Rhythmic auditory stimuli in a goal-directed reaching task with reduced visual feedback: Examining onset and source

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Abstract

Rhythmic auditory stimuli (RAS) have been proposed to improve motor performance in populations with sensorimotor impairments and typically developing individuals. However, reasons for the benefits are poorly understood. One idea is that RAS may supplement movement planning when other sensory input is diminished. The present thesis aims to gain a better understanding of how RAS may benefit performance through manipulating the onset, complexity and source of auditory stimuli. Two experiments each tested 24 typically developing young adults. Reaching movements were captured using 3D motion capture (Optotrak 3D Investigator) and vision was occluded using PLATO Visual Occlusion Spectacles. Experiment 1 used different onsets of RAS (no sound, sound before, sound during, and sound throughout; all with and without vision) and found that sound heard before movement initiation can elicit performance gains in reaction time and endpoint error. Experiment 2 used different complexities and sources of RAS (no sound, simple metronome, complex metronome, simple drum and, complex drum; all with and without vision), and participants reported subjective enjoyability for each auditory condition on a 5-point Likert scale. Analysis for rhythmic complexity revealed that increased rhythmic complexity did not benefit reaching performance. Participants enjoyed the drum conditions more than the metronome conditions, which was moderately correlated to improved performance in reaction time. Improved movement planning and attentional focus are considered in their role in improving movement with the inclusion of RAS. This thesis provides evidence that RAS heard before movement initiation benefit movement performance and provides preliminary evidence that source and subjective enjoyability contribute to performance.

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Introduction

Sensorimotor integration allows us to scale movement parameters to create accurate and efficient goal-directed reaching movements in a variety of tasks and environments. Motor performance during reaching tasks is critical in all aspects of daily living, including work, leisure, communication and sport. Sensory input and associated integration influence the quality of movement during reaching tasks. For example, visual and proprioceptive feedback have been shown to impact the quality and accuracy of goal-directed movements by influencing the planning and error correction portions of the movement (Elliott, Helsen, & Chua, 2001). Vision of a target prior to movement initiation allows us to plan the movement, while further visual and proprioceptive feedback allows us to make corrections to reach our goal.

Historically and cross-culturally humans have used forms of rhythmic auditory cueing in movement, including dance and military drum beats. There has been growing evidence for the use of rhythmic auditory cueing for performance of upper limb reaching tasks in both typically developing and clinical populations, such as stroke and cerebral palsy (Hatfield, Wyatt, & Shea, 2010; Johansson, Domellöf, & Rönnqvist, 2012; Johansson, Domellöf, & Rönnqvist, 2014; Ladwig, Prado, Marotta, & Glazebrook, 2016; Thaut, Kenyon, Hurt, McIntosh, & Hoemberg, 2002; Whitall & Waller, 2013; Whitall, Waller, Silver, & Macko, 2000).

Hatfield, Wyatt, & Shea (2010) investigated the impact of auditory feedback during a reciprocal aiming Fitts task, where typically developing participants had to move back and forth between two targets. When participants had auditory feedback at the endpoint of each movement they demonstrated decreased movement times and reached peak velocity closer to the midpoint of the movement, making the overall kinematic pattern more symmetrical (Hatfield et al., 2010). The authors proposed that the auditory feedback allowed participants to focus on planning the return movement rather than confirming completion of the current movement. This enhanced the movement planning phase by allowing the control phase to use less time and processing (Hatfield et al., 2010).

Rhythmic auditory cueing has also been used to facilitate reaching movements made by populations with significant sensorimotor impairments such as during stroke rehabilitation and individuals with cerebral palsy. A rhythmic metronome was used in a reciprocal tapping task in stroke rehabilitation patients. Movement performance was quantified by movement trajectory and timing variability (Thaut, Kenyon, Hurt, McIntosh, & Hoemberg, 2002). When participants were provided with the additional auditory information they demonstrated reduced timing variability and smoother kinematic patterns (Thaut et al., 2002). The improved movement kinematics suggests a coupling of the metronome to the temporal aspects of the motor program, improving kinematic stability, which could in turn allow for improvements in motor planning. The authors suggest that the additional auditory rhythm may be an effective way to improve sensorimotor control in the affected hemisphere (Thaut et al., 2002). Additionally, the repetitive nature of the reciprocal tapping task facilitates a high number of repetitions, which is essential for motor learning (Lee, Swanson, & Hall, 1991). In a population with cerebral palsy, Ladwig et al., (2016) used a discrete button press task with and without a metronome to assess reaching performance. Participants exhibited decreased reaction times, improved movement control and increased endpoint accuracy when they received the rhythmic auditory stimulus prior to movement initiation (Ladwig et al., 2016). This suggests that the rhythmic auditory stimulus had a positive impact on the movement planning stage.

Populations with significant sensorimotor impairments may have increased reliance on additional information, such as the rhythmic auditory stimulus, to compensate for sensory processing deficits in other areas. Motor control models such as the multiple-process model of limb control (Elliott et al., 2010) and the OPTIMAL theory of motor learning (Wulf & Lewthwaite, 2016) including improved attentional foci (Wulf, Shea, & Park, 2001a), may offer some insight as to how a rhythmic auditory stimulus may improve motor control for populations with sensorimotor impairments. The multiple-process model of limb control proposes that participants use multiple overlapping sources of sensory information for movement planning, execution and error correction (Elliott et al., 2010). Rhythmic auditory stimuli may provide the performer with additional temporal information, influencing the planning or execution of a movement. Having participants focus on the auditory stimulus may also cause them to shift towards an external focus of attention, which typically leads to improved motor performance, based on principals outlined in the OPTIMAL theory of motor learning (Wulf, 2007; Wulf & Lewthwaite, 2016). This rhythmic metronome may also have a motivational effect proposed to contribute to motor learning (Wulf & Lewthwaite, 2016).

In typically developing individuals, we can examine the impact of rhythmic auditory stimuli by manipulating the visual information that they receive during their reaching movement. Occluding vision upon movement initiation may cause individuals to rely more on other sources of information, such as auditory stimuli, proprioceptive feedback (Chua & Elliott, 1993) and memory representations (Elliott & Calvert, 1990; McIntyre, Stratta, & Lacquaniti, 1998) to complete the movement. Removing visual information and compelling individuals to use auditory and proprioceptive cues may result in a shift to an external focus of attention, resulting in improved kinematic performance (Wulf, 2007). The current experiment aims to create a controlled model of disrupted sensory feedback by occluding vision during movement execution.

The use of rhythmic auditory stimuli has been popular in clinical interventions. However, there is a lack of understanding about how this additional auditory information integrates with our current movement models to impact reaching performance. Currently, more information is needed to understand when and how the rhythmic auditory stimulus is most beneficial. This information will help inform clinical interventions as well as strengthen our understanding of motor control models. There is also a lack of understanding about which source of auditory stimulus is most beneficial. In the current literature, interventions typically use a metronome beat, however there could be differences in performance when using a more pleasant or complex stimulus such as a drum beat or rhythm. Additionally, the inherent variability associated with a human derived beat could have some impact on human movement control.

The current thesis addresses two questions about how rhythmic auditory stimuli influence movement control. Experiment 1 investigated the impact of different onsets of rhythmic auditory stimuli to determine when in the movement planning model this additional information is most beneficial in a goal-directed reaching movement. Overall, sound heard before movement initiation benefited performance in terms of reaction time and endpoint error. Experiment 2 examined the impact of different complexities and sources of rhythmic auditory stimuli including metronome and drum beats, and considered subjective enjoyability with a Likert scale rating. Increased rhythmic complexity did not benefit reaching performance, and participants tended to like drum conditions more than metronome conditions, which was moderately correlated to improved performance in reaction time. This thesis begins with a review of existing literature on limb control and rhythmic auditory cueing in typical and clinical populations. Methods and results are detailed for Experiments 1 and 2, and potential mechanisms facilitating improved performance, such as improvement planning and foci of attention are proposed.

Review of Literature

Control of goal-directed reaching movements

Since Woodworth's seminal paper in 1899 our understanding of how humans control goal-directed reaching movements has evolved. Woodworth (1899) had participants use a stylus to slide between two target lines on a rotating drum. Woodworth measured spatial accuracy, movement consistency and spatial-temporal aspects of movement trajectory. The results depicted an initial consistent and rapid movement, and as the stylus neared the target, movements slowed and became more variable. Woodworth (1899) hypothesized that these goal-directed movements had two components, an initial ballistic phase and a current control phase. The initial ballistic sub-movement was theorized to bring the limb in the vicinity of the target. The current control phase was hypothesized to use visual information about limb position relative to the target in order to accurately reach the target. Woodworth (1899) also used vision and no vision conditions with different movement time constraints to examine sensory contributions from the visual system to motor control. At movement times equal or less than 450ms there was no difference in error between vision and no vision conditions. Woodworth (1899) hypothesized that this rapid movement was composed of only the initial impulse phase, as there was no time for the current control phase due to temporal limitations in visual processing. Woodworth (1899) suggested that movements of a longer duration were able to use visual information to use current control to accurately reach the target.

The iterative correction model proposed by Crossman & Goodeve (1963), and later refined by Keele (1968), attempted to explain speed accuracy trade-offs in discrete and reciprocal reaching movements. This model states that rather than having distinct ballistic and current control phases, that movements were composed of a series of muscle commands (Crossman & Goodeve, 1963). This in turn creates multiple ballistic phases that use feedback obtained during the previous phase to make corrections. Secondary movements were then hypothesized to function as corrections with less error as they covered smaller distances than the initial ballistic movement (Keele, 1968). Endpoint error was considered to be dependent on the number of corrective sub-movements, with the limiting factor being the time required to process visual feedback (Elliott et al., 2001).

The iterative control model was later discarded for the single-correction model proposed by Beggs & Howarth (1970) which suggested that movements were composed of an initial ballistic phase followed by a single correction based on visual feedback. The authors suggested that this correction would occur within a fixed temporal distance from the target, which they hypothesized to be 300ms from the target location (Beggs & Howarth, 1970). The impulse variability model later hypothesized that endpoint variability of a goal-directed movement depended on the muscular forces used to accelerate and decelerate the limb, which would be dependent on the force and amplitude requirement of the movement (Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979). Schmidt & et al., (1979) hypothesized that with increased muscle forces there would be increased movement error.

The optimized sub movement model was later proposed by Meyer, Abrams, Kornblum, Wright, & Smith (1988). This model accounted for speed accuracy trade-offs in spatially constrained tasks while minimizing movement time. During an aiming task, movement speed and endpoint accuracy have an inverse relationship. This model highlights a compromise between the increased neuromotor noise and endpoint variability associated with more forceful movements, and the time-consuming demands of corrective sub movements (Meyer et al., 1988). The optimized sub movement model suggests that the initial sub movement does not land directly on the target due to the noise present in the neuromotor system (Meyer et al., 1988). A corrective sub movement is then required to reach the target. This model suggests that the motor system must find a compromise between the initial fast sub movement and the slower corrective sub movement that is more likely to hit the target to optimise speed and accuracy (Elliott et al., 2001).

During goal-directed reaching movements, individuals try to minimize the energy required to complete the movement (Elliott, Hansen, & Grierson, 2009). To minimize energy expenditure the primary sub movement tends to undershoot target locations (Elliott, Hansen, Mendoza, & Tremblay, 2004; Elliott, Binsted, & Heath, 1999; Elliott et al., 2009; Engelbrecht, Berthier, & O'Sullivan, 2003; Lyons, Hansen, Hurding, & Elliott, 2006) making secondary accelerations to reach the target more common than the reversal corrections associated with overshoot errors. With an overshoot error, the individual must fully stop and reverse their movement, travelling a greater total distance, making it an energetically costly error (Lyons et al., 2006). More recently, Elliott et al., (2014) found that no vision conditions yielded increased target undershoots in a vertical aiming task. When visual input was removed, participants may have adopted more conservative strategies to reach the lower target and avoid an overshoot error (Elliott et al., 2014) when the energetic cost of the error was larger (i.e., against gravity).

To accurately reach a target during a goal-directed reach, the sensorimotor system must be able to compare expected versus actual sensory consequences to make corrective movements. Forward models of motor control predict that humans compare current and expected sensory signals to create accurate movements (Miall & Wolpert, 1996). Forward models integrate sensory input and efferent motor commands to create an estimate of the expected position of the limb (Miall & Wolpert, 1996). Observer models are hypothesized to monitor efferent motor commands sent to the limb and afferent sensory feedback obtained from sensory inputs. The internal forward model is then able to estimate the next position of the limb based on current state and motor outputs, allowing for corrections to accurately complete goal-directed movements (Miall & Wolpert, 1996).

More recent evidence has shown that participants are able to exhibit some form of early online control (Elliott et al., 2009). Heath (2005) found that when there were early errors in movement trajectory, participants were able to begin the corrective process before the end of the primary sub movement. Supporting these results, Hansen, Elliott, & Tremblay (2007) used goggles to induce an illusion of a lateral shift in the target while quantifying reaching trajectory. They found that female participants in particular were able to adjust limb trajectories early in the movement to accommodate the perceived new target location. These results provide evidence for early online control, as the adjustments occurred prior to peak velocity of the primary sub movement (Hansen et al., 2007). This evidence of early online control suggests that the expected sensory consequences of the movement provide the basis for early online control, which in turn supports feed forward models of motor control. The internal representation of the expected sensory consequences is created concurrently with the movement planning process (Elliott et al., 2009). The model is then able to compare the expected and the actual sensory consequences. If they are the same, the trajectory will continue as planned, however if they differ, it may jumpstart the early corrective process. As the limb nears the target, there is an opportunity for a second sub movement for online control using visual and proprioceptive information (Elliott et al., 2009).

Elliott et al., (2010) built upon past models of movement control, including the two-component model (Woodworth, 1899), the iterative control model (Crossman & Goodeve, 1963), the single correction model (Beggs & Howarth, 1970, 1972), the optimized sub movement model (Meyer et al., 1988) and online control (Schmidt et al., 1979) to develop the multiple-process model of limb control. This model considers goal-directed reaching movements to be composed of two components, an initial planned component and if time permits, a corrective portion. Movement efficiency relies on limb position estimation from efferent motor commands and proprioception, and visual information about the target (Elliott et al., 2010). The model claims that the initial phase is not entirely ballistic, as over multiple trials, individuals will form a compromise between speed and endpoint variability to optimize performance and energy expenditure (Elliott et al., 2010). The multiple-process model of limb control also considers forward models of limb control and suggests that there are three unique types of online regulation. Early on in the movement, the performer can compare the efferent copy of the motor program to the efferent flow to the limb. Performers can also compare expected versus actual sensory consequences early in the movement and throughout the initial sub movement. Finally, performers can use visual control as the limb nears the target location and enters the central visual field (Elliott et al., 2010). In summary, throughout a reaching movement there are multiple overlapping processes, including impulse control at the initial stages of the movement, and limb-target control making discrete corrections near the target location (Elliott et al., 2017). A rhythmic auditory stimulus could play a role in this model by fine tuning temporal aspects in movement planning.

Alongside information processing-based models of limb control (Elliott et al., 2010; Elliott, Hayes, & Bennett, 2012) other groups of researchers have proposed alternate models of limb control including the equilibrium point hypothesis (Latash, 2010) and ecological theory (Michaels & Beek, 1995). The equilibrium point hypothesis emphasizes the principle of reafference, that any movement must consider afferent signals from proprioception (Latash, 2010, Elliott, Hayes, & Bennett, 2012). The equilibrium point hypothesis assumes that the central control is able to shift variables associated with muscle activation to re address postural stabilizing muscles used to create movement. The dynamical systems framework emphasizes the relationship between the performer and the environment, and considers how the performer's past experiences contribute to current movement (Elliott, Hayes, & Bennett, 2012). Information processing models are unique in emphasizing a movement planning phase (Elliott et al., 2010), however all models consider the importance of incoming sensory information, whether it be from the environment or proprioception. The current project frames movement control based on the information processing model (Elliott et al., 2010). However, a rhythmic auditory stimulus could fit within other models of human movement control by adding to the sensory information available to the performer.

Contributions of vision during goal-directed reaching

Two separate pathways have been proposed to be uniquely responsible for perception and action task requirements (Westwood & Goodale, 2011). The ventral stream which is processed in the inferotemporal cortex is used to identify objects, making it essential for conscious perception (Goodale & Milner, 1992). In contrast, the dorsal stream is processed in the posterior parietal region and processes spatial characteristics, making it essential for action (Goodale & Milner, 1992). While evidence of the two-visual streams has been identified in neurotypical populations, support for this model comes from research with individuals who have had damage to one specific pathway. Patients presenting with visual agnosia, caused by damage to the occipitotemporal region, are able to navigate and reach to objects without impairments, but are unable to identify faces or objects (Goodale & Milner, 1992). Patients with optic ataxia, caused by damage to the posterior parietal region, are able to identify objects, but have impairments when reaching for or navigating around objects (Goodale & Milner, 1992). These patients provide evidence for the two distinct visual streams responsible for action and perception (Westwood & Goodale, 2011). In the present project, the ventral stream is primarily responsible for identifying the goal of the action (i.e., the target) while the dorsal stream is primarily responsible for guiding the limb to the target. Vision has been heavily investigated in its role in controlling goal-directed reaching movements.

Woodworth's two-component model (1899) has been revisited over the last century to further understand the role of vision in goal-directed reaching movements. Keele & Posner (1968) examined the amount of time individuals need to use visual feedback for corrective sub movements. The authors occluded vision at movement initiation on random trials during a discrete reaching task (Keele & Posner, 1968). At movement times of 190ms, there was no difference in endpoint accuracy between vision and no vision conditions. However, at movement times of 260ms, there was a significant difference in endpoint accuracy between vision and no vision conditions (Keele & Posner, 1968). The authors concluded that participants needed between 190 and 260ms to use visual feedback to make corrections during goal-directed reaching movements (Keele & Posner, 1968). This estimate was later deemed inaccurate due to the randomization of the availability of vision. When participants did not know if they would have vision throughout movement execution, they behaved as though they would not have vision, which in turn overestimated visual processing time (Anson, Burgess, & Scott, 2010). Zelaznik, Hawkins, & Kisselburgh (1983) did a similar experiment but used blocked visual conditions so that participants would know if they were going to have vision throughout the reaching movement. At movement times of 100ms, there was no difference in endpoint accuracy between the vision and no vision conditions. Therefore, the authors suggested that individuals can use visual information in movement times as short as 100ms (Zelaznik et al., 1983). Elliott & Allard (1985) used vision and no vision conditions with both a blocked and random design to examine the role of vision in discrete reaching movements. Their results supported the conclusion drawn by Zelaznik et al. (1983). Elliott and Allard (1985) hypothesized that in the random conditions participants planned their movement based on the worst-case scenario, that is, that they would not have vision. In the random conditions, if vision was available, participants did not have time to switch to use visual feedback and therefore completed the pre-planned movement without error correction from visual input (Elliott & Allard, 1985).

