different stimulus location condition did not differ from baseline.

The binding effect size for same stimulus location condition did not differ from different stimulus location condition, indicating a similar degree of binding in each condition. Similar to the findings in Chapter 3 with audiotactile pairs (Experiment 3), the present study yet again demonstrates that audiotactile pairs produce more variable results than the ones observed with visuotactile and audiovisual pairs. Consequently, it is difficult to form clear conclusions when it comes to actions preceding audiotactile pairs.

Consistent with Experiments 1 and 2, the spatial location of the sensory stimuli relative to action did not impact spatial resolution. However, the act of performing a button press degraded the ability to distinguish order of the two modalities.

Table 4.1

*Summary statistics for Experiments 1-3*

| Experiment | Stimulus Location relative to Action | PSS[1] | | JND[2] | |
|---|---|---|---|---|---|
| | | M | SEM[3] | M | SEM[3] |
| 1 – Visuotactile | Same | -38.86 | 15.97 | 125.80 | 13.92 |
| | Different | 22.83 | 12.73 | 111.71 | 6.36 |
| | Wait | -32.89 | 8.13 | 91.41 | 4.51 |
| 2 – Audiovisual | Same | -66.48 | 15.72 | 149.36 | 15.67 |
| | Different | -61.38 | 16.68 | 142.93 | 18.99 |
| | Wait | -12.02 | 10.59 | 105.34 | 6.26 |
| 3 - Audiotactile | Same | -22.08 | 11.19 | 102.93 | 7.80 |
| | Different | 32.36 | 14.40 | 104.88 | 7.83 |
| | Wait | 14.22 | 8.95 | 86.82 | 4.87 |

[1] PSS values are in ms and were computed by averaging the lines of best fit for each participant. In Experiments 1, positive values indicate visual stimuli were presented first, and negative values indicate auditory stimuli were presented first. In Experiments 2 and 3 positive values indicate vibration was presented first. Negative values indicate light was presented first in Experiment 2, and audition was presented first in Experiment 3.

[2] JND values are in ms and were calculated by subtracting the SOA value at 0.75 proportion first response form the SOA value at 0.25 proportion first response on the line of best fit, for each participant. Once transforming the proportions into z-scores, algebraically, JND = 0.675/ slope.

[3] SEM represents standard-error of the mean as used in the ANOVA calculations.

## 4.6 General Discussion

### 4.6.1 Summary

In the present study, the effect of action on perceived timing of multisensory events was explored. In my previous work, it was observed that a button press prior to a bimodal TOJ task sped up the perceived onsets of some sensory stimuli (Finkelshtein, unpublished; chapter 3). The goal of the present chapter was to further investigate action effects on the perceived timing of events. Specifically, I explored whether the spatial location of actions relative to stimulus location influenced observers' ability to distinguish the order of bimodal stimuli. Contrary to preliminary predictions, across all three experiments it was observed that the spatial distance of the button press relative to stimulus location did not impact temporal resolution. However, performing an action prior to a TOJ task overall degraded temporal resolution compared to a baseline condition in which no action was performed.

A second and an unexpected finding revealed that the stimulus location relative to action impacted subjective perceptions of simultaneity. In the baseline condition of the visuotactile TOJ task, the tactile stimulus was processed before the visual stimulus. This result is in line with previous findings using visuotactile TOJs (e.g., Spence et al., 2001). Stimuli on the same side as action did not alter the PSS for visuotactile modalities. However, when actions were performed on a different side to stimulus presentation, visual information was processed before tactile information. In contrast, actions performed prior to an audiovisual TOJ resulted in faster visual perception compared to baseline, independent of the spatial location of the action in relation to stimuli. Lastly, button presses near audiotactile stimuli resulted in faster perception of tactile information. On the other hand, actions performed away from the stimulus location appeared to numerically speed up auditory perception. Although the PSS scores for different stimulus location condition did not differ from the baseline wait condition, the binding effect size was comparable for both action conditions. Therefore, interpretation of audiotactile data remain inconclusive. All together, the data indicate actions bind most strongly to vision (observed with visual bias in visuotactile TOJs and audiovisual TOJs), followed by seemingly equal binding to touch and audition (as observed with the same binding effect size in the audiotactile TOJ).

### 4.6.2 Spatial Modulation of Actions

Spatial location of actions relative to targets impacted how quickly some sensory targets were perceived. In general, the stimulus location relative to actions did not impact temporal sensitivity. This was observed by the lack of difference in temporal precision between same side and different side stimulus locations. However, same side stimulus locations that preceded audiotactile TOJ sped up tactile processing, while different side stimulus locations that preceded visuotactile TOJ sped up visual processing. These data imply that the spatial location of actions relative to both stimuli influenced perception of some sensory modalities: a tactile bias was observed at the location of the action, while a visual bias was observed when action was at a distance. In contrast, for audiovisual stimuli, spatial location did not impact the speed of processing; instead, visual information was always perceived to occur sooner following the action.

### 4.6.3 Tactile Bias Near Action Location

Perception of tactile targets may be influenced by the action’s spatial location. In audiotactile TOJs (Experiment 3), the tactile modality was perceived sooner if stimuli were presented at the location of the action. Similarly, in visuotactile TOJs (Experiment 1) tactile stimuli were perceived before visual stimuli for same side stimulus condition, although this condition was not different than baseline. The tactile bias observed at the same side stimulus location trials may have been a result of increased pressure after a button press at the location of vibration presentation. While increased pressure at the vibration location is a possible criticism for the current design, it is unlikely to account for the present data—if the observed tactile bias was simply a result of increased pressure following a button press, then it would be expected that temporal resolution would diminish when vibrations were presented on the same side as the action. This type of bias would lead participants to select “vibration first” responses more frequently. This was not the case; in fact, no differences in JND scores were observed for same versus different side trials. Additionally, the tactile bias was observed even when the tactile modality was presented second; if participants were biased to select the tactile modality as occurring first immediately after a button press, then the bias would only be expected when the tactile modality was presented first. To truly eliminate an increased pressure account from the tactile bias, future designs should deliver tactile stimuli at a different location on the hand than from the direct location of the button press.