Individuals will also prepare their movements differently depending on the anticipated sensory feedback available. Individuals take less time to prepare their movement, resulting in a shorter reaction time, when they know that vision will be available throughout their movement (Hansen, Glazebrook, Anson, Weeks, & Elliott, 2006). Participants may be taking less time to plan the movement as they know that they will have vision available to make online corrections to reach the target (Hansen et al., 2006). Consequently, when individuals know they will not have vision throughout their movement, they take more time to plan their movement, resulting in an increased reaction time, and will exhibit a more symmetric velocity profile (Hansen et al., 2006). The increased time spent preparing the movement could allow participants to strengthen memory representation(s) of the target, in turn increasing endpoint accuracy (Hansen et al., 2006). This highlights the importance of participants knowing the expected sensory outcomes of their movement, which then allows them to either plan movements in anticipation of having information for corrections, or plan an initial ballistic movement that will reach the target without corrections (Anson et al., 2010). Hansen et al.'s (2006) experiment also supports the hypothesis that when participants do not know if they will have vision that they will move as though they will not have vision. Based on the above literature, the amount of time needed to use visual feedback to make corrections during a reaching movement has been proposed to be 100ms, when participants know that they will have vision throughout their movement (Elliott & Allard, 1985; Hansen et al., 2006; Zelaznik et al., 1983).

The context and timing of the availability of vision is also important in determining the use of vision in goal-directed reaching movements. Elliott & Allard (1985) used a prism distortion to increase early movement error and task difficulty. Participants had visual information for the first 80ms of their movement, however this brief amount of time was not always enough to correct errors prior to target acquisition in the more difficult prism task (Elliott & Allard, 1985). Overall, the authors hypothesized that time may not be the only limiting factor in visual control of movement, as it is also likely context specific, depending on the difficulty of the task (Elliott & Allard, 1985). The timing that participants receive visual feedback also has an impact on endpoint error. Chua & Elliott (1993) created an experiment constructed on the assumption that if the secondary sub-movement is based on visual feedback and there is no delay between first and second sub-movements, there must be some visual processing happening during the first sub-movement. The authors tested this hypothesis by removing vision at different timepoints during movement execution, where participants would have either full vision, no vision, first half vision or last half vision, during a cursor aiming task (Chua & Elliott, 1993). The authors found that for reduced endpoint error, is was essential that participants had vision at the end of their movement, in either the full vision or last half vision conditions (Chua & Elliott, 1993). More recently, Tremblay, Hansen, Kennedy, & Cheng (2013) examined initial impulse and limb-target regulation in a discrete reaching task to evaluate the hypothesis that impulse regulation begins early in movement trajectory, while limb-target regulation occurs after peak acceleration. The authors occluded vision either before or after the participant reached a certain velocity criteria (Tremblay et al., 2013). When vision was available at a higher velocity criteria, and therefore later in the movement, participants needed additional time to process sensory information and make corrections to reach the target, which resulted in longer movement times (Tremblay et al., 2013). Vision provided before the limb reached velocities of 0.8 and 0.9m/s, therefore earlier in the movement resulted in improved movement accuracy. Similarly, when vision was available before the limb reached 1.0m/s, participants demonstrated reduced endpoint variability (Tremblay et al., 2013). The above results highlight the importance of vision at key points of the movement trajectory to reduce endpoint error.

Vision is useful in both the planning and correction of movement trajectories, it is important to also consider whether vision of the effector or target have different contributions to movement control. Carson, Chua, Elliott, & Goodman, (1990) examined differences in endpoint error when participants had vision of either the limb or the target. They found that when participants had vision of only the limb, they performed similarly to the no vision condition. However, when they had vision of only the target, they performed better than the no vision condition (Carson et al., 1990). This suggests that the visual information about the target is most beneficial, as the participants could gain some information of the relative position of the limb through proprioception (Carson et al., 1990). Chua & Elliott (1993) examined visual contributions to aiming tasks by evaluating trajectory modifications in different vision conditions during a computer cursor aiming task and also found proprioceptive contributions minimizing endpoint error. The first experiment considered different target sizes and different vision conditions where participants had either full or no vision of the cursor. When participants had vision of the cursor, they had an increased movement time and had a more consistent trajectory and endpoint (Chua & Elliott, 1993). In terms of movement trajectory, in the vision conditions participants reached peak velocity earlier and spent a larger portion of movement time in the deceleration phase, allowing time for corrections based on visual feedback (Chua & Elliott, 1993). In the no vision condition, there were still some trajectory adjustments, suggesting that participants were using other sources of information such as proprioception to make corrections (Chua & Elliott, 1993).

Consistent with Chua and Elliott's (1993) results, numerous models include multiple sources of information available to control reaching movements, including visual and proprioceptive information. Welch & Warren (1980) proposed the modality appropriateness hypothesis, stating that performers weigh the importance of different types of sensory information depending on task requirements. Each sensory modality is capable of controlling different aspects of a motor task (Freides, 1974), however certain modalities may be best suited for controlling specific movement characteristics (O'Connor & Hermelin, 1972). O'Connor & Hermelin (1972) proposed that vision is best suited to control spatial characteristics, and audition is best suited to control temporal aspects. Sober & Sabes (2005) suggest that visual and proprioceptive inputs are weighted differently during the two distinct phases of reach planning. When reaching to a target, individuals may rely more on vision because both the target and the limb exist in the same coordinate frame. For proprioceptive feedback to be used, the signals must be transformed into visual coordinates, which could allow room for error. The scale of the errors will in turn scale the relative weighting of the proprioceptive information from the limb (Sober & Sabes, 2005). Altogether, visual, auditory and proprioceptive information contribute to reaching performance, however the relative importance of different sources may depend on the specific task requirements.

It is clear that individuals use vision to guide goal-directed movements, however it is also important to consider the role of memory representations of the target location in partial vision conditions. Elliott & Calvert (1990) examined whether memory representations were of the target location or the entire movement sequence. Participants were instructed to move within certain time bandwidths, fast being 200-300ms and slow being 400-500ms. Participants either had full vision throughout the reaching task, or no vision with a 0-, 5- or 10-second delays between visual occlusion and movement initiation in blocked conditions (Elliott & Calvert, 1990). There was greater endpoint error in the delay conditions compared to the 0 second no vision delay condition, suggesting that memory representations of target locations begin to decay in under 2 seconds (Elliott & Calvert, 1990). To further examine the memory representation of visual targets during goal-directed reaching movements, McIntyre, Stratta, & Lacquaniti (1998) tested and found support for the hypothesis that discrete movements to reach visual targets may depend on short term memory stores. The authors used different timing delays, 0.5s, 5s or 8s, during either full or no vision conditions. Results from both Elliott & Calvert (1990) and McIntyre et al. (1998) depict increased movement error with increased delay, suggesting that the memory representations of a target location are highly dependent on short term memory. Similar results are consistent with different types of reaching tasks. Binsted et al. (2006) used a reciprocal tapping task where participants had 11 seconds to move as quickly and accurately as possible between two targets, having full vision of the targets for the first 5 seconds, and no vision of the targets for the remainder of the trial. For the first 5 seconds of the trial where participants had vision of the targets, participants made accurate movements (Binsted et al., 2006). However, during the next 4 seconds where the target light was extinguished, there was a substantial decrease in endpoint consistency, and during the last 2 seconds, there was another step decrease in endpoint consistency (Binsted et al., 2006). The reciprocal tapping task by Binsted et al. (2006) highlights that these short-term memory stores are still important in achieving endpoint accuracy during a reciprocal movement.

Visual information about a target can also be used to give advance information about the target to help control accurate movements (Eversheim & Bock, 2002). Eversheim & Bock (2002) examined the roles of visual sensory memory and working memory in reaching tasks with precued information about the target. In Experiment 1, the authors used a visual mask between precue information and target display to examine the effects of visual sensory memory on precued movement. Experiment 2 used a modified Stroop task between the precue information and target display to examine the effects of working memory and attention on precued movements (Eversheim & Bock, 2002). In Experiment 1, participants exhibited decreased reaction times with the precued information, even with the presence of a visual mask, suggesting that precues do not facilitate movement performance via visual sensory memory (Eversheim & Bock, 2002). When participants completed the Stroop task in Experiment 2, the improved reaction times typically seen with precued information were nullified by the presence of the Stroop task. The authors suggest that persistent attention to the visual target is essential for the performer to be able to exhibit reaction time benefits (Eversheim & Bock, 2002). It is possible that a rhythmic auditory stimulus could play a similar role in drawing attention to pre-movement information.

Rhythmic Auditory Stimuli

Rhythmic auditory stimuli have been used to enhance movement quality of goal-directed reaching movements in a variety of populations in both motor control and motor learning paradigms. Auditory information has been used as both a cue and a feedback mechanism.

Furthermore, auditory information has been implemented in different types of reaching movements. There has been consistent evidence of performance improvements, however there is a lack of understanding of how this additional information integrates with current models of motor control.

Rhythmic auditory stimuli have been used to enhance movement quality in goal-directed upper limb movements in a variety of populations. Hatfield, Wyatt, & Shea (2010) hypothesized that in a reciprocal aiming Fitts' task, auditory feedback near the movement endpoint would benefit motor control. The authors hypothesized that typically developing participants would incorporate the auditory feedback into their sensory representation of the movement, associating it with successful attainment of the target, allowing them to focus on preparations for the reciprocal movement (Hatfield et al., 2010). Typically developing young adults were told to move as quickly and accurately as possible during a reciprocal aiming task on a tablet. Conditions included sound and no sound conditions, under three different task indices of difficulty, which were created by manipulating target width and movement amplitude (Hatfield et al., 2010). In the sound condition, participants received auditory feedback once they were within the target zone. Participants demonstrated decreased movement times and reached peak velocity later in the movement closer to movement midpoint, creating a more symmetric velocity profile, in all levels of difficulty (Hatfield et al., 2010). This more symmetric velocity profile is typically associated with a lower index of difficulty (Glover, 2004). The authors suggested that the inclusion of auditory feedback had a similar effect as lowering the index of difficulty by 0.5. Hatfield et al., (2010) hypothesized that the auditory feedback facilitated confirmation of movement completion, allowing the current control phase to use less resources, which in turn allowed for more resources to be used to plan the reciprocal movement (Hatfield et al., 2010).

This experiment provides evidence that auditory feedback has the potential to improve movement performance in a reciprocal aiming task by enhancing movement planning of the reciprocal movement in a typically developing population.

Beyond work with typically developing individuals, there has been growing interest in using rhythmic auditory stimuli within a rehabilitation context with populations with neurological impairments where sensory input is disrupted. Rhythmic auditory stimuli have also been used to facilitate motor control in upper extremity rehabilitation contexts in populations with sensorimotor impairments such as stroke and cerebral palsy (Johansson et al., 2012; Johansson et al., 2014; Ladwig et al., 2016; Thaut et al., 2002; Whitall & Waller, 2013; Whitall, Waller, Silver, & Macko, 2000). These experiments have examined both long term training effects and short-term motor control effects to evaluate the impact of a rhythmic auditory stimulus during goal directed upper limb movements. Overall, these studies saw performance improvements in populations with sensorimotor impairments mirroring the results seen by Hatfield et al., (2010) with typically developing individuals.

Whitall et al., (2000) used bilateral arm training with rhythmic auditory cueing (BATRAC) in a rehabilitation program for participants recovering from a stroke with upper extremity hemiparesis. The training protocol emphasized repetition, goal setting, feedback and task specificity during twenty-minute sessions, three times per week for six weeks (Whitall et al., 2000). The authors hypothesized that the auditory cue would function as an attentional cue, feedback mechanism and provide a basis for entrainment. The training task required participants to slide a T shaped handle along a friction free track in synchronization with a metronome beat, which was predetermined based on the participants own movement speed (Whitall et al., 2000). Participants made both in-phase and anti-phase movements. Following the intervention, participants saw performance improvements in the Fugl-Meyer Upper Extremity Test, the Wulf Motor Function Test and the University of Maryland Questionnaire for Stroke, suggesting that metronome training may provide a basis for improved function (Whitall et al., 2000). Whitall & Waller (2013) suggested that the metronome training encourages repetition, which is an important factor for motor learning and plasticity (Lee et al., 1991). Additionally, Whitall & Waller (2013) hypothesized that the rhythmic auditory stimulus promotes attentional focus and processing by adding a temporal goal, which in turn requires conscious attention to anticipate the beat and scale movement parameters accordingly. Finally, Whitall & Waller (2013) considered the role of passive entrainment and how the metronome beat could guide the firing of the motor neurons. The concept of entrainment will be discussed in depth later in the review of literature.

Training effects of rhythmic auditory stimuli have also been observed in an interactive metronome training program with children with cerebral palsy (Johansson, Domellöf, & Rönnqvist, 2012; Johansson, Domellöf, & Rönnqvist, 2014). These four-week training programs emphasized functional uni- and bi-manual rhythmic upper limb movements with a metronome set at 54 beats per minute. Johansson et al., (2012) and Johansson et al., (2014) assessed kinematic features of a sequential button press task and a questionnaire to depict subjective measures of functional ability (Johansson et al., 2014) pre-intervention and following a 1-week and 6-month retention period. While there was individual variability in overall results between the cases, many of the children saw improved movement control following the intervention, including smoother and shorter movement trajectories, and two children reported improved subjective functional ability, which remained following the 6-month retention period (Johansson et al., 2012; Johansson et al., 2014).

Thaut et al. (2002) considered the use of an auditory rhythm on paretic arm function to cue upper limb reaching movements in stroke patients. Participants completed a horizontal reaching reciprocal tapping task in the sagittal plane, moving between two sensors for 30 seconds with and without the rhythmic auditory stimulus (Thaut et al., 2002). In the rhythmic auditory stimulus condition, participants began the movement after hearing the metronome beat 2-3 times, therefore hearing the beat both before and during movement execution. The metronome frequency was predetermined based on the participants movement speed (Thaut et al., 2002). Movement analysis cameras captured reaching movements in the x, y and z axis' to examine movement kinematics in each condition (Thaut et al., 2002). Participants demonstrated a reduction in trajectory variability during the rhythmic auditory stimulus condition, with the reduction becoming apparent within the first few repetitions of each trial. The rhythmic auditory stimulus condition also produced overall kinematic smoothing of the trajectory and increased elbow range of motion compared to the control no sound condition (Thaut et al., 2002). This evidence shows that a rhythmic auditory stimulus has the potential to improve motor control in stroke rehabilitation.

In an adult population with cerebral palsy Ladwig et al., (2016) examined movement performance during a goal-directed reaching task with an auditory stimulus heard before or during the task, as well as a no sound condition. In the sound during condition, participants were instructed to match their button press with the final auditory beat. Participants showed decreased (faster) reaction times, improved movement control and increased endpoint accuracy when they heard the rhythmic auditory stimulus prior to movement initiation in the sound before condition (Ladwig et al., 2016). The sound during condition did not improve movement control and elicited some performance decrements. The authors hypothesized that the addition of the rhythmic auditory stimulus presented during the movement created a dual task paradigm by adding a temporal goal to the task, making it more difficult (Ladwig et al., 2016). The above results demonstrate that a rhythmic auditory stimulus heard prior to movement initiation was able to improve movement control by impacting the movement planning stage.

Overall the above studies demonstrate that rhythmic auditory stimuli have the potential to improve upper limb function in typically developing individuals and populations with sensory motor impairments. However, there is a lack of understanding on the mechanisms that contribute to improvements. Motor priming, action-perception coupling, neural correlates and entrainment should be considered when hypothesizing how a rhythmic auditory stimulus may positively impact the motor planning stage of movement control.

Multisensory Integration

The human brain is able to process multiple sources of information concurrently, including auditory and visual information. Multisensory processing of visual and auditory stimuli is seen on the neuronal level, where individual neurons in the cochlear nucleus and inferior colliculus may respond to one, or multiple modalities (Shore & Dehmel, 2012). In some cases, the magnitude of a response may be changed with the presence of additional modalities (Shore & Dehmel, 2012). Multisensory convergence is also facilitated with projections originating from varying processing areas (Hackett, 2012). Falchier, Cappe, Barone, & Schroeder (2012) explain that these projections from cortical and subcortical areas provide support for multisensory convergence in the superior temporal cortex. These projection areas are also evident in the superior temporal sulcus, where clusters of cells respond to visual stimuli, auditory stimuli, or a combination of the two (Beauchamp, 2012). There is behavioural evidence for multisensory convergence in humans using simple reaction time experiments. Overall, participants tend to have faster reaction times in conditions that use a multisensory stimulus compared to conditions that use a single stimulus modality (Murray, Cappe, Romei, Martuzzi, & Thut, 2012). Murray et al. (2012) suggests that sensory convergence occurs in both the visual and auditory cortices, leading to a functional coupling between the two regions which in turn facilitates responses to multisensory information. The evidence for multisensory processing in the brain of visual and auditory stimuli highlight the importance of considering multiple modalities to prepare individuals for movement.

Auditory information has the potential to be used as a priming mechanism to prepare the motor system for the go stimulus initiating movement. Davis and Green (1969) used visual and auditory cues prior to a choice response task. Their results depicted decreased reaction times with auditory warning signals compared to the visual warning signal. The authors hypothesize that an auditory warning signal may have a faster central arrival to the primary auditory cortex, making it more beneficial as a priming mechanism than a visual warning signal (Davis & Green, 1969). This faster arrival to the primary auditory cortex compared to visual information arriving in the primary visual cortex could be due to anatomical differences in processing system distances (Stein, 2013). The literature on auditory priming has since progressed to examine how pre movement auditory information can influence cortical spinal excitability, which it turn has the potential to improve effector specific excitability. Stephan, Lega, & Penhune (2018) consider how auditory information can be used to predict sequences of sensory events. The authors wanted to assess effector specific excitability following an auditory tone in a familiar melody with a trained response compared to an unfamiliar melody. They hypothesized that auditory information would activate motor regions priming the effector for the trained response, therefore facilitating movement preparation (Stephan et al., 2018). The authors used a learned and an unfamiliar melody to assess motor excitability using motor evoked potentials elicited by transcranial magnetic stimulation (TMS) (Stephan et al., 2018). Results showed increased cortical spinal excitability for a specific finger, which was the trained effector, prior to the trained tone in the learned melody, without muscle movement of the finger (Stephan et al., 2018). This suggests a passive coupling between auditory perception and action preparation occurring with passive listening of a learned melody (Stephan et al., 2018). This coupling of a rhythmic stimulus and cortical spinal excitability could be evidence of enhanced movement planning with an auditory stimulus during a discrete task.