### 4.6.4 Baseline Audiovisual TOJs

Typically, auditory information is processed prior to visual information (King, 2005; Zampini et al, 2003; Vallet & Shore, unpublished; Vroomen, Keetels, de Gelder, & Bertelson, 2004). In Experiment 2 (audiovisual TOJ) baseline condition, auditory and visual modalities were perceived as simultaneous when presented at the same time. Tones had to lead light by an average of 12 ms to achieve PSS, but this effect was not different than zero. This finding was unexpected. In a similar audiovisual TOJ task design, Zampini et al. (2003) demonstrated that visual information needed to lead auditory information for PSS to be achieved. However, the amount of time by which visual stimuli needed to lead was less when both modalities were presented at one location compared to when they were presented at different locations. In their experiment, participants performed an audiovisual TOJ task with same and different stimulus locations intermixed within the experiment (Zampini et al., 2003). In contrast, in the present study the two stimuli were always presented at the same location. It is therefore possible that the observed decrease in time required for visual stimuli to lead auditory stimuli when targets were presented at the same stimulus location (Zampini et al., 2003) was intensified with the present design. No previous research has explored differences in perceived subjective simultaneity for audiovisual targets always presented at one location. Further exploration of this effect is required. Future experiments should investigate differences in audiovisual PSS scores when the two modalities are presented either on the same or different sides, in a blocked design versus mixed design.

Alternatively, failure to observe faster auditory than visual processing in the baseline condition could have been a result of experimental error. In general, participants appeared to have more difficulty performing audiovisual TOJs (Experiment 2) than with the other two bimodal combinations. More participants had to be removed in Experiment 2 due to poor performance. It is possible that audiovisual TOJs are by nature more challenging for observers. In addition, experimenter error could have accounted for the discrepancy—the data from each of the experiments were collected by different experimenters and at slightly different times. In fact, the JND scores, which are indicative of task precision, appeared to be larger in the audiovisual TOJ task than for the other two TOJ tasks. However, given that performance was better in the wait condition compared to the action conditions, it seems unlikely that participants just had an overall difficulty with auditory and visual stimuli. It appears that producing an action imposed the task challenge.

### 4.6.5 Temporal Orienting to Enhance Performance

Performing an action prior to a TOJ task reduced temporal precision relative to when no action was performed. The observed increased difficulty in deciphering order of bimodal pairs following a button press was surprising. It was initially hypothesized that nearby button presses would enhance temporal resolution. According to the action-centered representation account, motor movements direct attentional processes to guide perception (Tipper et al., 1992). Accordingly, it was postulated that same side stimulus locations would aid with perception. One possibility is that executing a button press directs attentional processes toward the hand, but away from the stimuli and TOJ task. Because the TOJ task followed immediately after the button press, it is possible that observers did not have enough time to re-direct resources away from the hand and toward the task. In previous research, it has been demonstrated that when participants were unprepared (e.g., directed with an invalid cue), performance did not suffer if they had time to re-orient their attention. However, performance did suffer if not enough time was allocated for re-orienting of attention (Coull & Nobre, 1998). Uncertainty for the location of the targets also may impede re-orienting effects (Correa, Lupiáñez, Madrid, & Tudela, 2006). An inability to re-orient resources from the location of the button press may account for the observed diminished temporal precision following a button press.

Rather than degraded temporal precision following an action, temporal sensitivity could have been enhanced in the wait condition. In the baseline condition, the first target always appeared 500 ms after trial initiation. The ability to predict the temporal onset could promote temporal preparation to improve performance. When observers are able to orient attention to a point in time, perception has been reported to be faster (Coull & Nobre, 1998; Correa et al., 2006). For example, cues that accurately predicted the onset of a target led to faster response times compared to invalid cues (Coull & Nobre, 1998; Correa et al., 2006). Enhanced performance following temporal preparedness has been observed with temporal gaps as little as 300 ms (Coull & Nobre, 1998). According to the temporal orienting account, enhanced performance in the wait condition could be an overestimation resulting from preparedness. Participants did not have the ability to prepare in the action condition because not enough time is given for temporal orienting to occur. Future studies could control for temporal enhancement by presenting targets in the wait condition at unpredicted intervals.

### 4.6.6 Conclusion

The relation between action and perception is dynamic and complex. Not only do actions impact perceived stimulus onsets, but the current data also demonstrated that actions affect the perceived onsets of some sensory stimuli based on the distance between actions and stimuli. In addition, for the first time, actions were shown to influence overall ability to decipher order of bimodal pairs. Together, the findings add to the results described earlier in this thesis in creating the empirical foundation for a framework of action effects on the perceived timing of multisensory events.

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## 5.0 Chapter 5: General Discussion

### 5.1 Summary of Results

The main goal of this thesis was to investigate how actions impact subsequent multisensory perception. Specifically, the perceived timing of events that followed motor movements was explored. The first empirical chapter (Chapter 2) examined the effects of motor movements on the relative perceived onsets of visual and tactile events. The investigation was extended to other multisensory domains in Chapter 3, including audiovisual and audiotactile. The final empirical chapter (Chapter 4) investigated whether actions influenced temporal resolution of multisensory events. A secondary interest of this thesis was to determine whether different action types, voluntary or involuntary, affected perception in distinct ways. In this chapter, I review the current findings concerning action effects on perceived timing of events, and discuss the significance of the findings within the literature at large.

In Chapter 2, the effects of motor movements on perceived visual and tactile onsets were explored. Because research regarding action effects on multisensory perception is limited, a secondary purpose of Chapter 2 was to establish the optimal methodology for the rest of the research program. The visuotactile TOJ task was used as in previous research that investigated the effects of attention on subsequent perception (Spence, Klein, & Shore, 2001). In Chapter 2, similar methods to those presented by Spence et al. (2001) were employed while replacing the manipulation of attention with the manipulation of motor movement. Chapter 2 also served to establish the optimal methods for the research in question. The first experiment of Chapter 2 acted as a baseline comparison to a no action condition prior to performing the visuotactile TOJ task. The findings in Chapter 2 revealed that motor movements bound to the most spatially proximate modality—in other words, motor movements sped up the perceived onset of the visual or tactile stimulus that was presented on the same side as the action.

Because Chapter 2 was also used to establish the methodology for this study, there were several challenges that were addressed in later data chapters. First, it was difficult to compare the action condition to the baseline condition because it was obtained in a separate experiment while using different methods and participants. These inter-experimental differences disallowed reliable comparisons. Second, the free and forced action conditions were also divided across experiments, again, making it challenging to perform valuable comparisons across conditions. Lastly, the studies used a small number of psychophysical observers, introducing greater variability and a challenge to statistically analyze the data. From this, it was evident that while overall patterns regarding binding effects can be concluded, individual variability exists. These issues were addressed and corrected in Chapter 3, where a baseline "no action" condition, and free and forced action conditions were intermixed within each experiment. For the first time, this thesis demonstrated that actions could spatially bind to stimuli and influence subsequent perception across multiple senses.

In Chapter 3 the exploration of action effects on perceived onsets was applied to other bimodal pairs. Based on the data of Chapter 2, it was possible that action would bind to the most proximate modality. However, perception of each bimodal pair involves unique mechanisms (e.g., Harrar & Harris, 2008). It was therefore hypothesized that actions would bind to either the visual and tactile stimulus, depending on the modality presented closest to the action, and that the effects of action on other bimodal pairs would be unique, depending on the sensory stimuli presented after the action. Given the explorative nature of this research, the exact binding patterns of different bimodal pairs were difficult to predict and this was the main goal of Chapter 3—to investigate the effects of action on bimodal pairs other than visual and tactile.

Actions behaved in an idiosyncratic manner for each bimodal pair. The PSS and JND data from Chapter 3 for Experiments 1-3 are depicted in Figure 5.1. As predicted, action effects on visuotactile perception were replicated—executing movements sped up perception of spatially proximate sensory stimuli. Through the addition of a baseline (no action condition) the data revealed that the magnitude of binding was greater between actions and proximate visual stimuli compared to actions and proximate tactile stimuli. The spatial distance between actions and subsequent audiovisual stimuli did not impact binding. Instead, the visual modality was perceived before the auditory modality regardless of the action location—this result was contrary to that in the baseline condition in which auditory perception was faster than visual perception. Like with visuotactile pairs, for audiotactile pairs, actions appeared to bind to the stimulus modality presented closest to the action location. However, the PSS for actions performed near vibration did not significantly differ from baseline. So while numerically the data seemed to indicate a bidirectional shift following an action toward whichever modality appeared on the same side as the action, conclusions regarding audiotactile pairs remain unclear. All together, the findings reveal that actions influence multisensory perception in unique ways, contingent on the modalities that follow.

In Chapter 4, the influence of action on temporal resolution was explored. It was postulated that because directing attention to a spatial location impacts temporal resolution (e.g., Stemalch & Herdman, 1991; Yeshurun & Levy, 2003), performing an action at the location of the stimulus pairs could also improve temporal resolution. Contrary to this prediction, the data revealed that temporal sensitivity was poorer following a motor movement relative to a no action baseline, regardless of the action location. Figure 5.2 illustrates the PSS and JND data for Experiments 1-3 in Chapter 4. Together, the findings of Chapters 2, 3, and 4 provide the groundwork for a novel framework to explain how our behaviours influence subsequent multisensory perceptions.

The effect of different action types (free or forced) on subsequent perception was explored within all three data chapters. It was predicted that free or chosen action types would result in a greater degree of binding relative to forced or fixed action types (Haggard, Clark, & Kalogeras, 2002; Engbert, Wohlschlager, Thomas, & Haggard, 2007; Engbert, Wohlschlager, & Haggard, 2008). Contrary to this prediction, the present studies failed to demonstrate an effect of action type. The lack of effect calls to question the methodology used and/or the role of agency and decision in perceptual binding. This issue is discussed later in this chapter.