Other researchers have examined brain regions that are active in perceiving a rhythmic auditory stimulus (Chen, Penhune, & Zatorre, 2009; Efraimidou et al., 2016; Grahn & Rowe, 2009; Grahn & Brett, 2007). The supplementary motor area, dorsal premotor area, basal ganglia and areas in the cerebellum are involved in passively listening to a rhythmic beat (Grahn & Brett, 2007). Using magnetic resonance imaging during a passive rhythm perception task, the presence of a rhythmic auditory stimulus elicited increased connectivity between the putamen and the supplementary motor area, as well as the premotor cortex and the auditory cortex (Grahn & Rowe, 2009). Chen et al. (2009) found increased activation in the supplementary motor area, dorsal premotor area and cerebellar regions with increased rhythmic complexity. These findings indicate there is activation in over lapping areas involved in both rhythm perception and motor preparation. This in turn highlights how a rhythmic auditory stimulus has the potential to prime the motor system for movement. Additionally, the increased activation in the supplementary motor area, dorsal premotor area and cerebellar regions with increased rhythmic complexity could lead to improved motor control in conditions using a more complex rhythm (Chen et al., 2009). This could provide rationale for including a more complex rhythmic stimulus in a rhythmic auditory training protocol.

When considering rhythm perception in a rhythmic auditory stimulus paradigm, the rhythmic features that construct a rhythm must also be defined. An isochronous stimulus train refers to a beat with a uniform length between each auditory tone, a uniform beat duration, and a consistent volume and tone of the auditory stimulus (Schaefer, 2014). A meter refers to higher level beats that can produce a rhythm by manipulating relative timing, and accents are able to manipulate the duration and intensity of the beats (Schaefer, 2014). Rhythmic movements to a rhythmic auditory stimulus highlight timing, where the focal point of a movement is explicitly timed to the auditory stimulus (Schaefer, 2014). Hearing a rhythmic auditory stimulus could help strengthen the mental representation of the relative timing of the movement, allowing the motor system to fine tune the mental representation (Schaefer, 2014). Given the importance of relative timing, it is possible that a richer rhythmic auditory stimulus with increased rhythmic complexity will lead to improved fine tuning by providing additional, more precise timing cues.

Auditory information can be used to prime the motor system for a task, however it is also important to consider the context in which this information fits. During a motor task, an individual receives information from a variety of sources, including visual, proprioceptive and auditory (Bulkin & Groh, 2006; Novembre & Keller, 2014; Sober & Sabes, 2005). Information from different sources may be valued and used differently depending on the spatial and temporal goals of a task (Sober & Sabes, 2005). Bulkin & Groh (2006) suggest that during goal directed movements, the roles of the visual and auditory systems overlap to control movement. They hypothesize that the visual system is able to benefit spatial parameters of the task, while auditory information is able to benefit the temporal parameters of the task (Bulkin & Groh, 2006). The two systems are therefore able to provide complementary information to the motor system, increasing the accuracy of the overall information received (Bulkin & Groh, 2006). Similarly, Novembre & Keller (2014) highlight the role of both temporal and spatial information in entrainment. The authors emphasize how movement sequencing, a spatial modality, is critical in producing human motor entrainment (Novembre & Keller, 2014). Overall, existing literature is consistent with respect to the importance of different sensory modalities for controlling human movement.

Potential Reasons for Improved Performance

Rhythmic auditory stimuli may impact movement performance through improvements in movement planning and/or movement execution. Elliott et al. (2010) hypothesized more precise planning was responsible for reduced endpoint variability with practice. It is possible that rhythmic auditory stimuli could provide a constant temporal reference during movement planning, resulting in improved planning and therefore execution. Rhythmic auditory stimuli may play a role in reducing the inherent variability associated with the motor plan (Schmidt et al., 1979). Additionally, having the rhythmic auditory stimuli before movement initiation may allow the performer to focus less attentional resources on the imminent go signal, in turn allocating more attention to the spatial demands (amplitude and direction) of the task. Rhythmic auditory stimuli could also benefit performance through improvements in movement execution. Elliott et al. (2010), proposed that performers could use multiple sources of information to engage in three types of online regulation throughout the movement including; early comparisons of the copy of the motor program to the efferent flow, expected versus actual sensory consequences, and visual information as the limb nears the target. It is possible that a consistent temporal frame of reference provided by the rhythmic auditory stimuli could allow more attentional resources to compare the efferent copy to the efferent flow and expected sensory outcomes, benefiting movement execution

One of the potential reasons for improved upper limb performance seen with the inclusion of a rhythmic auditory stimulus is the idea of entrainment between the auditory stimulus and the motor firing. Entrainment refers to the temporal synchronization of two independently oscillating bodies, where the stronger signal guides the weaker signal (Thaut, 2013, 2015). In a rhythmic auditory stimulus protocol, the stronger guiding stimulus would be the auditory rhythm, while the weaker stimulus would be the neural firing to control the movement. There is evidence for entrainment to an auditory stimulus occurring on a neural level (Bengtsson et al., 2009; Crasta, Thaut, Anderson, Davies, & Gavin, 2018; Gao et al., 2009; Lakatos et al., 2013; Nozaradan, Peretz, & Mouraux, 2012). Gao et al. (2009) observed entrainment patterns of membrane potentials in nonlemniscal auditory thalamic neurons in guinea pigs with rhythmic auditory stimulation. Similarly, a rhythmic auditory stimulus evoked multiple steady state potentials, matching the frequency of the auditory rhythm (Nozaradan et al., 2012). In this protocol, neurons in the auditory cortex synchronized their firing rates to the frequency of the external auditory stimulus (Nozaradan et al., 2012). Similar results have been observed in human participants with magnetic resonance imaging. For example, when listening to an auditory rhythm, regions in the brain were activated that are typically not associated with auditory processing (Bengtsson et al., 2009). Some of the activated areas were associated with motor functioning, including the dorsal premotor cortex, pre- and supplementary motor areas and the lateral cerebellum (Bengtsson et al., 2009). Authors suggest that activation of these areas may be related to stimulus prediction along with auditory processing (Bengtsson et al., 2009). Initially, this may seem only relevant for a rhythmic auditory stimulus heard during the task.

However, some evidence suggests that neural oscillatory activity continues after cessation of the stimulus (Lakatos et al., 2013), which could in turn modulate future movements. Hickok, Farahbod, & Saberi (2015) suggest that rhythmic information is coded as a perceptual feature, and that rhythmic information can influence subsequent perception. This in turn could help modulate timing when planning movements. Crasta, Thaut, Anderson, Davies, & Gavin (2018) looked at neural entrainment in a finger tapping task synchronized to a rhythmic auditory stimulus in motor only, auditory only and a combined condition. Results found that the rhythmic auditory stimulus drives delta, alpha and low beta oscillations, which are likely important for auditory-motor interactions (Crasta et al., 2018). Given the neural activation associated with entrainment, it is possible that this is a mechanism that is aiding movement control during rhythmic auditory stimulus protocols. Entrainment fits well with continuous movement such as reciprocal movements or repeated finger tapping, however there may be limited application in a goal-directed reaching movement.

Another potential reason for improved performance with the inclusion of a rhythmic auditory stimulus could be through factors that promote motor learning. A recent model is the OPTIMAL theory of motor learning. Proposed by Wulf & Lewthwaite (2016), the model highlights motivational features, which encompass intrinsic motivation and self-efficacy, autonomy and an external focus of attention. Wulf & Lewthwaite (2016) argue that these components enhance human motor learning by considering human motivational and attentional influences on behaviour. A shift towards an external focus of attention has elicited performance benefits in a variety of types of tasks in both motor control and motor learning paradigms (Wulf, 2007). An external focus of attention is defined as focusing on something external to the body during a motor task (Wulf, 2007). The authors hypothesize that an external focus of attention is superior, as an internal focus may create an increased cognitive load by causing the performer to focus on the internal mechanics of the task (Wulf, 2007). Within the OPTIMAL theory frame work, a rhythmic auditory stimulus may provide a basis for improved performance by eliciting an external focus of attention. The auditory stimulus may help promote an external focus of attention by having participants focus on something external to their body, rather than focusing on the internal mechanics of how they will have to move to attain the target. Additionally, different sources of rhythmic information may have different motivational components through relative enjoyability. A drum beat may enhance intrinsic motivation by providing a more enjoyable training and testing experience compared to basic metronome conditions. This could be further extended to music which could further enhance the experience of the performer. Given the use of rhythmic music historically and cross culturally, it is likely that having a rhythmic or musical element will enhance individual enjoyment. Another important component of the OPTIMAL theory is autonomy, which suggests that participants should have some control over choices made during motor performance (Wulf & Lewthwaite, 2016). In future studies using a rhythmic auditory stimulus, participants could have a choice in rhythm or music style heard prior to movement initiation, therefore enhancing autonomy and in theory, improving motor control and learning.

In line with the OPTIMAL theory of motor learning, some studies have examined the role of emotion in music and metronome movement experiments (Kang & Gross, 2015, 2016; Magennis, Beatty, & Janelle, 2019; Park, Hass, & Janelle, 2019). Kang and Gross (2015 & 2016) used autobiographical memories to elicit an emotional response and examined gait characteristics in young adults. The authors found that compared to a neutral condition, sadness was associated with decreased performance on a sit-to-walk test, and anger and joy were associated with improved performance (Kang & Gross, 2015). In a later experiment, anger and joy elicited improved performance seen in gait speed and movement smoothness in the vertical direction in healthy young adults (Kang & Gross, 2016). More recently, some experiments have investigated how auditory stimuli can elicit emotional responses and in turn impact movement performance (Magennis et al., 2019; Park et al., 2019). Park et al., (2019) wanted to assess emotional contributions of music on gait of participants with Parkinson's disease. Participants walked to pleasant music, unpleasant music, a neutral metronome and an uncued control condition. Overall, when listening to music in the pleasant condition participants had increased gait velocity, stride length and arm swing velocity compared to unpleasant, metronome and uncued conditions and the improved performance was also associated with positive subjective ratings of enjoyment (Park et al., 2019). In an upper limb circle tracing task, Magennis et al., (2019) used neutral, pleasant and unpleasant auditory information and a no sound control to examine the influence of emotion. The neutral condition elicited a slower and jerkier trace, and the pleasant and unpleasant conditions were both faster than the control (Magennis et al., 2019). The authors suggest that both the pleasant and unpleasant conditions created high arousal situations, resulting in improved performance (Magennis et al., 2019).

Other experiments have investigated differences in performance comparing metronome and music conditions (Styns, Van Noorden, Moelants, & Leman, 2007; Wittwer, Webster, & Hill, 2013). Styns et al., (2007) asked young adults to synchronize gait timing to music or metronome fragments. The authors found differences in performance between music and metronome conditions, but not between different types of music (Styns et al., 2007). Wittwer et al., (2013) used music and metronome cueing with healthy older adults during gait, in time to the auditory cue. Music elicited an increased mean gait velocity, but the metronome did not (Wittwer et al., 2013). Overall, these experiments suggest that different types of rhythmic auditory cues may not be interchangeable.

The present project was composed of two experiments to evaluate the contributions of rhythmic auditory stimuli during goal-directed reaching movements made by typically developing young adults with and without visual feedback. The overreaching objective of Experiments 1 and 2 was to gain insight into when and how rhythmic auditory stimuli improve performance of goal-directed reaching tasks. Experiment 1 varied the onset of a rhythmic metronome to determine when in a movement the auditory information is most beneficial. This experiment included no sound, sound before, sound during and sound throughout conditions to vary the onset of the auditory stimulus. Experiment 1 examined goal-directed movement characteristics under vision and no vision conditions to create a controlled model of disrupted sensory feedback. Experiment 2 examined the influence of rhythmic complexity and subjective enjoyability by varying the source of the auditory stimulus. Conditions included a no sound control, a simple metronome, a complex metronome, a simple drum beat and a complex drum beat, all heard before movement initiation. All auditory conditions were performed with and without vision to create a total of 10 experimental conditions. To examine how rhythmic complexity impacted reaching performance, this experiment compared no sound, a simple metronome and a complex metronome. To examine how subjective enjoyability impacted reaching performance, participants responded to a 5-point Likert scale following each auditory condition. Together this series of experiments furthers our understanding of how individuals incorporate rhythmic auditory stimuli into movement planning and execution of goal-directed reaching movements, and the features of the rhythm that are important to elicit observed benefits.

Experiment 1

Objectives

The objective of Experiment 1 was to examine the differences between no sound, sound before, sound during and sound throughout conditions in vision and no vision settings on movement performance in a discrete goal-directed reaching task. Dependant variables measured include performance measures such as reaction time (RT) and variability, movement time (MT) and variability, constant (CE) variable (VE) and absolute (AE) endpoint error, as well as kinematic measures such as movement trajectory variability, mean marker position throughout the movement, peak velocity (PV) and the ratio of time to peak velocity to movement time (ttPV:MT). Additionally, vision and no vision conditions created a controlled model of reduced sensory feedback to evaluate whether typically developing participants would rely more on the additional information provided by the rhythmic auditory stimulus when they lacked information from the visual system.

Hypothesis

For reaction time, I hypothesized that no vision conditions would have an increased mean RT compared to full vision conditions. Additionally, I hypothesized that in auditory conditions where the rhythm was presented before the movement, including sound before and sound throughout condition, participants would exhibit shorted reaction times compared to no sound and sound during conditions.

For reaction time variability, I expected no vision conditions to have more RT variability than vision conditions. I also expected less RT variability in sound before and sound throughout conditions, compared to no sound and sound before.

For movement time, I expected increased movement times in vision conditions compared to no vision conditions. I also hypothesized that conditions where participants heard sound during the movement, including sound during and sound throughout, would have increased movement times compared to no sound and sound during due to the additional sensory information during the movement.

For movement time variability, I did not expect to see an effect for vision. I also hypothesized that sound during and sound throughout conditions would have less movement time variability compared to no sound and sound before conditions.

For peak velocity, I expected no vision conditions to reach higher mean peak velocities compared to vision conditions. I also hypothesized that sound before and sound throughout conditions would reach higher peak velocities than no sound and sound during conditions.

For the ratio of time to peak velocity to movement time, I expected vision conditions to reach peak velocity earlier in the movement compared to no vision conditions. I also expected sound during and sound throughout conditions to reach peak velocity earlier in the movement compared to no sound and sound before.

For endpoint error, I expected to see increased error in no vision conditions compared to vision conditions. More specifically, I also expected to see increased movement undershoots in constant error in no vision conditions. For auditory conditions, I expected conditions where sound was heard before the movement, including sound before and sound throughout, to have less endpoint error that no sound and sound during conditions.

For movement trajectory variability, I hypothesized that no vision conditions would have more variability than vision conditions near the endpoint of the movement. I also expected that auditory conditions where the rhythm was heard before movement initiation, including sound before and sound throughout, to have less trajectory variability.

For mean marker position throughout the movement, I expected no vision conditions to undershoot throughout movement trajectory compared to vision conditions. However, I did not expect to see an effect for auditory condition.

Finally, I expected to see interactions between vision and auditory condition in reaction time, movement time, peak velocity, endpoint error and trajectory variability.

Participants

The required sample size was calculated using G*Power 3.1.9.3 (Faul, Erdfelder, Lang, & Buchner, 2007). An a priori power analysis was conducted with alpha was set at 0.05 and power set at 0.95. The number of groups was set as 1, number of measurements set at 8, and the correlation among repeated measures set at a conservative 0. The calculation was performed with partial eta squares from the pilot experiment, from a temporal variable, being reaction time, and a spatial variable, being endpoint variable error in the Y (primary) axis. Mean reaction time, condition by vision interaction had a partial eta squared of 0.2033 resulting in an effect size f of 0.5052, and a sample size of 12. Endpoint variable error in the Y (primary axis) had a partial eta squared of 0.1218 resulting in an effect size f of 0.3725, and a sample size of 21.

Twenty-four typically developing young adults (mean 24.04, SD 3.14, 14 female) were recruited from the University of Manitoba community for Experiment 1. Three participants were excluded from analysis, including two left handed participants, and one participant with over 50% of trials having missing data points. Twenty-one right handed participants were included in analysis (mean 23.57, SD 2.29, 12 female). All participants reported normal or corrected to normal vision and hearing, no neurological conditions, orthopedic injuries or surgeries to the dominant arm within the past 6 months. Prior to participating in the experiment, participants completed written informed consent (Appendix A) and a demographics questionnaire (Appendix

B). Participants were compensated for their time with a $10 honorarium. All procedures were approved by the University of Manitoba, Education and Nursing Research Ethics Board (Protocol #E2014:133 (HS17400)).