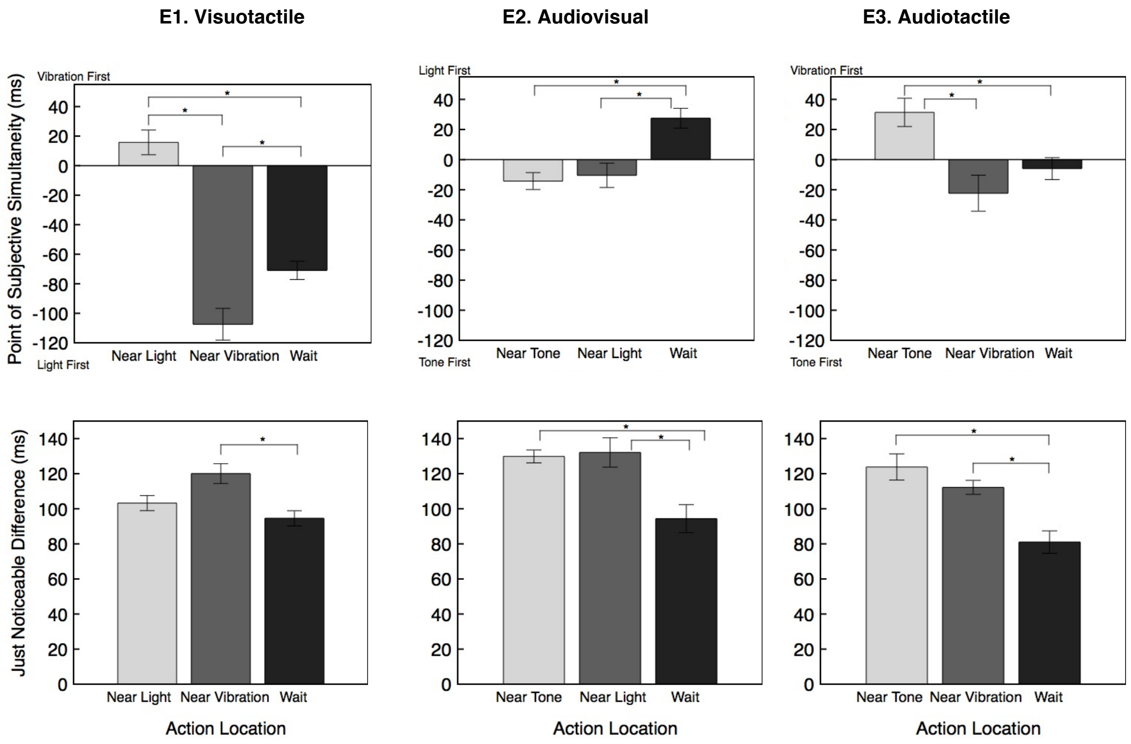

*Figure 5.1* Chapter 3: PSS scores (top row) and JND scores (bottom row) displayed for the action near stimulus 1, action near stimulus 2, and wait conditions for Experiments 1-3. The PSS scores represent the amount of time one stimulus needed to lead another stimulus (in ms) to be judged as simultaneous. Negative PSS scores indicate lights led vibration, tones led light, and tones led vibrations for Experiment 1, 2 and 3 respectively. The JND scores represent the smallest interval required between the two stimuli to accurately judge the temporal order on 75% of trials Error bars reflect standard error of the mean, corrected for within-participants comparisons.

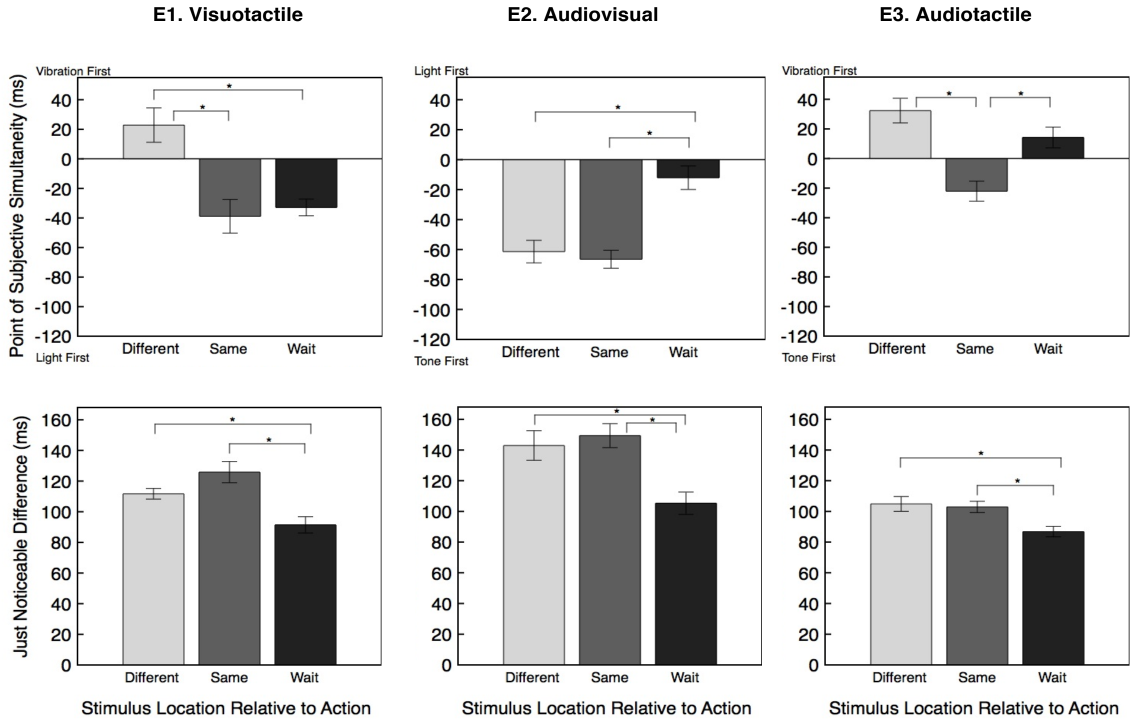

*Figure 5.2* Chapter 4: PSS scores (top row) and JND scores (bottom row) displayed for the same side stimulus location, different side stimulus location, and wait conditions for Experiments 1-3. The PSS scores represent the amount of time one stimulus needed to lead another stimulus (in ms) to be judged as simultaneous. Negative PSS scores indicate lights led vibration, tones led light, and tones led vibrations for Experiment 1, 2 and 3 respectively. The JND scores represent the smallest interval required between the two stimuli to accurately judge the temporal order on 75% of trials. Error bars reflect standard error of the mean, corrected for within-participants comparisons.

## 5.2 Implications and Significance

Previous explorations regarding action effects on subsequent perception are relatively limited. For example, preceding studies have not investigated the influence of action on the perception of more than one competing sensory modality. In addition, the spatial and temporal relation between motor movements and stimuli remained poorly understood. Moreover, action effects on temporal resolution have not been previously explored. Accordingly, the current work forms the groundwork concerning motor movement effects on the perceived timing of multisensory events.

Four main findings were established within the current research. First, actions bound in an idiosyncratic way to each bimodal pair. Actions sped up perception of some sensory modalities, depending on the bimodal pair. Previous research demonstrated that attending to one sensory stimulus over another sensory stimulus speeds up its perception—an effect known as the multisensory prior entry effect (Spence et al., 2001). Analogous to this finding, I demonstrated that in some cases, executing movements prior to a stimulus sped up the perception for some sensory stimuli.

The tendency for action to behave in unique ways on subsequent perception challenges the ability to generalize the widely reported intentional binding effect (Haggard et al., 2002; Engbert et al., 2007; Engbert et al., 2008; Strother, House, & Obhi, 2010). The intentional binding effect describes a perceived temporal compression between a voluntary action and a subsequent stimulus. It was first observed when a voluntary action preceding a tone was perceived to occur later in time, while the tone was perceived to occur earlier in time. Until now, the intentional binding effect was yet to be explored with multisensory targets. The current findings indicated that voluntary actions do not behave in a unified manner on subsequent perception. Thus, the perceived temporal compression between an action and a sensory stimulus is contingent on the bimodal stimuli that follow the action. It is evident that intersensory differences exist within the intentional binding effect.

A pattern observed consistently across all studies is that action preferentially binds to vision. For visual and tactile pairs presented on different sides, action bound to both modalities but to a greater degree to vision (Chapter 3). When visuotactile pairs were presented on the same side, either far or close to the action (Chapter 4), a visual preference was observed for motor movements executed at a different location than the stimulus location. Actions preceding audiovisual pairs bound solely to vision (Chapter 3 and 4). Second, in specified cases, motor movements spatially bound to sensory modalities, illustrating action's ability to follow the spatial rule of multisensory integration previously observed for multiple stimuli. Third, although executing motor movements sped up perceived onsets of some sensory modalities, somewhat surprisingly it diminished temporal resolution compared to a baseline wait condition. Lastly, the ability to choose the side to execute a motor movement appeared to have no influence on binding. Different accounts for these novel findings are discussed below.

## 5.3 Patterns of Action Effects on Bimodal Perception

### *5.3.1 Visual Dominance*

Actions appeared to preferentially bind to the visual modality. This was observed with visuotactile and audiovisual stimulus combinations. Visual preference over auditory and tactile modalities has been previously reported (Colavita, 1974; Koppen & Spence, 2007; Hartcher-O'Brien, Gallace, Krings, Koppen, & Spence, 2008). For example, in an audiovisual modality judgment task, observers often failed to notice the presence of an auditory stimulus that was simultaneously presented with a visual stimulus—an effect known as the Colavita effect (Colavita, 1974). This effect has been robustly replicated following various manipulations (Koppen & Specnce, 2007), and with visuotactile stimuli as well (Hartcher-O'Brien et al., 2008). According to the visual dominance account, vision is characteristically less alerting than other senses. As a result, visual perception requires increased attentional resources and this leads to faster visual perception (Posner, Nissen, & Klein, 1976).

The effects of motor movements on the visual bias have not been previously explored. Specifically, no previous research has investigated the impact on perception of the spatial location of an action relative to a visual stimulus location. Previous research using visuotactile pairs demonstrated a greater visual dominance effect when stimuli were presented near each other as opposed to separated from each other (Hartcher-O'Brien et al., 2008). Interestingly, in Chapter 4 (Experiment 1) when visuotactile stimuli were presented near each other and at the same location as the action, a visual bias was not observed. This result is in contrast to when stimuli were presented at a different location than the action, in which case a visual bias was present. Thus, the present findings suggest that the visual bias following nearby visual and tactile target presentation is altered after performing an action, and more specifically, the location of the action impacts the bias.

Actions speed up perception of relevant targets (Wykowaska, Schubo, & Hommel, 2009; Fagioli, Hommel, & Schubotz, 2007). Stimuli presented close to actions are more likely to be interpreted as causal (e.g., Moore et al., 2009), and therefore may be seen as more relevant. Following an action, more resources may be allocated toward tactile perception because tactile information serves an immediate value (Gregory, 1967). This could imply that tactile information is more spatially bound to an action than visual information. In support of this idea, during a duration judgment task observers were more accurate to judge tactile durations that were delivered to the same finger that executed an action*,* as opposed to a neighbouring finger (Press, Berlot, Bird, Ivry, & Cook, 2014). On the other hand, accuracy of duration judgments of visual stimuli did not differ for same or different side motor movements (Press et al., 2014). These results imply that tactile information is more spatially bound to actions. In the present study, the observed absence of binding between action and tactile stimulus when visuotactile stimuli were both presented at a different location than the action (Chapter 4, Experiment 1), could possibly be because tactile information is more spatially dependent on the action. In other words, when tactile information occurs further away from the action location it may be more difficult for the brain to associate the action and vibration together. In this scenario, there may be a higher reliance on visual stimuli. Indeed, when visual and tactile stimuli were presented at a different location than the action (Chapter 4, Experiment 1), the brain was more likely to rely on visual information.

Visual dominance may be more prevalent when tactile information is presented away from the action. The findings of Chapter 4 (Experiment 1) indicated that visual binding occurred only in the case where visual and tactile stimuli were presented at a single location away from the action location. On the other hand, when visual and tactile stimuli were presented at a single location and on the same side as the action, no binding between action and the visual stimulus was observed. When actions are executed away from the stimulus location, the lack of immediate proprioceptive feedback of tactile stimuli may enhance the less alerting visual stimulus leading to a visual dominance effect. Research regarding the influence of spatial location of actions on visual dominance requires further exploration.

### *5.3.2 Tactile Bias*

Another emerging pattern across all experiments was a tactile bias after actions were executed near vibrations. For visuotactile pairs, tactile stimuli were perceived sooner if the vibrations were presented on the same side as the action (Chapters 2 and 3), and if both visual and tactile stimuli were on the same side as the action, as opposed to both on the opposite side of the action (although faster perception of tactile stimuli in the condition that stimulus location was on the same side as the action did not differ from a baseline wait condition; Chapter 4, Experiment 1). Moreover, the degree of binding for actions performed near vibrations appeared numerically larger than for actions performed near light (Chapter 2). For audiotactile pairs, actions performed on the same side as vibration that followed spatially separated auditory and tactile stimulus presentation revealed a tactile bias similar to that of the baseline condition (Chapter 3, Experiment 3). Although statistically non-significant, numerically same side vibrations appeared to bind to actions (Chapter 3, Experiment 3). In contrast, when both auditory and tactile stimuli were presented together in space, a tactile bias was observed following an action that was performed on the same side as stimulus presentation (Chapter 4, Experiment 3).