Apparatus

Participants were tested in a quiet, dimly lit room to reduce distractions. The apparatus board was placed on a table at mid-torso height in front of the seated participant. The board was

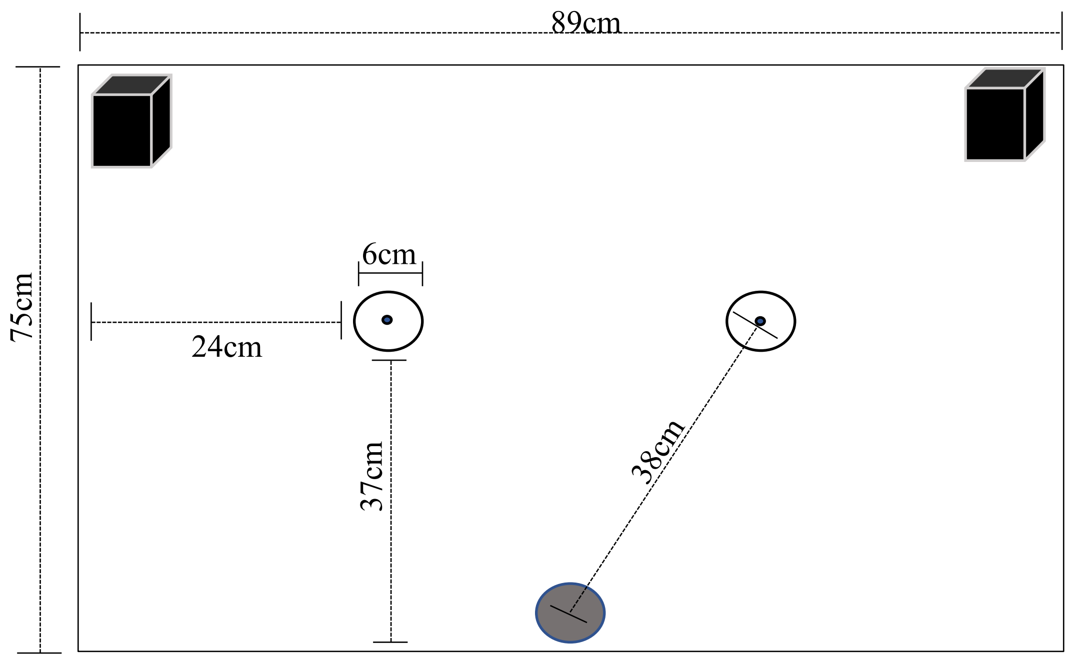


Figure 1. Set up and dimensions of the apparatus board. The board is 75 x 89cm. The home button is located at the centre of the anterior edge, with two target switches located 36.5cm away from the home button. Two black Logitech speakers were placed on the lateral posterior corners of the board.

outfitted with three buttons with one being a red home position, and two clear target buttons with a 6mm sticker at the centre to create a precise spatial goal. Target buttons were located in the left and right hemispace, as depicted in Figure 1.

Buttons were constructed using snap action switches with a long lever actuator (LKG Industries) (Figure 2a & 2b). The body of the switch was embedded in a foam disk with a height of 2.5cm and a diameter of 6cm. At the two target locations, colorless translucent domes housed a white LED light and the leaf of the switch. T-shaped pins connected the dome to the body of the switch, facilitating an accurate and finite button press. The home position button plastic dome was made of translucent red plastic and did not contain an LED light. Two black Logitech speakers were placed at the posterior lateral corners of the apparatus board to deliver the auditory stimuli at a volume of 65 decibels, measured at 95cm from speakers (measured from approximately where the head of the participant will be located). To occlude vision, participants wore PLATO Visual Occlusion Spectacles (Translucent Technologies, Inc.) during all experimental conditions. Experimental protocols were programmed with E-Prime software (version 2.0, Psychology Software Tools, Inc.) to trigger LED lights, rhythmic auditory stimulus, Optotrak 3-D Investigator (Northern Digital, Inc.) and Visual Occlusion Spectacles (Translucent Technologies, Inc.), and to record input from the switches to trigger the timing of the

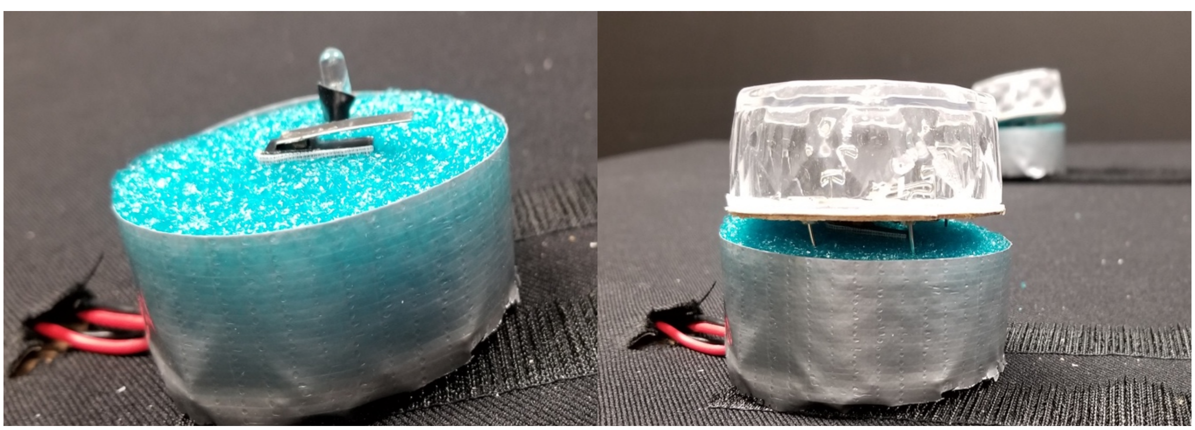


Figure 2a- Target button interior set up, including long lever actuator (LKG Industries) and white LED light embedded in foam.

Figure 2b- Plastic dome attached to the foam base with T shaped pins to complete target button.

experiment. An Optotrak 3-D Investigator (Northern Digital, Inc.) was mounted on the wall in front of apparatus board to capture and quantify movement performance and kinematics.

Data Recording

An Optotrak 3-D Investigator (Northern Digital, Inc.) was used to capture and quantify limb movement throughout the reaching task. Infrared markers (IREDS) were placed on the participants dominant hand on the posterior surface of the second phalanx of the index finger using Blenderm (3M) medical tape. To prevent excessive IRED movement, wires were secured to the forearm of the participant with medical tape. The Optotrak captured 3-D positional data in the x- (medio-lateral), y-, (anterior-posterior) and z- (vertical) axis and collected data points at a frequency of 250Hz. At the beginning of each testing session, target files were collected to quantify the relative location of the IREDS at each target location and at the home position. This was used to calculate constant, variable, and absolute endpoint error for each participant. Throughout the protocol, the experimenter recorded field notes to confirm E-Prime trial numbers and Optotrak files, and to note any errors that occurred during the testing session (Appendix C).

Programming

Conditions were blocked, and the condition order was randomized and counterbalanced between participants. Participants performed a 24-trial familiarization block, which included three blocks of 8 trials of vision no sound, vision sound throughout and no vision sound during. Following the familiarization block, participants performed 24 trials in each condition, resulting in a total of 192 trials. There was a short break between each experimental condition, and participants could take additional breaks at any point in the experiment to avoid fatigue. At the beginning of each experimental condition, participants were informed of the auditory and visual condition that they would be performing in the upcoming block of trials.

Procedure

The independent variable manipulated in Experiment 1 was the timing of the onset of the rhythmic auditory stimulus including the following variations: sound before movement initiation (sound before), sound at movement initiation (sound during), sound throughout (composed of sound before and after movement initiation), and a no-sound control condition (Figure 3). These conditions were performed with and without vision, resulting in a total of eight conditions (Table 1). Condition order was randomized and counterbalanced between participants, and target location was randomized.

Table 1- Experimental conditions in Experiment 1

	No Sound	Sound Before	Sound During	Sound Throughout
Vision	V-NS	V-SB	V-SD	V-ST
No Vision	NV-NS	NV-SB	NV-SD	NV-ST

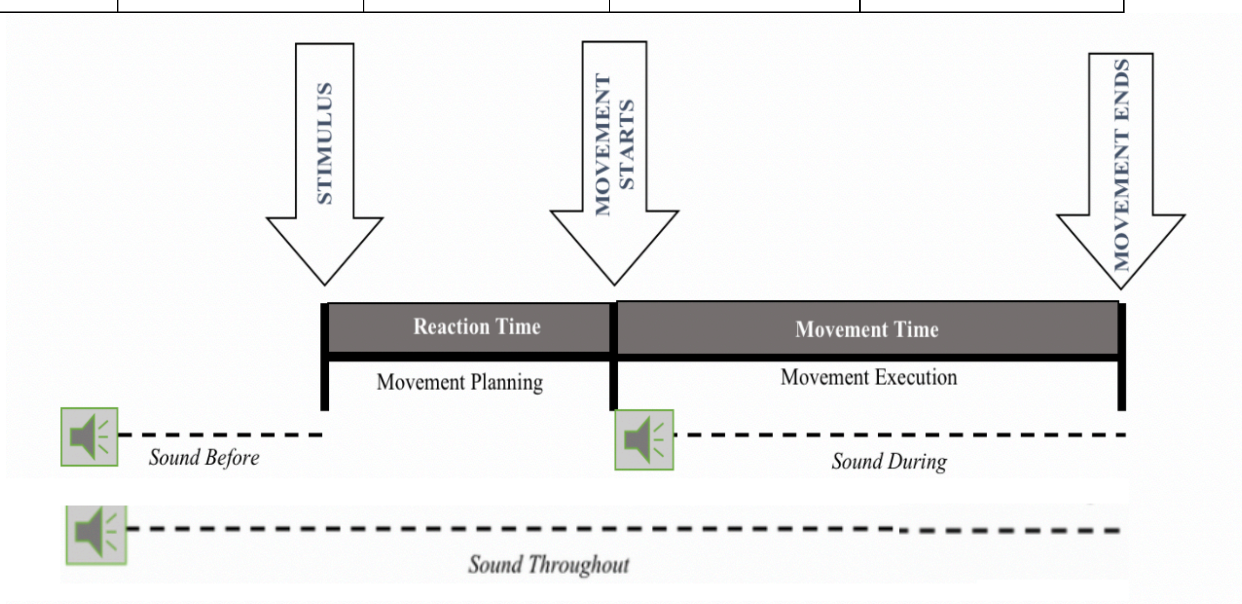


Figure 3- Figure of auditory condition onsets, and reaction time and movement time measurements.

In each experimental condition, the participant began with the index finger of their dominant hand on the home switch. One of two target LEDs illuminated, and the participant was instructed to move as quickly and accurately as possible to press the target button. The participant was instructed to hold the button for 2 seconds before moving back to the home switch for the subsequent trial. A tone of 575Hz was produced for 200ms, followed by a 200ms pause, repeated three times, with the onset depending on the condition. The sound before condition had three beats prior to movement initiation, the metronome in the sound during condition was triggered upon movement initiation and the three beats continued throughout movement execution. The sound throughout condition had three beats prior to movement initiation and three beats continued throughout movement execution. In conditions where the metronome was present during the movement (sound during and sound throughout), participants were instructed to complete their movements as quickly and accurately as possible, rather than matching the button press with the metronome beat. In the no vision conditions, PLATO Visual Occlusion Spectacles (Translucent Technologies, Inc.) occluded vision upon the release of the home switch and restored vision approximately 2 seconds after the participant reached the target switch. Participants knew whether or not they had vision in each block.

Data Treatment

Raw data points collected with the Optotrak 3-D Investigator (Northern Digital, Inc.) were processed using MatLab (The Mathworks, Inc). The reaching analysis program was created by Kinsilico Labs (Toronto, Ontario). Prior to analysis, blank files and trials with errors were deleted and excluded from analysis. Blank files occurred when E-Prime software (version 2.0, Psychology Software Tools, Inc.) automatically externally triggered the Optotrak when switching conditions during the protocol. Any trial errors, including low IRED visibility and participant distraction, were noted in the field notes. Movement onset was defined as the first frame that the marker on the limb reached a velocity of 30mm/s and maintained that velocity for 30ms. Movement offset was defined as the first frame that the marker velocity fell below 30mm/s and remained there for 30ms. Movement kinematics were smoothed with a third order Butterworth Lowpass at 15Hz, and gaps up to 10 points large after movement completion were filled in MatLab (The Mathworks, Inc). Any trials with gaps in movement trajectory were manually excluded from analysis. The Y axis was defined as the primary axis, and the X axis as the secondary axis.

Prior to statistical analysis, outlier trials were removed. Upper and lower limits were calculated for each participant with 2.5 standard deviations above and below the mean in reaction time, movement time, and endpoint variable error in the primary axis. Trials that fell outside of these limits were excluded from analysis. For Experiment 1, 14.16% trials were excluded from analysis during MatLab (The Mathworks, Inc.) processing and manual outlier removal.

Statistical Analysis

Statistical analysis was performed with Statistica software v.12 (Statsoft, Inc.). A 4 Condition (no sound, sound before, sound during and sound throughout) x 2 Vision (vision and no vision) repeated measures, within factors ANOVA was used. The dependant variables analyzed were: mean reaction time (RT), RT standard deviation, mean movement time (MT), MT standard deviation, constant error (CE), variable error (VE), absolute error (AE), peak velocity (PV) and the ratio of time to peak velocity to movement time (ttPV:MT). A 4 Condition x 2 Vision x 5 Position ANOVA investigated marker standard deviation (variability) at 20, 40, 60, 80 and 100 percent of movement completion. A 4 Condition x 2 Vision x 5 Position x 2

Target location ANOVA investigated mean marker position, at 20, 40, 60, 80 and 100 percent of movement trajectory. Significance (alpha) was set at $p<0.05$, and main effects were investigated with a Tukey's HSD post hoc at a significance (alpha) set at $p<0.05$. Any comparisons where sphericity was violated (Mauchly's Test of Sphericity, $p<0.05$) were corrected with the Greenhouse-Geisser procedure.

Results

For mean reaction time (RT) there was a significant effect for both vision ($F(1, 20)=24.44$, $p<0.01$) and auditory condition (uncorrected: $F(3, 60)=66.40$, $p<0.01$, corrected: $F(2.05, 41.09)=66.40$, $p<0.01$). As expected, no vision conditions had a significantly longer mean RT of 293ms compared to vision conditions which had a mean RT of 273ms. Consistent with the hypothesis, post hoc analysis using Tukey's HSD revealed that sound before (244ms) and sound throughout (246ms) conditions had decreased mean RTs compared to both no sound (322ms) and sound during (320ms), with no significant difference between no sound and sound during, and sound before and sound throughout conditions. There was no interaction between auditory condition and vision ($F(3, 60)=0.71$, $p=0.55$).

There was a significant effect for the standard deviation of RT for both vision ($F(1, 20)=5.04$, $p=0.04$) and auditory condition ($F(3, 60)=11.01$, $p<0.01$). No vision conditions had significantly more RT variability with a standard deviation of 43ms compared to 38ms in vision conditions. Post hoc analysis with Tukey's HSD revealed that sound during had significantly more RT variability (48ms) than all other auditory conditions (no sound=39ms, sound before=34ms, sound throughout=39ms). There was no significant interaction between auditory condition and vision ($F(3, 60)=1.52$, $p=0.22$).

As anticipated, there was a significant effect for mean movement time for vision F(1, 20)=5.72, p=0.03. No vision conditions had a significantly shorter mean MT of 498ms compared to vision conditions with a mean MT of 516ms. There was no significant effect for auditory condition or auditory condition by vision interaction (F(3, 60)=1.23, p=0.31).

There were no significant effects for vision (F(1, 20)=0.35,p=0.56), auditory condition (F(3, 60)=0.64, p=0.59), or vision by condition interaction (F(3,60)=0.05, p=0.99) for movement time variability.

There was a significant effect for peak velocity for vision in both the primary (F(1,20)=9.75, p<0.01) and secondary (F(1,20)=10.10, p<0.01) axes. No vision conditions had higher peak velocities in both the primary (1454mm/s) and secondary (887mm/s) axes compared to vision conditions (primary axis=1403mm/s, secondary axis=853mm/s). There were no significant effects for auditory condition (primary axis= uncorrected: F(3, 60)=0.95, p=0.42, corrected: F(2.03, 40.66)=0.95, p=0.40) secondary axis=F(3, 60)=0.61, p=0.61) or auditory condition by vision interaction (primary axis=F(3, 60)=0.81, p=0.49, secondary axis=F(3, 60)=0.13, p=0.94).

For the ratio of time to peak velocity to movement, there were no significant effects for vision (F(1, 20)=0.51, p=9.48), auditory condition (F(3, 60)=2.30, p=0.09), or vision by auditory condition interaction (uncorrected: F(3, 60)=0.74, p=0.53, corrected: F(1.87, 37.44)=0.74, p=0.48).

There was no effect for auditory condition (F(3, 60)=0.19, p=0.90), vision (F(1, 20)=1.24, p=0.28) or condition by vision interaction (F(3, 60)=0.29, p=0.83) for constant error in the primary axis. For endpoint constant error in the secondary axis, there was no effect for vision (F(1, 20)=1.92, p=0.18) and a significant main effect for auditory condition F(3, 60)=4.42, p<0.01. Post hoc analysis with Tukey's HSD revealed that the no sound condition had a larger undershoot of -1.5mm compared to both the sound before (-0.1mm) and sound throughout (-0.1mm) conditions. The main effect was superseded by a significant interaction between auditory condition and vision for endpoint constant error in the secondary axis, F(3, 60)=4.44, p<0.01. Post hoc analysis with Tukey's HSD revealed that the no vision no sound condition tended to undershoot the target location significantly more (-2.9mm) than any other condition, depicted in Figure 4.

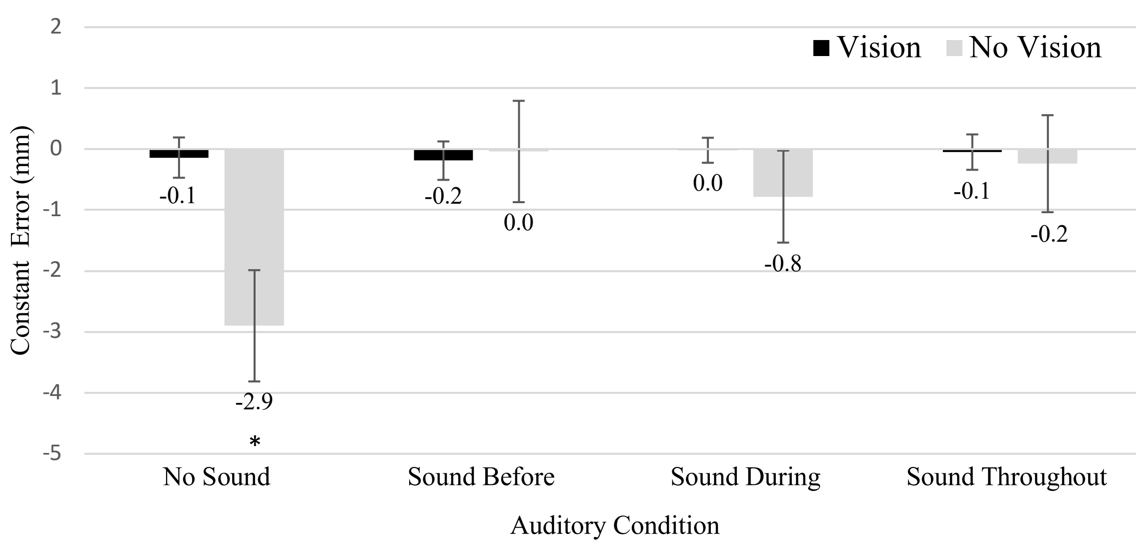


Figure 4. Constant error (mm) in the secondary axis. Interaction between auditory condition and vision. Error bars represent standard error.