### *5.3.3 The Binding Effect Following Audiotactile Stimuli*

The binding effect of action to auditory and tactile stimuli produced inconclusive findings. Unlike with visuotactile and audiovisual pairs that demonstrated consistent findings across the studies, the results of actions following audiotactile TOJs were less clear. As explained above, when auditory and tactile stimuli were presented separately (Chapter 3, Experiment 3), actions bound to auditory stimuli presented on the same side. Numerically, actions also appeared to bind to tactile stimuli presented on the same side, but this was not significant form the baseline condition. Secondly, the difference in effect size for actions performed near vibrations did not differ from the effect size for actions performed near tones. This implied no preferential binding of actions to either sensory stimulus. On other hand, when auditory and tactile stimuli were presented together, actions appeared to numerically bind to the auditory modality if stimuli were at a different location than the action (but this was not significant from baseline), and to significantly bind to the tactile modality if stimuli were presented at the same location of the action (Chapter 4, Experiment 3). Together, these findings make it difficult to draw clear conclusions regarding the binding effect of audiotactile stimuli.

Audiotactile pairs appear to be unique. Previous research exploring binding effects of bimodal stimuli (when no action was performed) demonstrated that audiotactile pairs behave differently than visuotactile and audiovisual pairs (e.g., Zampini et al., 2005). For example, audiovisual and visuotactile stimuli presented at one location are more likely to be perceived as a single percept (Spence et al., 2001), however this is not the case for audiotactile pairs (Zampini et al., 2005). Instead, auditory and tactile stimuli must be presented together close to the head to be perceived as a single percept (Kitawaga, Zampini, & Spence, 2005). These findings outline a unique property in audiotactile stimuli. In nature, vibrations and related auditory information often occur in peripersonal space (Navarra, Soto-Faraco, & Spence, 2007). Presenting auditory and tactile stimuli at separate locations (like in Chapter 3, Experiment 3) is seemingly unnatural, and could have contributed to the inconclusive findings. When auditory and tactile stimuli are separated, a lower reliance may be placed on tactile feedback and this may increase overall noise in the experiment. In contrast, In Chapter 4 when sounds and vibrations were presented together, the immediate proprioceptive feedback following a same side button press could account for the tactile bias (Gergory, 1967). Vibrations occurring near actions may be interpreted as an immediate consequence of the motor movement. This tactile bias was not evident if the action was performed away from the stimuli, which again, may be unnatural for the brain to interpret.

## 5.4 Action and the Rules of Multisensory Integration

The brain often perceives two or more related stimuli as one unified precept (e.g., Vatakis & Spence, 2007; Welch & Warren, 1980). The rules of multisensory integration posit that stimuli presented in spatial and temporal proximity are integrated and perceived as belonging to a single event (e.g., Spence et al., 2001). In the present thesis, I explored whether actions could follow similar rules of multisensory integration, and therefore, behave as a sensory stimulus. In other words, would actions presented in spatial or temporal proximity to sensory modalities be bound together with those sensory stimuli?

The present findings revealed that, in certain cases, actions followed the temporal and spatial laws of multisensory integration. With respect to the temporal law, stimuli that immediately followed an action tended to bind to the action (depending on the modality pair). In some cases, stimuli were perceived sooner following an action compared to when no action was performed. With respect the spatial law, there was also support in specified cases. Vallet and Shore (unpublished) previously reported that actions do not follow the spatial law for audiovisual pairs. Consistent with their findings, in the present study, actions did not appear to follow the spatial law when it came to audiovisual stimuli, but did follow the spatial law for other stimulus pairs—actions executed prior to the presentation of visuotactile and audiotactile targets bound to the stimuli most proximate to the action. Thus, the ability of actions to spatially bind to sensory stimuli was demonstrated.

## 5.5 Relation to Time Keeping Models

One ongoing issue regarding temporal perception concerns how time is perceived in the brain—temporal perception may occur centrally through an amodal pacemaker, or rather, temporal perception may be distributed throughout the brain (e.g., Muller & Nobre, 2014). While the main focus of this thesis was not to address mechanisms involved in time keeping, the current findings provide insight regarding temporal perception.

The pacemaker model assumes a single, centralized, supramodal mechanism (Treisman, 1963). According to this model, a counter computes the number of ticks emitted by the pacemaker per unit of time to form temporal estimates (Treisman, 1963). This model postulates time is generated as a linear metric (Karmarkar & Buonomano, 2007). Contrary to this prediction, the present findings imply temporal perception does not follow a linear mechanism. Instead, a simple button press can alter the order in which events are perceived to appear. For example, in Chapter 3 it was observed that without any action, auditory information was perceived before visual information. Following a button press, visual information was perceived before auditory information. Temporal recalibration of events following an action is incompatible with the notion that time is perceived linearly. Secondly, the pacemaker model assumes an amodal time-keeper. Based on the present findings discussed above, it is evident that each modality is perceived at varied times following an action. The idiosyncratic differences in the intentional binding effect argue against a supramodal and linear time-keeping mechanism.

Although the present findings fail to support a centralized time-keeping mechanism, it is still possible that such a mechanism exists in parallel to other dispersed mechanisms (Karmarkar & Buonomano, 2007; Muller & Nobre, 2014). Karmarkar and Buonomano (2007) suggested temporal information might be perceived through different mechanisms, depending on the length of the interval to be estimated. A linear metric of time may be possible for intervals that are longer than 1 second. However, shorter intervals (500 ms or less) may depend on dispersed changes in neuronal activity through time (Karmarkar & Buonomano, 2007). As described in Chapter 1, the state-dependent network model posits that interactions with stimuli result in synaptic activity that progresses through time, and in turn, provides estimates of the time elapsed (Buonomano & Merzenich, 1995). Together, the present findings further support the notion that temporal perception is dynamic and flexible.

### 5.6 Free versus Forced Actions

A secondary aim of this thesis was to compare the influence of different action types on subsequent perception. No differences were observed in binding for actions that were voluntary compared to involuntary. Based on the literature, it was predicted that intentional binding effects (perceived shorter delays between actions and effects) would only emerge when button press sides were chosen (e.g., Haggard et al., 2002; Engbert et al., 2007; Engbert et al., 2008). Contrary to this prediction, binding was observed equally for chosen (free) and predetermined (forced) actions.  Although this finding was surprising, differences in methodology across experiments can possibly account for the discrepancy.

The lack of action type effect could be attributed to the way in which voluntary and involuntary actions were defined. Action types were defined in terms of choice—in the voluntary condition, observers chose between a left and right button press and in the forced condition button press sides were fixed. Accordingly, action types were defined in terms of decisional mechanisms. However, in previous literature, actions were often defined in terms of motor control. For example, in the voluntary action condition, participants exerted physical control over the action, whereas in the involuntary action condition, motor movements were either generated by others (Engbert et al., 2007; Engbert et al., 2008; Strother, House, & Obhi, 2010), or were TMS-induced (Haggard et al., 2002; Haggard & Clark, 2003; Haggard & Cole, 2007). Therefore, the difference between decisional and motor contributions to voluntary/involuntary actions could be responsible for the different findings.

The way in which people experience control over actions and subsequent effects remains unclear. When a stimulus follows immediately after a motor movement, observers may experience a sense of agency over the effect (e.g., Hommel, 1996). This sense of agency may account for the observed binding effects between actions and stimuli (e.g., Moore, Lognado, Deal, Haggard, 2009a; Strother et al., 2010). The sense of agency could be internally or externally driven (Moore, Wegner, & Haggard, 2009b). An internal sensation is evoked through internal signals to act, which are then compared against a sensory outcome. In contrast, external cues could be in the form of primed thoughts to produce an action (Moore et al., 2009b). When actions were either TMS-induced or generated by someone other than the participant, the formation of both internal and external agency cues were prevented, which might have eliminated the binding effect (Engbert et al., 2007; Engbert et al., 2008; Haggard et al., 2002; Haggard & Clark, 2003;

Haggard & Cole, 2007). In contrast, in the present study, involuntary actions were generated by the participant and followed an immediate sensory consequence. Therefore, both internal and external cues could be present, thus fostering a sensation of agency, and consequently an intentional binding effect.

According to one model, intentional binding effects are mediated by three factors: what, when and whether (Brass & Haggard, 2008). The "what" refers to the decision of which action to execute, the "when" refers to the point in time at which the observer decides to physically execute the motor movement, and the "whether" refers to the decision to either execute the action or not. Manipulating these three factors could influence binding. For instance, in the present study, the "what" factor was somewhat predetermined in both conditions—participants executed a button press in all cases despite having a choice of side. The "when" factor was not controlled—in both action type conditions, participants had an unlimited time to press the button. Lastly, the "whether" factor did not differ between voluntary and involuntary decisions—participants always had to make the action. Changing different parameters of the model could alter the degree of agency and binding (Brass & Haggard, 2008).

The ability to make a decision should hypothetically influence the "what" part of the model, and therefore influence binding. Although choice is not a requirement for a sense of agency, it does impact agency (e.g., Gallagher, 2012). It is therefore surprising that no difference was observed between the choice and forced conditions. Previous observations support choice as a contributing factor to binding (Barlas & Obhi, 2013). Barlas and Obhi (2013) predicted that the intentional binding effect between an action and sensory consequences would increase as a function of the number of choices. Indeed, they observed that with a high number of button press choices (seven possible buttons) compared to a medium number of choices (three possible button presses) or no choices (one possible button press), the magnitude of binding was greater. Increasing the number of choices increased the sensation of agency; more choices create a sense of "freedom" (Barlas & Obhi, 2013). In the present experiments, participants only had two buttons to choose from. Given that Barlas and Obhi (2013) did not observe a difference in intentional binding between one button option and three button options, it is possible that two-choice buttons were insufficient in creating the perception of opportunities, and therefore, the sense of agency.

Future experiments could manipulate different factors to either reduce or increase the sense of agency to observe its influence on binding effects. First, as discussed above, the "what" factor of the Brass and Haggard (2008) model could be manipulated by increasing the number of choices for the button press. For example, in the choose condition, participants could have four buttons on the left and four buttons on the right to choose from. This would possibly increase the sense of freedom, and therefore, agency. Secondly, the "when" factor could be altered by allowing participants more or less time to execute the button press. The present design permitted an unlimited amount of time in both the free and forced conditions—allowing for less time could decrease the sense of agency, and therefore decrease binding effects. Lastly, to investigate decisional processes compared to motor processes in the sensation of agency, an external apparatus that applies pressure on the finger to execute the button press could be used in the forced condition. This would prevent the physical control over the action, and therefore decrease the sense of agency. These manipulations could be done together or separately to better understand the factors contributing to the sense of agency and how it impacts binding.

## 5.7 Temporal Preparedness

In Chapter 4, it was predicted that the spatial location of the action relative to the stimulus location would influence temporal resolution. In contrast, temporal resolution did not differ when actions were executed from the same or different stimulus location—instead temporal precision was overall diminished after a motor movement compared to baseline. Temporal resolution was measured as the just noticeable difference (JND) and it indicated the smallest interval of time required between the two modalities to accurately judge presentation order. The benefit in temporal resolution (lower JNDs) when no action was performed was revealed whether the two stimuli were separated from each other (Chapter 3) or presented within the same spatial proximity to each other (Chapter 4); this was the case for all bimodal pairs. It remains unclear whether action degrades temporal resolution or rather a lack of action enhances temporal resolution.

Temporal resolution may have been enhanced when no action was executed as result of temporal preparedness (e.g., Coull & Nobre, 1998). The ability to predict the onset of targets allows observers to direct attentional resources to enhance performance (Coull & Nobre, 1998; Correa, Lupianez, Milliken, & Tudela, 2004; Lange & Roder, 2006). For example, when participants were provided with valid temporal cues that predicted the temporal onset of a target, performance was enhanced for both detection and discrimination tasks—the benefit in performance following temporal preparedness has been demonstrated for visual, auditory and tactile perception (Coull & Nobre, 1998; Correa et al., 2004; Lange & Roder, 2006). In the present studies, following the "wait" command, the first stimulus appeared after a fixed amount of time (500 ms). Because the target was always validly presented after the 500 ms delay, this potentially allowed observers to direct attentional resources to improve performance, despite being unaware of the exact target location. The interval time between the cue (wait command) and the first stimulus (500 ms) is within the optimal range to temporally orient attention to a point in time (Coull & Nobre, 1998; Correa et al., 2004; Lange & Roder, 2006). In contrast, in the action condition, participants did not have sufficient time to temporally orient attention because the target followed immediately after the action.