There was a significant effect for endpoint variable error in the primary axis for both vision (F(1, 20)=138.00, p<0.01) and auditory condition (F(3, 60)=5.64, p<0.01). No vision conditions had significantly more endpoint variable error (8mm) than vision conditions (5mm). Post hoc analysis with Tukey's HSD revealed that sound before (6mm) had significantly less endpoint variable error in the primary axis compared to the no sound (7mm) and sound during (7mm) conditions. There was no significant effect for auditory condition by vision interaction (F(3, 60)=2.01, p=0.12).

There was a significant effect for endpoint variable error in the secondary axis for vision F(1, 20)=116.76, p<0.01. As hypothesized, no vision conditions yielded significantly more endpoint variable error (10mm) compared to vision conditions (5mm). There was no significant effect for auditory condition (F(3, 60)=2.59, p=0.06) or auditory condition by vision interaction (F(3, 60)=1.52, p=0.22).

For absolute endpoint error in the primary axis, there was a significant effect for vision (F(1, 20)=146.61, p<0.01) and auditory condition (F(3, 60)=4.83, p<0.01). No vision conditions had significantly more endpoint error (7mm) compared to vision conditions (4mm). Post hoc analysis with Tukey's HSD revealed that the sound before condition (5mm) had significantly less endpoint error than both the no sound (6mm) and sound during (6mm) conditions. The main effects were superseded by an interaction between auditory condition and vision (uncorrected:

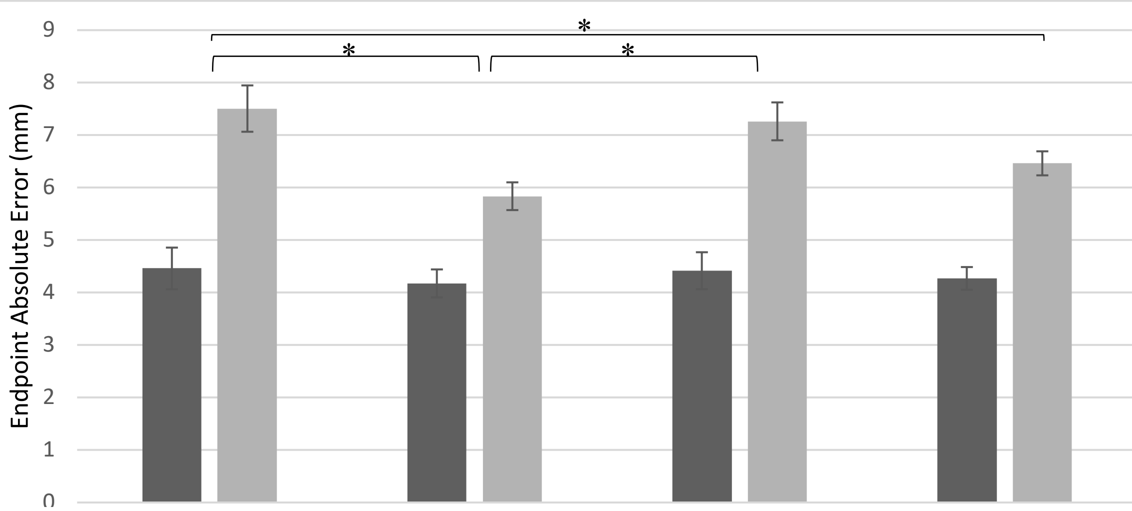


Figure 5. Endpoint absolute error in the primary axis. Interaction between vision and auditory condition. Measured in millimeters. Error bars represent standard deviation.

$F(3, 60)=3.38$, $p=0.02$, corrected: $F(2.19, 43.82)=4.20$, $p=0.04$). Post hoc analysis revealed that the NV no sound condition (8mm) had significantly more endpoint error than the NV sound before (6mm) and NV sound throughout (7mm) conditions, the NV sound before condition also had less error than the NV sound during condition (7mm). There were no significant differences between NV sound before and NV sound throughout, or NV sound during and NV sound throughout (Figure 5).

In the secondary axis for endpoint absolute error, there was a significant effect for vision ($F(1, 20)=102.22$, $p<0.01$) and auditory condition ($F(3, 60)=4.65$, $p<0.01$). No vision conditions (8.0mm) had significantly more endpoint error compared to vision conditions (4mm). Post hot analysis with Tukey's HSD revealed that the no sound condition (7mm) had significantly more endpoint error than the sound during condition (6mm). There was no significant interaction between auditory condition and vision ($F(3, 60)=2.37$, $p=0.08$).

For marker trajectory variability (standard deviation) there was a significant interaction between vision and position (percent movement completion per trial) in the primary axis ($F(4, 80)=92.00$, $p<0.01$) (Figure 6). Post hoc analysis revealed that as expected, no vision conditions, participants had more marker variability at 80 (12mm) and 100 (10mm) percent of movement completion compared to full vision conditions (80%=9mm, 100%=7mm). However, there was no difference between vision and no vision conditions at 20, 40 and 60 percent of movement completion. There was no significant effect for auditory condition by vision interaction ($F(3, 60)=0.32$, $p=0.81$).

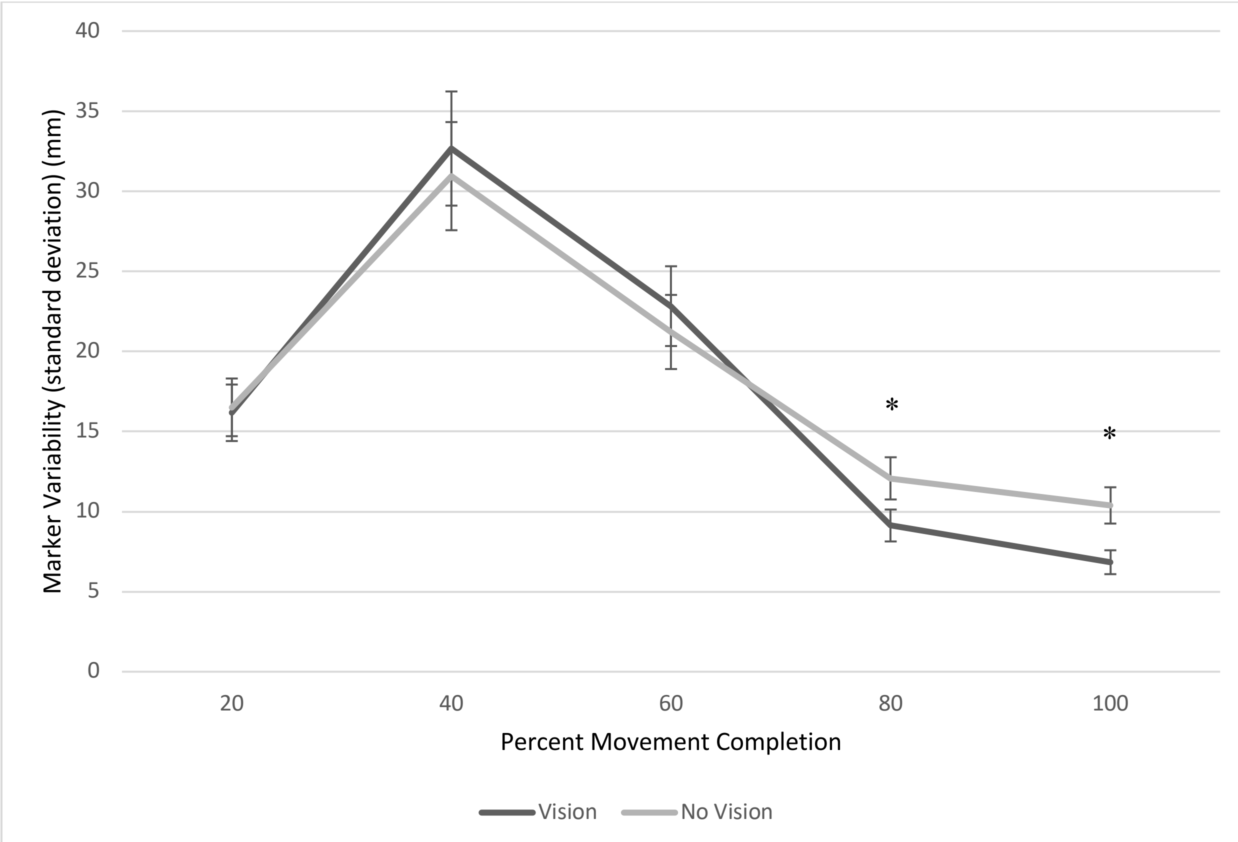


Figure 6. Marker standard deviation throughout movement trajectory in the primary axis. Measured in millimeters. Error bars represent standard error.

For marker trajectory variability in the secondary axis, there was a main effect for vision ($F(1, 20)=6.79$, $p=0.02$). Overall, no vision conditions (16mm) had significantly more marker variability than vision conditions (14mm). There was also a significant interaction between vision and position (percent movement completion) for marker variability ($F(4, 80)=35.13$, $p<0.01$). Post hoc analysis revealed that no vision conditions had significantly more position variability at 80 and 100 percent of movement completion (80=14mm, 100=13mm) compared to full vision conditions (80=10mm, 100=6mm) (Figure 7). There was no significant effect for auditory condition ($F(3, 60)=0.07$, $p=0.98$) or auditory condition by vision interaction ($F(3, 60)=0.12$, $p=0.95$).

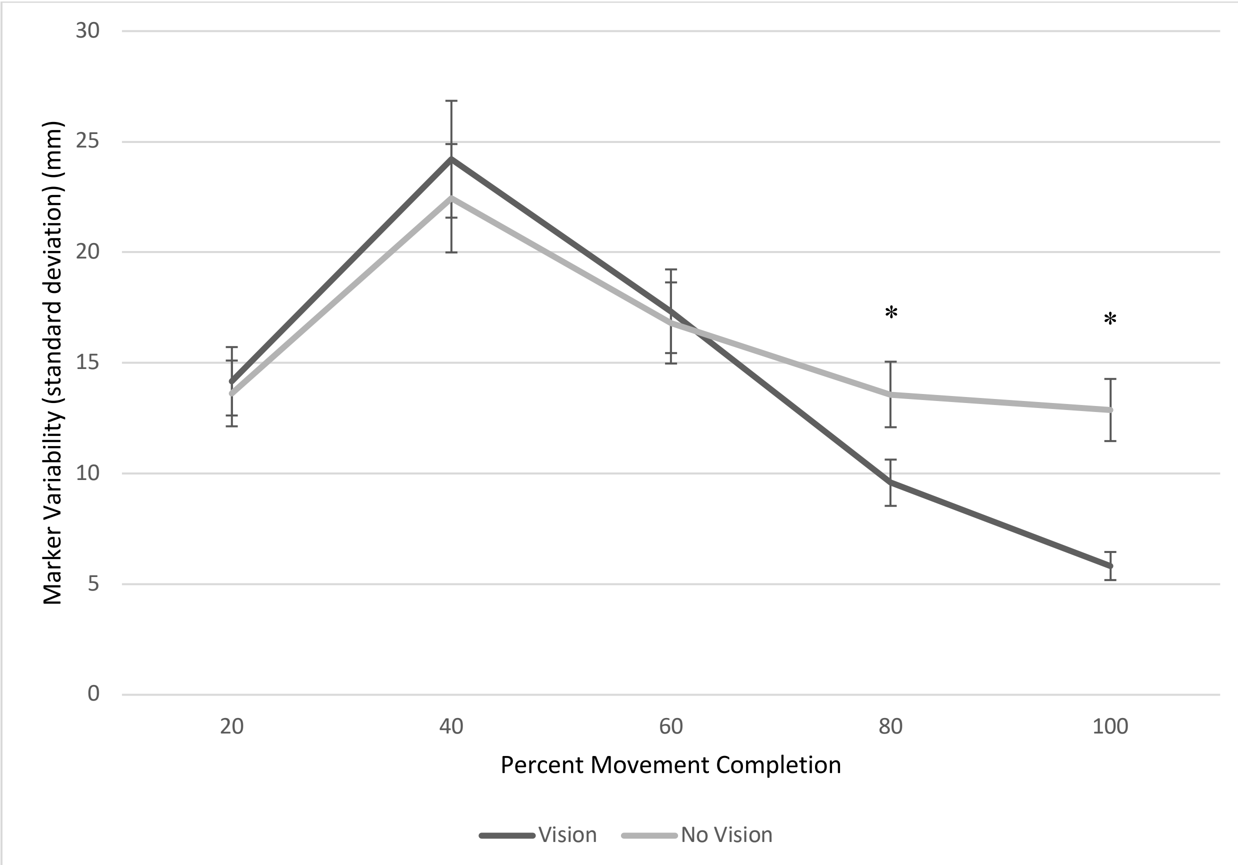


Figure 7. Marker standard deviation throughout movement trajectory in the secondary axis. Measured in millimeters. Error bars represent standard error.

For mean marker position at 20, 40, 60, 80 and 100 percent of movement completion in the primary axis, there was no significant effect for vision (F(1, 20)=0.72, p=0.41), but there was a significant effect for auditory condition (F(3, 60)=5.34, p<0.01). Post hoc analysis with Tukey's HSD revealed that no sound conditions had a significantly different mean marker position (222mm) compared to sound before (225mm) sound during (226mm) and sound throughout (226mm) conditions. The main effect was superseded by a significant interaction between condition and position in the primary axis (F(12, 240)=3.12, p<0.01). Post hoc analysis revealed that the no sound condition had a significantly different mean marker position than sound before, sound during and sound throughout at 20, 40 and 60 percent of movement completion (Figure 8).

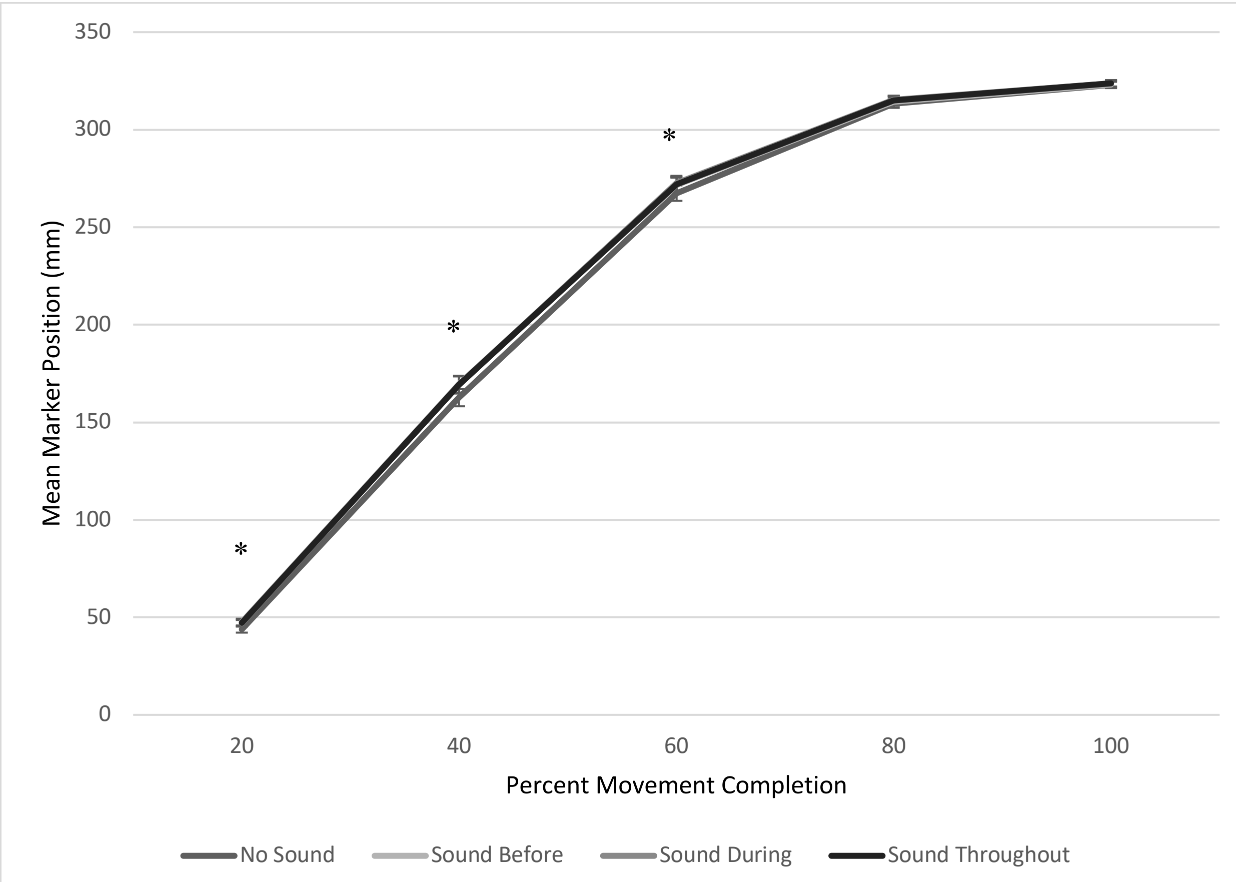


Figure 8. Mean marker position in the primary axis. Interaction between auditory condition and percent movement completion. Error bars represent standard error.

There was also a three way interaction between vision, position and target location ($F(4, 80)=5.40$, $p<0.01$) (Figure 9). Post hoc analysis with Tukey's HSD revealed that left and right target locations had significantly different mean marker positions at 20, 40, 80 and 100 percent of movement completion in both the vision and no vision conditions.

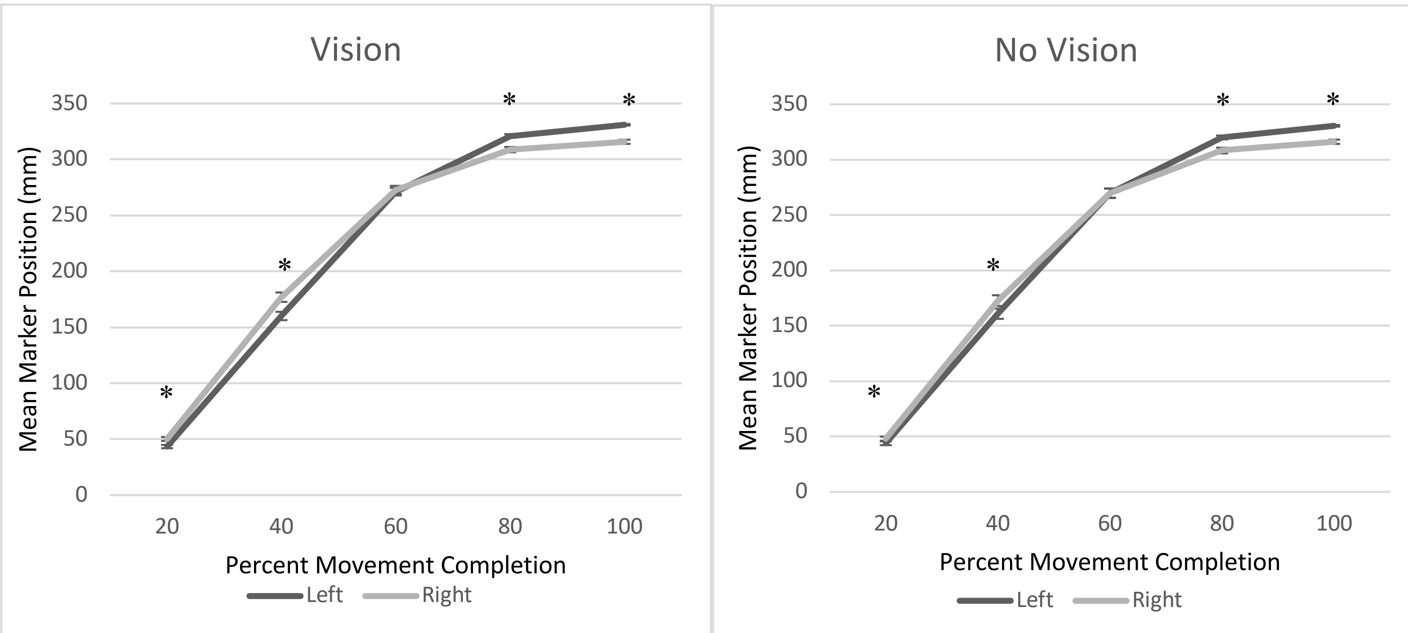


Figure 9. Mean marker position throughout movement trajectory. Interaction between vision, position and target location. Measured in millimeters. Error bars represent standard error.

In the secondary axis, there was a significant effect for vision for mean marker position at 20, 40, 60, 80 and 100 percent of movement completion (F(1, 20)=27.71, p<0.01). No vision (12mm) conditions had a lower mean marker position compared to vision conditions (15mm). The main effect was superseded by an interaction between vision and position (F(4, 80)=3.98, p<0.01), where no vision conditions the mean marker position was significantly lower than vision conditions at all points in the movement (Figure 10). Additionally, there was a significant interaction between condition and target location (F(3, 60)=4.59, p<0.01). Post hoc analysis with Tukey's HSD revealed that at the right target, the no sound condition had a significantly different mean marker position of -121mm compared to the sound throughout condition (-124mm).

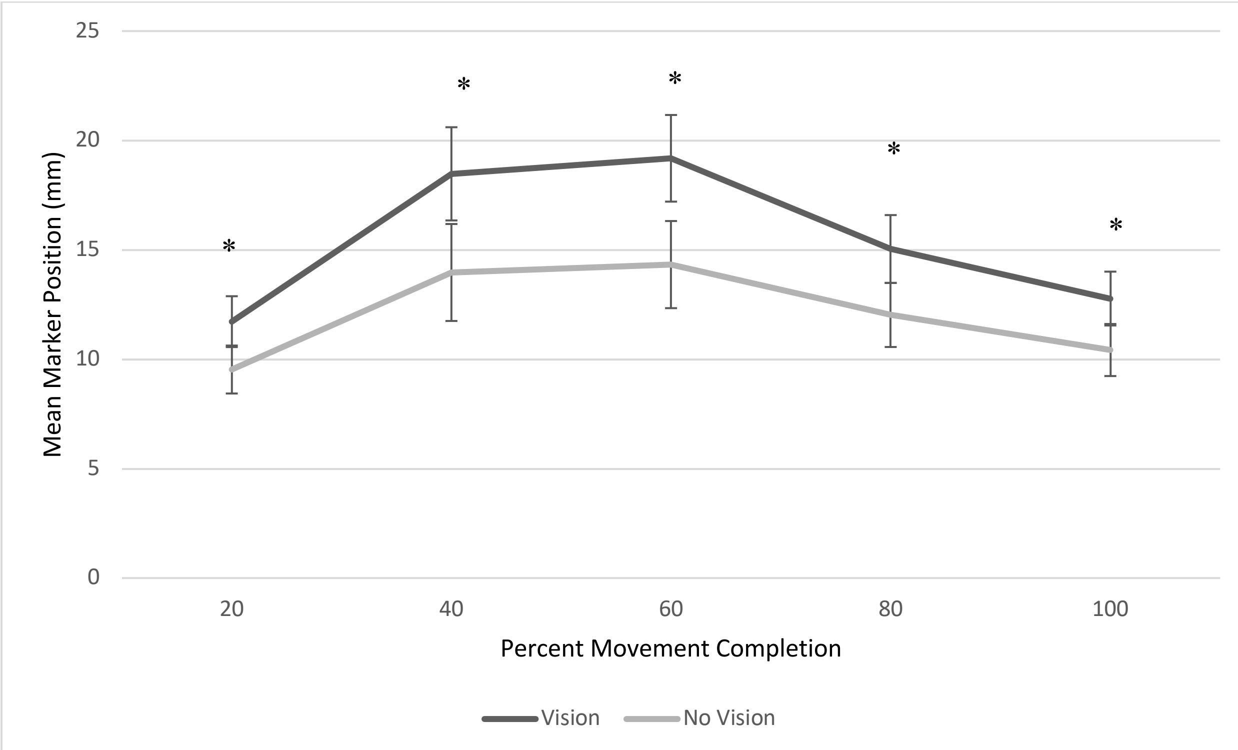


Figure 10. Mean marker position in the secondary axis. Interaction between vision and percent movement completion. Error bars represent standard error.

Discussion

In this experiment rhythmic auditory stimuli were implemented under vision and no vison conditions during a goal-directed reaching task to investigate how additional auditory information impacts motor performance. Experiment 1 manipulated the onset of auditory information including no sound, sound before, sound during and sound throughout conditions. I predicted that typically developing adults would use the auditory information more when they had reduced visual feedback in movement execution. Overall, hearing the rhythmic sound before movement initiation (i.e., in the sound before and sound throughout conditions) may be most important to elicit performance gains in RT and endpoint error. Sound heard during the movement also elicited some performance improvements in terms of absolute error in the secondary axis. The following discussion considers two possible mechanisms in which the rhythmic metronome may have facilitated performance improvements. The first proposal is that when sound is heard before movement initiation, the benefits are gained by improving the temporal accuracy of the movement plan, and that the improved consistency and accuracy of the plan leads to improved endpoint accuracy. Second, I suggest that the rhythmic sound functions as an attentional cue, facilitating an external focus of attention and in turn resulting in performance improvements (Wulf, 2007). The benefits observed when sound was heard during the movement may also be a function of improved attentional focus.

Vision

Overall the effects of vision are consistent with existing literature. Longer RT's were expected during the no vision conditions as participants were likely using the time to solidify their memory representations of the target location, as they knew they would lose visual information upon movement initiation (Hansen et al., 2006; Khan, Elliott, Coull, Chua, & Lyons, 2002a). Participants will plan movements based on the sensory feedback available during the movement, therefore in no vision conditions, participants spend more time planning the movement so they can reach the target without visual feedback during the movement (Khan et al., 2002a). In full vision conditions, participants took less time to plan the movement, as they can spend more time after peak deceleration using visual information to make online corrections (Elliott et al., 2010; Khan et al., 2002a) This effect is also evident in terms of MT, with the no vision condition having shorter MT's than full vision. The shorter MT in NV conditions may be in part due to the decay of memory representations of the target location that occur once participants lose sight of the target (Binsted et al., 2006). Participants may have faster MT's in NV conditions in an attempt to maintain memory representations of the target. Peak velocity was higher in NV conditions compared to vison, which relates to the decreased MT, and is consistent with past literature (Hansen et al., 2006) in which participants had longer MTs when they knew vision would be unavailable.

Spatial outcomes of movement performance, including trajectory variability, mean marker position during movement trajectory and endpoint error, were also consistent with our predictions and existing literature. No vision conditions had more endpoint variable and absolute error in both the primary and secondary axis. This was expected as participants were unable to make any error corrections based on visual feedback (Carson et al., 1990; Chua & Elliott, 1993; Elliott et al., 2010). This effect was evidenced by the increased marker trajectory variability near the end of the movement in no vision conditions in both primary and secondary axes. This was expected, as participants were not able to make limb to target corrections based on visual feedback. For mean marker position throughout movement trajectory in the secondary axis, no vision conditions tended to take a more conservative strategy throughout the movement, resulting in a lower mean marker position throughout. This supports the conclusion drawn by Elliott et al., (2014) that participants will adopt a more conservative movement strategy when vision is unavailable.

Auditory Condition

Consistent with predictions, mean RTs were shorter in conditions where participants heard the sound before movement initiation, including sound before and sound throughout conditions. This was expected as participants essentially had a countdown giving them advance information about when the go signal would occur. Additionally, the advance auditory information could have functioned as a precue, eliciting increased attention to the imminent go signal and target locations (Eversheim & Bock, 2002). There was also increased reaction time variability (standard deviation) in sound during conditions compared to all other auditory conditions. When participants had no auditory information during movement planning, but expected auditory information during movement execution, they may have had more variable reactions times as they were unable to plan for the additional auditory information.

There were no significant effects for auditory condition for movement time, peak velocity or the ratio of time to peak velocity to movement time. Increased (longer) movement times are typically seen in vision conditions compared to no vision conditions and are attributed to the additional time required to make corrections based on visual information (Chua & Elliott, 1993). Similarly, participants reach peak velocities earlier in the movement in vision conditions compared to no vision conditions, to allow more time for limb-target regulation near the target location (Elliott, Garson, Goodman, & Chua, 1991). The lack of significant effects for auditory condition for movement time, peak velocity, or the ratio of time to peak velocity to movement time, likely indicates that participants were not using anything that they heard during the movement to control the movement. In this paradigm for temporal measures, including reaction time, RT variability, movement time, MT variability, peak velocity and ttPV:MT, there were no significant interactions between auditory condition and vision. The lack of significant interaction between auditory condition and vision indicates that changes related to the RAS are not interacting with movement strategy related to knowing vision will be removed.

When sound was heard before movement initiation, there was improved performance in endpoint variable error in the primary axis. Sound before conditions also had reduced endpoint absolute error in the primary axis compared to no sound and sound during conditions. This supports the hypothesis that the sound before movement initiation can elicit performance improvements in endpoint error. This effect was mirrored in endpoint absolute error in the secondary axis, where the sound before condition had less endpoint error than no sound and sound during. Based on the improved endpoint consistency it is possible that the improved performance was due to improvements in movement planning (Elliott et al., 2010) due to the additional temporal information available to the sensorimotor system prior to movement initiation. The multiple-process model of limb control proposed by Elliott et al., (2010) suggests that performers will use multiple overlapping processes including an initial movement based on the available sensory information. Hearing the rhythmic auditory stimuli before the movement provided additional information to the performer during movement planning, which was able to improve both a temporal and spatial outcome. It is possible that this additional information allowed them to fine tune temporal aspects of the movement. This hypothesized improvement in movement planning, carried over to movement execution, evidenced by reduced endpoint variable and absolute error in the primary axis in the sound before condition.

Contrary to predictions, in endpoint absolute error in the secondary axis, no sound conditions had more endpoint error than the sound during condition. This may be a function of improved attentional focus (Wulf, 2007) during movement execution.

When performing in the no vision no sound condition participants tended to undershoot the target location in the secondary axis significantly more than any other condition. Past literature has attributed an undershoot to participants adopting time and energy conserving strategies (Elliott et al., 1999, 2009, 2004; Engelbrecht et al., 2003; Lyons et al., 2006). Target overshoot errors are more temporally and energetically costly than undershoot errors, as participants must perform a movement reversal to reach the target (Lyons et al., 2006). A primary movement undershoot may require the participant to make a secondary sub movement to reach the target, however this strategy is less energetically costly than a target overshoot (Lyons et al., 2006). More recently, Elliott et al., (2014) found that no vision conditions yielded increased target undershoots in a vertical aiming task. When visual input was removed during movement execution, participants may have adopted more conservative strategies to reach the target and avoid a costly overshoot error (Elliott et al., 2014). This worst-case scenario strategy of cost minimization is evident in the no vision no sound condition, where participants received the least amount of sensory information from vision and audition. It seems the presence of auditory information at any point in the movement is enough that participants do not display the target undershoot associated with energy conservation strategies. This effect is also evident in mean marker position in the primary axis throughout the movement, where no sound conditions had a significantly lower mean position at 20, 40 and 60 percent of movement completion. This mirrors the undershoot in endpoint constant error and supports the existing body of literature. In no vision conditions, auditory information presented at any point in the movement provided the participant with an additional temporal frame of reference. This additional frame of reference seems to be enough information for participant to avoid adopting the worst-case scenario strategy of an undershoot error. In each experimental block, participants were aware of the upcoming visual and auditory condition, which allowed participants to alter their strategy and adjust how they were using various sources of sensory input.

I hypothesized that participants would rely more on the auditory information in no vision conditions. There were two statistically significant interactions between auditory condition and vision, in endpoint absolute error in the primary axis and endpoint constant error in the secondary axis. In endpoint absolute error when vision was unavailable, conditions where sound was presented before movement initiation (sound before and throughout) had less endpoint error than when sound was not present before the movement. Based on the existing body of literature supporting the use of rhythmic auditory stimuli in populations with disrupted sensory input

(Johansson et al., 2012; Johansson et al., 2014; Ladwig et al., 2016; Thaut et al., 2002; Whitall et al., 2000), I hypothesized that by creating a controlled model of reduced sensory input, participants would rely more on the addition auditory information. One hypothesis is that sound before movement initiation would benefit reaching performance through improvements in movement planning (Elliott et al., 2010; Hatfield et al., 2010; Ladwig et al., 2016). Reduced in endpoint absolute error when sound was heard before movement initiation provides support for this hypothesis. In the protocol, participants had the most amount of information, both visual and auditory, during movement planning when sound was heard before movement initiation. This increased sensory input may have strengthened the movement plan, resulting in overall improved movement execution in sound before conditions.

Results from Experiment 1 were used to inform the onset of rhythmic auditory stimuli in Experiment 2. Given the performance improvements in reaction time and endpoint error with sound before movement initiation, Experiment 2 investigated the impact of auditory complexity, source and subjective enjoyability on reaching performance using rhythmic auditory stimuli prior to movement initiation.

Experiment 2

Objective

Experiment 2 aimed to examine if and how increased rhythmic complexity and enjoyability benefited goal-directed reaching movements. Thus, Experiment 2 examined differences in motor performance of a goal-directed reaching task with different sources of rhythmic auditory stimuli including a simple metronome, a complex metronome, a simple drum beat matching the rhythm of the simple metronome, a more complex drum matching the rhythm of the complex metronome, and a no sound condition. It also compared subjective enjoyability of two different sources of auditory information, including a metronome and a drum beat, to see whether enjoyment contributed to any observed benefits in reaching performance. Auditory conditions were performed under full vision and no vision conditions to examine whether participants relied more on the rhythmic auditory stimuli when they had reduced visual input. Participants also rated how much they enjoyed each auditory condition on a 5-point Likert scale, which provided a basis to see if subjective enjoyability of each auditory condition influenced reaching performance.

Hypothesis

For reaction time, I hypothesized that no vision conditions would have increased and more variable mean RTs compared to vision conditions. For rhythmic complexity, I hypothesized that the complex metronome would have shorter and less variable mean RTs compared to simple metronome conditions. Finally, I expected that participants would have shorter and less variable mean RTs with the preferred (i.e., more enjoyable) auditory source.

For movement time, I expected that no vision conditions would have shorter and less variable mean MTs compared to vision conditions. Based on the results from Experiment 1, I did not expect to see an effect for rhythmic complexity or subjective enjoyability for mean MT or MT variability.

For peak velocity, I predicted that no vision conditions would reach higher peak velocities compared to vision conditions. I did not expect to see an effect for rhythmic complexity or subjective enjoyability. Based on the results from Experiment 1, I did not expect to see any effects for the ratio of time to peak velocity to movement time for vision, rhythmic complexity or subjective enjoyability.

For endpoint error, I expected no vision conditions to have increased endpoint constant, variable and absolute error compared to vision conditions. I also expected the complex rhythm to have less endpoint constant, variable and absolute endpoint error compared to no sound and simple metronome conditions. I also expected to see less endpoint error in the condition that participants enjoyed more.

For trajectory variability throughout movement execution, I expected no vision conditions to have more variable movement trajectories towards the end of the movement compared to vision conditions. I did not expect to see an effect for rhythmic complexity. Finally, I expected to see less trajectory variability in conditions that participants enjoyed more.

For mean marker position throughout movement execution I expected that no vision conditions would undershoot throughout the movement compared to vision conditions. I also expected participants to undershoot the target in the no sound condition compared to the complex and simple metronome conditions. I did not expect to see an effect for subjective enjoyability.

Based on the results from Experiment 1, I expected that there would be an interaction between rhythmic complexity and vision or enjoyability and vision, in endpoint error.

For the Likert scale recording the subjective enjoyability of each auditory condition, I expected that participants would rate the drum conditions higher (more enjoyable) compared to the metronome conditions.

Finally, I hypothesized that subjective enjoyability would be positively correlated to movement performance. More specifically, I expected that if participants liked the drum more than the metronome that their performance would reflect similar performance improvements.