Alternatively, performing an action may degrade temporal resolution. It was initially postulated that executing motor movements could direct attentional resources to the location of the action (e.g., Tipper, Lortie, & Baylis, 1992; Gherri & Eimer, 2010). However, if attention was directed to the location of the button press (the hand) this may have interfered with the TOJ task, in which stimuli were presented in front of the hand. With the exception of the vibrations, the light and sound stimuli were not presented on the hand. If attention was allocated to the hand immediately following an action, then there may have been an insufficient amount of time for participants to re-direct attention from the hand to an immediately appearing target. This allocation of attention would degrade rather than enhance temporal resolution.

Future studies should address participants' ability to temporally prepare during a "wait" condition. If targets were presented at random times after the "wait" command, it would prevent observers from temporally preparing for the target onset. Alternatively, if a short delay was added after the action condition, then participants could temporally prepare for the targets in the same way as in the wait condition. However, a delay too long between the action and the target would prevent binding from occurring (e.g., Vallet & Shore, unpublished). Lastly, the experimental design of Chapter 4 could be repeated while manipulating the percentage of stimulus locations on the same versus different side as the action. If the majority of the trials occurred at one location, then participants could expect the target location to direct attention to that location and possibly improve temporal resolution. It is important to note, however, that it remains unclear whether directing attention to the location of the target would improve temporal resolution—temporal resolution also depends on the experimental task and stimulus properties (e.g., Nicol, Watter, Gray, & Shore, 2009). Ensuring that temporal preparedness was either allowed or disallowed for both the action and no action conditions would permit a true assessment of the effects of action on temporal resolution relative to a baseline.

## 5.8 Other Limitations and Future Directions

### *5.8.1 Tactile Bias due to Increased Pressure*

A possible criticism of the current design is that an increase in physical pressure following a button press resulted in the observed tactile bias. The vibrations were delivered to the same digit (i.e. the thumb) that pushed the button. If participants did not fully release after making the button press, the increased pressure may have been falsely interpreted as the vibration occurring sooner, thus, increasing the likelihood that tactile stimuli were judged as occurring first. In all of the present experiments, tactile bias was observed only when vibration was on the same side as the action. However, it did not matter if the vibration followed immediately after the action, or if it followed after another modality that was preceded by a delay. This argues against a vibration bias due to increased pressure. There was also no difference in participants' ability to accurately judge which modality occurred first (measured as JND scores) when the vibration was presented on the same side of the action compared to the opposite side of the action (Chapter 3). If increased physical pressure following same side vibration trials biased participants, then it would be expected that accuracy would differ for same compared to different side trials.

Future studies should control for the possibility of a tactile bias. For example, if tactile stimuli were delivered to a part of the hand (such as the palm) other than the one executing the action (the finger) then it would prevent increased physical pressure following the action. This would eliminate the possibility of a tactile bias due to increased pressure.

### *5.8.2 Stimuli Presented from Different Locations*

In Chapters 3 and 4, the experiments contained an audiotactile and an audiovisual TOJ task. Unlike with visuotactile stimuli, the sounds were not presented from the same apparatus as lights and vibrations (which were on the cube). Experimental instructions emphasized maintaining the hands holding the cubes directly in front the speakers. Between each block, the experimenter ensured that the participants complied with these instructions. However, observers could have moved their hands away from the speakers in between trials. Because sensory information for different modalities is conducted at different rates, presenting stimuli from different locations could impact the time required for each modality to reach the sensory organs that decode the signals (e.g., King, 2005). Presenting both modalities from the same spatial location is therefore crucial. To ensure signals are delivered from the same spatial location, future apparatus could incorporate speakers within the wooden cubes.

### *5.8.3 Psychophysical Observers*

The first empirical chapter (Chapter 2) was also designed to establish the methodology for the intended purposes. The early experimental designs produced noisy data, which were not included in this thesis. It was thereafter decided that psychophysical observers would be best to establish the effects of action on visuotactile perception. Psychophysical data may not be representative of the general population, and therefore lacks ecological validity. Moreover, the Chapter 2 results illustrated that great variability exists between participants, and therefore a larger number of participants is required for a more accurate interpretation of the data. Interestingly, Chapters 3 and 4 followed similar experimental designs with more observers. The visuotactile effect in Chapters 3 and 4 generally followed the effect observed in Chapter 2. It is therefore reasonably safe to assume that the data utilizing psychophysical observers represent the general population.

### *5.8.4 Spatial Effects of Action*

One purpose of this thesis was to determine spatial effects between actions and modalities on perception. This issue was explored by looking at how action affects perception of bimodal pairs, and it was concluded that the effects were unique to each pair. However, no studies have looked at how action binds to each modality individually within one experimental design. It would therefore be interesting to include a baseline that investigates how action binds to each modality that is not competing with another modality, within one experiment. This would allow for interesting conclusions regarding how actions influence binding of competing bimodal stimuli as opposed to stimuli within a single modality.

### 5.9 Conclusion

Actions influence subsequent perception in a dynamic manner (Haggard et al., 2002; Haggard & Clark, 2003; Haggard & Cole, 2007; Vallet & Shore, unpublished; Engbert et al., 2007; Engbert et al., 2008). The literature exploring the effects of action on subsequent perception is extended further within the current work to account for multisensory domains. The present thesis provides three main contributions to the current literature: actions can follow the spatial and temporal laws of multisensory integration in the same manner as sensory stimuli; actions exhibit unique intentional binding effects on each bimodal pair; and actions appear to degrade temporal resolution for bimodal stimuli. Taken together, these findings greatly progress the action-perception literature to provide a more complete understanding of how our behaviours influence how we view the world.

## 5.10 References

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