Participants

Twenty-four typically developing young adults (mean age 23.87 years, SD 2.19, 11 female) were recruited from the University of Manitoba community. Three participants were excluded from analysis, including one left handed participant, and two participants with over 50% of trials having missing data points. Twenty-one right handed participants were included in analysis (mean age 23.71 years, SD 2,10, 11 female). All participants reported normal or corrected to normal vision and hearing, with no neurological conditions, orthopedic injuries or surgeries to the dominant arm within the past 6 months. Prior to participating in the experiment, participants completed written informed consent and a demographics questionnaire. Participants were compensated for their time with a $10 honorarium. All procedures were approved by the University of Manitoba, Education and Nursing Research Ethics Board.

Apparatus

The apparatus for Experiment 2 was identical to the one detailed in Experiment 1.

A 5-point Likert scale collected subjective enjoyability following each experimental condition (Appendix D).

Programming

Conditions were blocked, and the condition order was randomized and counterbalanced between participants. Participants performed a 16-trial familiarization block, which included two blocks of 8 trials of vision simple metronome, and no vision complex drum. Following the familiarization block, participants performed 24 trials in each condition, resulting in a total of 240 reaches. There was a short break between each experimental condition, and participants could take additional breaks at any point in the experiment to avoid fatigue. At the beginning of each experimental condition, participants were informed of the auditory and visual condition that they would be performing in the upcoming block of trials.

Procedure

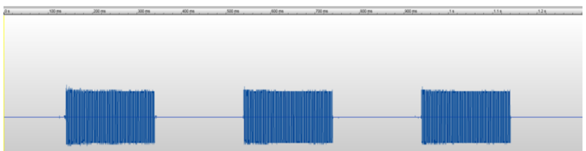
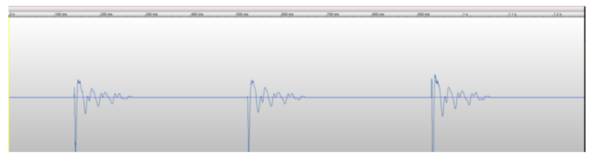
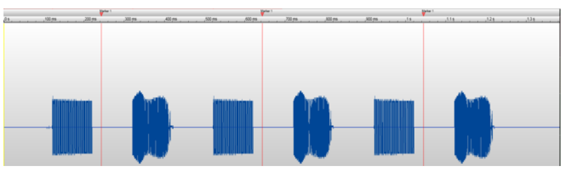
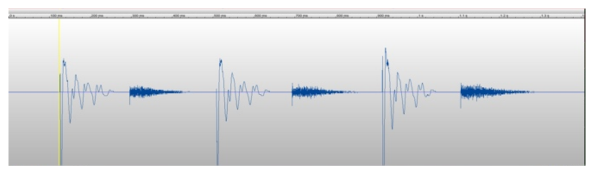
The independent variable manipulated was the source of the rhythmic auditory stimulus, with conditions including: no sound, simple metronome, complex metronome, simple drum beat matching the timing of the metronome, and a more complex drum rhythm (Table 2). Conditions were performed with and without vision for a total of 10 conditions. Following the familiarization block, condition order was randomized and counterbalanced between participants, and target location was randomized.

Table 2 Experimental conditions in Experiment 2

	No Sound	Simple Metronome	Complex Metronome	Simple Drum	Complex Drum
Vision	V-NS	V-SM	V-CM	V-SD	V-CD
No Vision	NV-NS	NV-SM	NV-CM	NV-SD	NV-CD

The experimental procedure was identical to that of Experiment 1, with the exception of the rhythmic timing and source of rhythmic auditory information. In each condition, the rhythmic auditory stimulus was presented prior to movement initiation. In the metronome condition a tone of 575Hz was presented for 200ms, followed by a 200ms pause, repeated three times, identical to the sound before condition in Experiment 1. The complex metronome was composed of the base beat of the simple metronome, with a higher-toned beat on the half counts. The simple drum beat condition was a recording of a bass drum playing at the same intervals as the simple metronome. The complex drum was composed of the base bass beat of the simple drum beat condition, with the beat of a high-hat drum overlaid on the half counts. The simple and complex drum beat conditions both included three beats of the base drum beat so that the timing matches the timing of the metronome conditions (Table 3).

Table 3. Visual representation of auditory conditions.

Simple Metronome 	Simple Drum 
Complex Metronome 	Complex Drum 

Participants performed all auditory conditions with and without vision. In no vision conditions, PLATO Visual Occlusion Spectacles (Translucent Technologies, Inc.) occluded vision upon movement initiation and restored vision approximately two seconds after reaching the target location. Participants knew if they would have vision in each upcoming block of trials. Following completion of each experimental block, participants were asked to rate the auditory condition from; 1-very unpleasant, 2-somewhat unpleasant, 3-neutral, 4-somewhat pleasant, 5-very pleasant. The experimenter recorded the response before advancing to the next experimental block.

Data Treatment

Data treatment followed the same protocol outlined in Experiment 1. Through removal of field note errors, trials with missing marker points during movement trajectory, and trials that fell over 2.5 standard deviations away from the mean (reaction time, movement time and endpoint variable error in the primary axis, 18.43% of trials were excluded from statistical analysis.

Statistical Analysis

For Experiment 2, a 3 Condition (no sound, simple metronome, complex metronome) x 2 Vision (vision and no vision) repeated measures ANOVA was used to investigate the effect of rhythmic complexity on the dependant variables with significance (alpha) set at 0.05. Significant effects were analysed with Tukey's HSD with alpha set at 0.05. For Likert scale data, auditory conditions (no sound, metronome, drum) were averaged across participants for a descriptive view of relative enjoyability. To examine performance based on relative enjoyability, a 3 Condition (no sound, metronome, drum) x 2 Vision (vision and no vision) repeated measures ANOVA investigated differences in the dependant variables with significance (alpha) set at 0.05. Any significant effects were investigated with Tukey's HSD with alpha set at 0.05. Finally, to correlate relative enjoyability to performance, Spearman's correlation was used to correlate the differences between individual participant enjoyability ratings and their difference in performance between conditions in the dependant variables. Any comparisons where sphericity was violated (Mauchly's Test of Sphericity, $p<0.05$) were corrected with the Greenhouse-Geisser procedure.

Rhythmic Complexity

Results

There was a significant effect for reaction time for auditory condition (uncorrected: $F(2, 40)=82.14$, $p<0.01$, corrected: $F(1.35, 26.94)=82.14$, $p<0.01$). Post hoc analysis with Tukey's HSD revealed that the no sound condition had a significantly longer (increased) mean reaction time of 323ms compared to simple (243ms) and complex metronome (241ms) conditions. There was no significant effect for vision ($F(1, 20)=3.21$, $p=0.09$), or auditory condition by vision interaction ($F(2, 40)=1.47$, $p=0.24$).

For reaction time variability, there were no significant effects for vision ($F(1, 20)=0.96$, $p=0.34$) auditory condition ($F(2, 40)=2.58$, $p=0.09$) or auditory condition by vision interaction ($F(2, 40)=2.12$, $p=0.13$).

For movement time, there was a significant effect for vision ($F(1, 20)=13.10$, $p<0.01$). Vision conditions had a significantly longer (increased) mean movement time of 461ms compared to no vision conditions that had a mean movement time of 439ms. There was no significant effect for auditory condition ($F(2, 40)=0.10$, $p=0.90$) or auditory condition by vision interaction ($F(2, 40)=0.03$, $p=0.97$).

For movement time variability, there were no significant effects for vision ($F(1, 20)=0.64$, $p=0.43$), auditory condition ($F(2, 40)=0.60$, $p=0.55$) or auditory condition by vision interaction ($F(2, 40)=0.44$, $p=0.65$).

For peak velocity, there was a significant effect for vision in both the primary ($F(1, 20)=12.56$, $p<0.01$), and secondary ($F(1, 20)=5.92$, $p=0.02$) axes. No vision (primary: 1486mm/s, secondary: 886mm/s) conditions had significantly higher mean peak velocities than vision (primary: 1437mm/s, secondary: 853mm/s) conditions. There was no effect for auditory condition in the primary (uncorrected: $F(2, 40)=0.81$, $p=0.45$, corrected: $F(1.48, 29.53)=0.81$, $p=0.42$)) or secondary ($F(2, 40)=0.79$, $p=0.46$) axis. Additionally, there was no interaction between auditory condition and vision in the primary ($F(2, 40)=0.22$, $p=0.81$) or secondary ($F(2, 40)=0.74$, $p=0.48$) axis.

There were no significant effects for the ratio of time to peak velocity to movement time for vision ($F(1, 20)=3.56$, $p=0.07$), auditory condition ($F(2, 40)=2.65$, $p=0.08$) or auditory condition by vision interaction ($F(2, 40)=0.63$, $p=0.54$).

For endpoint variable error, there was a significant effect for vision in both the primary ($F(1, 20)=62.34$, $p<0.01$) and secondary ($F(1, 20)=79.21$, $p<0.00$) axis. No vision conditions yielded significantly more endpoint variable error in both the primary (9mm) and secondary (9mm) axis compared to vision conditions (primary: 6mm, secondary: 5mm). There was no significant effect for auditory condition in the primary ($F(2, 40)=1.44$, $p=0.25$) or secondary ($F(2, 40)=1.34$, $p=0.28$) axis. There was also no significant interaction between auditory condition and vision in the primary ($F(2, 40)=0.42$, $p=0.66$) or secondary ($F(2, 40)=0.43$, $p=0.66$) axis.

For endpoint constant error, there was no significant effect for vision in the primary axis ($F(1, 20)=1.32$, $p=0.26$), but there was a significant effect in the secondary axis ($F(1, 20)=5.67$, $p=0.03$). In the secondary axis, no vision conditions had mean target undershoot of -1.7mm compared to vision condition which had a mean undershoot of -0.4mm. There was no significant effect for auditory condition in the primary (uncorrected: $F(2, 40)=0.02$, $p=0.98$, corrected: $F(1.52, 6.19)=0.22$, $p=0.95$) or secondary ($F(2, 40)=0.80$, $p=0.46$) axis. There was no significant interaction between auditory condition and vision in the primary ($F(2, 40)=0.33$, $p=0.72$) or secondary ($F(2, 40)=2.25$, $p=0.12$) axis.

There was a significant effect for absolute error for vision in both the primary ($F(1, 20)=97.88$, $p<0.01$) and secondary ($F(1, 20)=87.24$, $p<0.01$) axis. No vision (primary: 8mm, secondary: 8mm) conditions had significantly more endpoint absolute error compared to vision conditions (primary: 5mm, secondary: 5mm). There was no significant effect for auditory condition (primary: $F(2, 40)=1.05$, $p=0.36$, secondary: $F(2, 40)=1.01$, $p=0.37$) or auditory condition by vision interaction (primary: $F(2, 40)=0.97$, $p=0.39$, secondary: $F(2, 40)=0.75$, $p=0.48$).

For marker position variability (standard deviation) at 20, 40, 60, 80 and 100 percent of movement completion in the primary axis there were no significant effects for vision ($F(1, 20)=0.00$, $p=0.99$) or auditory condition ($F(2, 40)=1.93$, $p=0.16$). There was a significant interaction between auditory condition and position ($F(8, 160)=2.37$, $p=0.02$) and vision and position ($F(2, 80)=9.78$, $p<0.01$). The no sound condition had significantly more marker variability at 40 and 60 percent of movement completion compared to both the simple and complex metronome (Figure 11). No vision conditions had significantly more marker variability at 60, 80 and 100 percent of movement completion compared to full vision conditions (Figure 12).

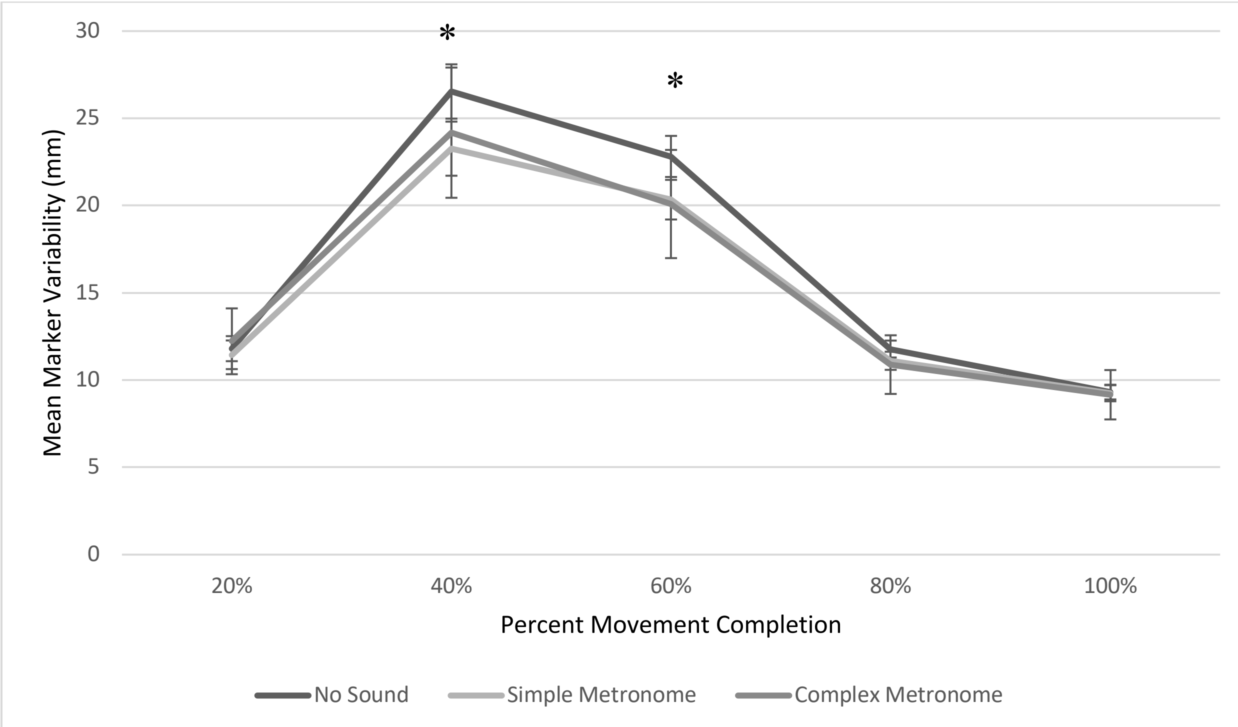


Figure 11. Marker variability in the primary axis. Interaction between auditory condition and vision. Measured in millimeters. Error bars represent standard error.

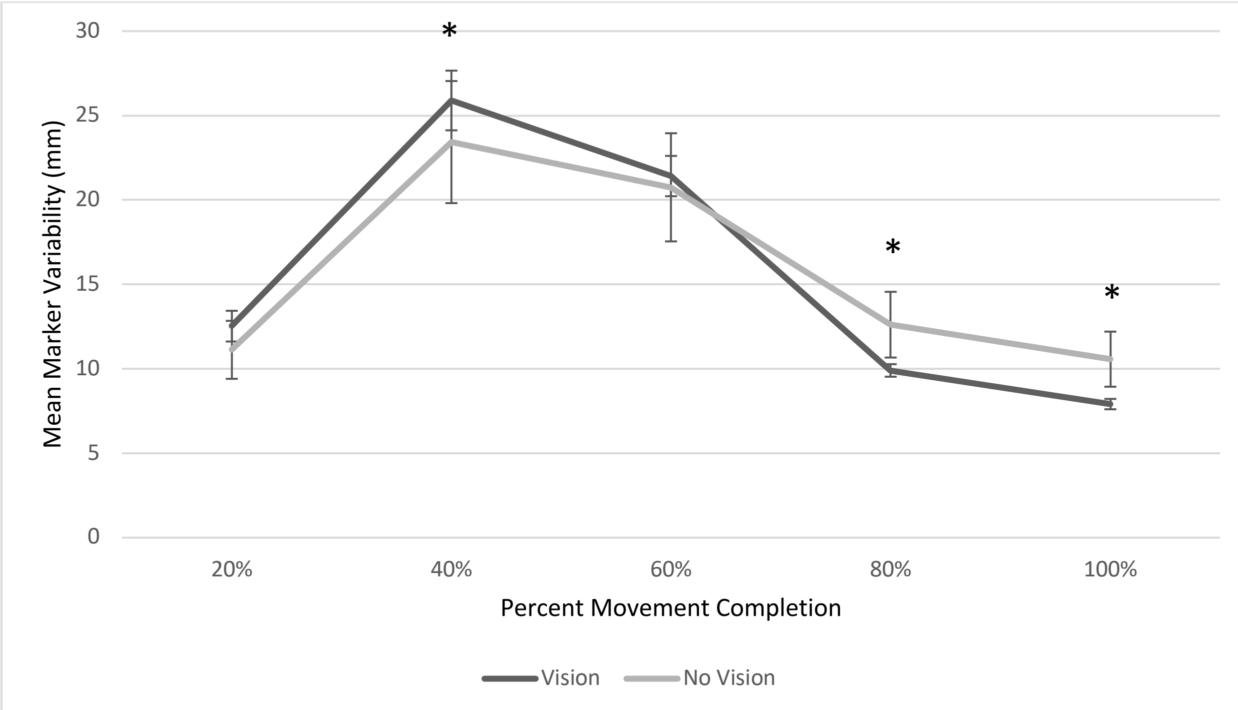


Figure 12. Mean marker variability in the primary axis. Interaction between vision and position. Measured in millimeters. Error bars represent standard error.

There was a significant effect interaction between vision and position ($F(4, 80)=34.19$, $p<0.01$) for marker position variability (standard deviation) and 20, 40, 60, 80 and 100 percent of movement completion in the secondary axis. Vision conditions had significantly more marker variability at 20, 40 and 60 percent of movement completion, while no vision conditions had significantly more marker variability at 80 and 100 percent of movement completion (Figure 13). There were no significant effects for auditory condition ($F(2, 40)=0.14$, $p=0.87$) or vision by condition interactions ($F(2, 40)=0.08$, $p=0.92$).

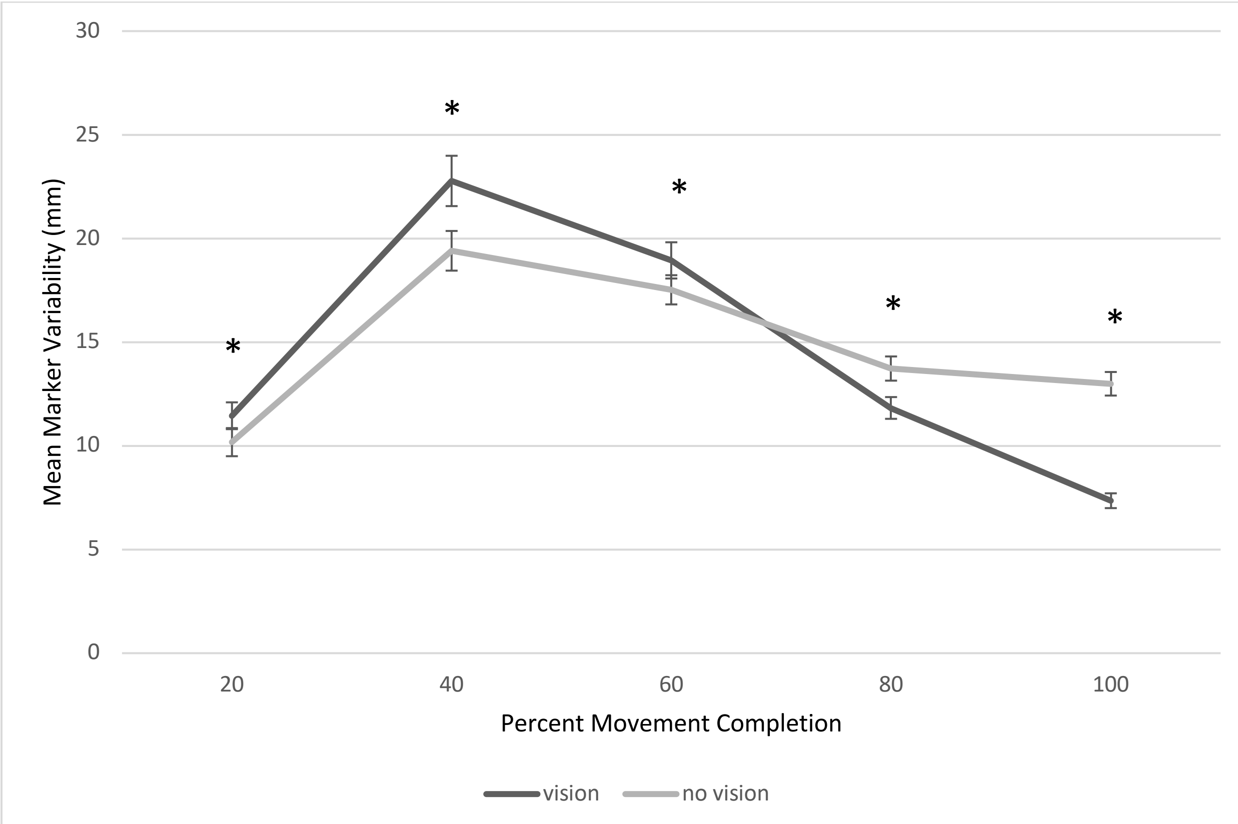


Figure 13. Mean marker variability in the secondary axis. Interaction between vision and position. Measured in millimeters. Error bars represent standard error.

For mean marker position at 20, 40, 60, and 100 percent of movement trajectory in the primary axis, there was a significant interaction between auditory condition and position (F(8, 160)=2.43, p=0.02) and vision and position (F(4, 80)=3.14, p=0.02). Post hoc analysis with Tukey's HSD revealed that at 100% of movement completion, the no sound condition had a mean position of 328mm compared to the simple (324mm) and complex (324mm) metronome conditions (Figure 14). Post hoc analysis with Tukey's HSD revealed that no vision conditions had a significantly lower mean position at 40, 60, 80 and 100 percent of movement completion compared to vision conditions (Figure 15).

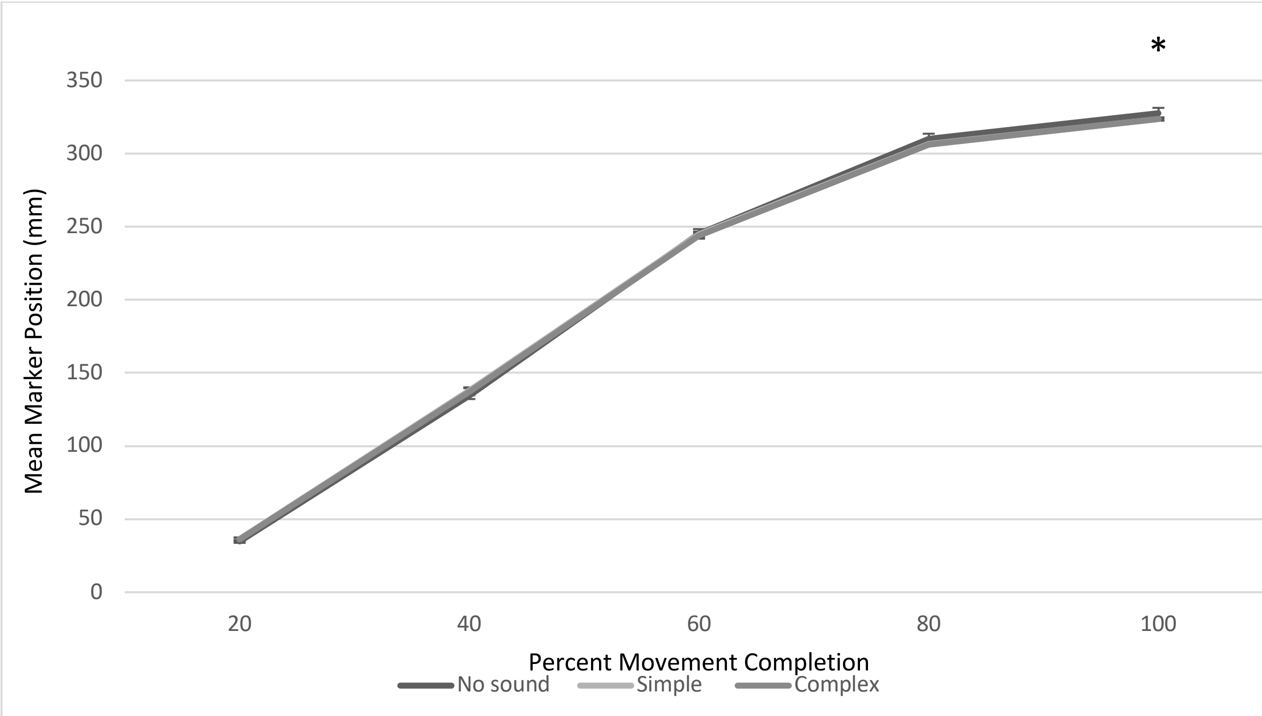


Figure 14. Mean marker position in the primary axis. Interaction between auditory condition and position. Measured in millimeters. Error bars represent standard error.

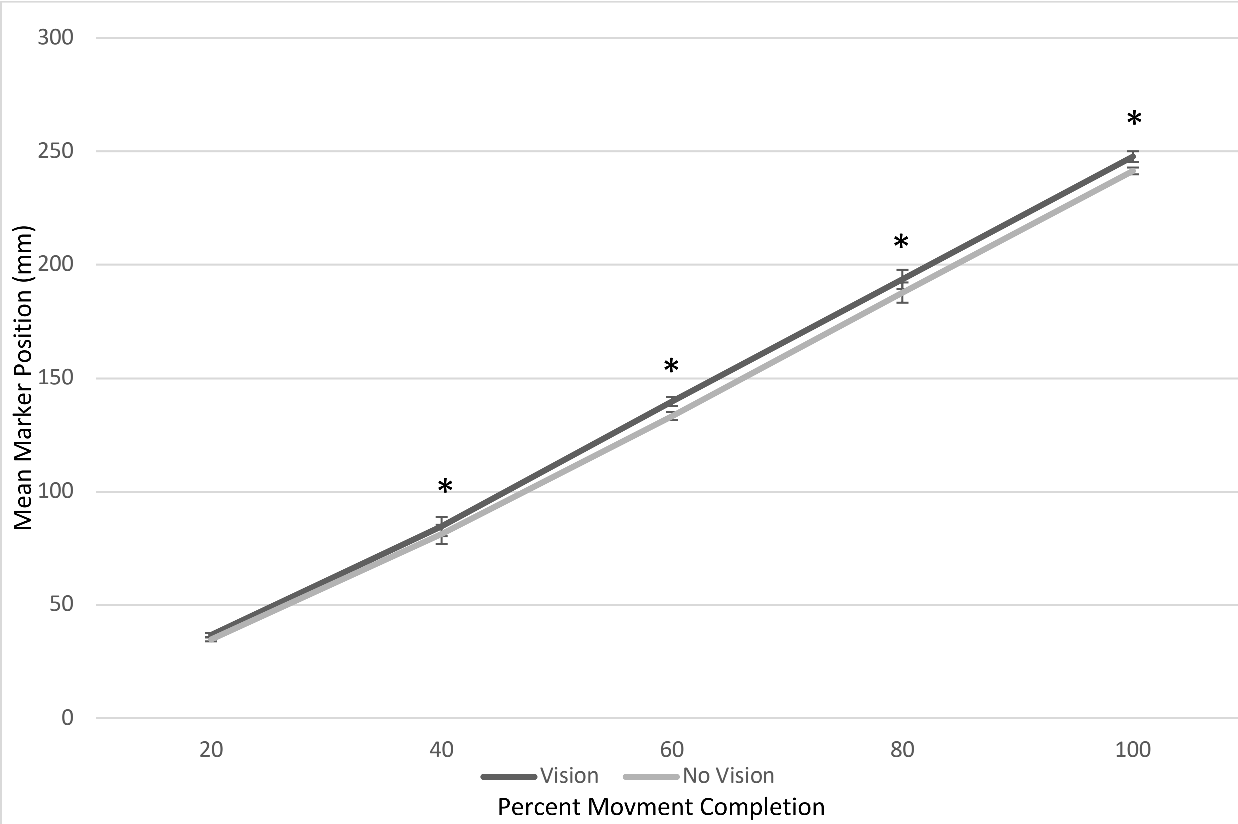


Figure 15. Mean marker position in the primary axis. Interaction between vision and position. Measured in millimeters. Error bars represent standard error.

For mean marker position at 20, 40, 60, 80 and 100 percent of movement trajectory in the secondary axis, there was a significant interaction between auditory condition and position ($F(8, 160)=3.72$, $p<0.01$). No sound conditions had a decreased mean marker position at 100% of movement completion compared to both simple and complex metronome conditions (Figure 16). There was also an interaction between vision and position ($F(4, 80)=3.14$, $p=0.02$).

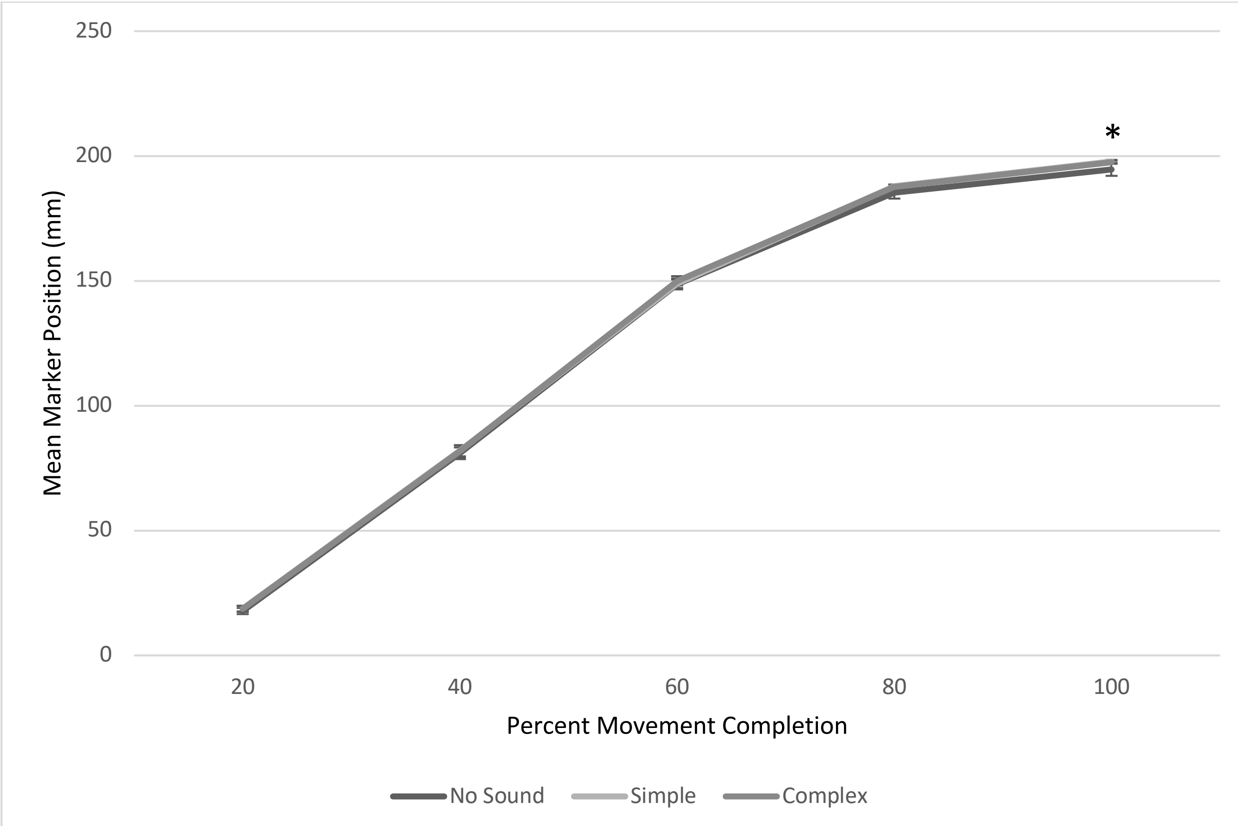


Figure 16. Mean marker position in the secondary axis. Interaction between auditory condition and position. Measured in millimeters. error bars represent standard error.

Discussion

The above analysis aimed to examine the effect of rhythmic complexity on movement performance in a goal-directed reaching task. This analysis compared no sound, simple metronome and complex metronome conditions, all performed with and without vision. Results for vision mirrored the outcomes of Experiment 1 and are consistent with existing literature. There were no significant differences between simple and complex metronome conditions in any of the dependant variables. One prediction for Experiment 2 was that increased rhythmic complexity would improve movement performance in terms of reaction time, reaction time variability and endpoint error. This prediction was based on an overarching hypothesis that improvements in reaching performance when a rhythmic auditory stimulus was heard before movement initiation are due to temporal improvements in movement planning, increasing the stability of the movement plan and therefore execution. Results did not provide support for this prediction.

Vision.

Effects of vision were consistent with the existing body of literature. Contrary to expectations, there was no effect for visual condition in reaction time or reaction time variability. This effect could have been lost as the rhythm was presented prior to movement initiation in all conditions except the no sound control, providing participants with additional information during movement planning and negating the expected effects of vision on reaction time. Full vision conditions had longer movement times compared to no vision conditions. This is consistent with the results of Experiment 1 and is predicted to result from participants using visual information during the movement to make online corrections to reach the target (Elliott et al., 2010). This effect was also reflected in peak velocity, where no vision conditions had higher peak velocities compared to vision conditions (Hansen et al., 2006). In marker trajectory variability in the primary and secondary axis, where no vision conditions had significantly more mean marker variability near the endpoint of the movement.

No vision conditions had significantly more variable and absolute endpoint error in both the primary and secondary axis compared to vision conditions. This was expected as participants were unable to make corrections based on visual feedback (Carson et al., 1990; Chua & Elliott, 1993; Elliott et al., 2014). Consistent with Experiment 1 and existing literature, participants tended to have a larger undershoot error in the secondary axis in no vision conditions compared to vision conditions. Participants may have been adopting energy conserving strategies to avoid overshooting the target and having to make reversal corrections (Elliott et al., 1999, 2009, 2004; Engelbrecht et al., 2003; Lyons et al., 2006). This energy conserving strategy was paralleled in mean marker position throughout movement completion in the secondary axis, where no vision conditions tended to have lower mean marker positions at 40, 60, 80 and 100 percent of movement completion.

Rhythmic Complexity.

For the most part, results were inconsistent with predictions. While there were some significant effects for auditory condition, both the simple metronome and complex metronome conditions outperformed the no sound condition, with no differences between the simple and complex metronome.

For mean reaction time, no sound conditions were significantly slower compared to both the simple and complex metronome conditions. It was expected that participants would have increased reaction times in no sound conditions because the condition lacked the countdown. Similar to Experiment 1, the auditory information may have functioned as a precue (Eversheim & Bock, 2002), directing the participants attention towards the imminent go signal. Inconsistent with predictions, complex and simple metronome conditions were not significantly different from each other for RT or RT variability. I expected the more finely tuned temporal intervals in the complex metronome condition would result in improvements in RT and RT variability. It seems like any rhythmic auditory information heard before movement initiation is able to elicit performance gains in reaction time. As predicted, there was no effect for auditory condition for movement time or movement time variability. Consistent with predictions, there was no significant effect for auditory condition for peak velocity. This is consistent with Experiment 1, where there was no significant effect for auditory condition.

Similar to Experiment 1, for auditory complexity there were no significant effects for movement time, movement time variability, peak velocity and the ratio of time to peak velocity to movement time. This was expected as participants were not receiving any additional auditory information during the movement. This supports the hypothesis that auditory information heard before movement initiation improved performance through improvements in movement planning rather than movement execution.

For endpoint error, I hypothesized that the complex metronome would elicit less endpoint error compared to the simple metronome conditions. In Experiment 1, participants had less variable and absolute endpoint error when they heard the metronome before movement initiation, however in Experiment 2, there was no significant effect for auditory condition in any endpoint error outcome. The discrepancy between the two experiments may have been due to the timing of the auditory information. With a total of ten auditory conditions (and all sound before), and only two of them being no sound control conditions, there may have been carry over effects from the sound conditions to the no sound condition that impacted the overall comparison. Condition order was randomized and counterbalanced, therefore many participants began the protocol with a condition that had sound before movement initiation. There could have been a learning effect that resulted in improved performance in the no sound conditions.

Despite there being no significant effect for auditory condition in endpoint error, there were significant differences between auditory conditions in spatial aspects of movement trajectory. In the primary axis, no sound conditions had significantly more marker variability throughout the movement compared to both simple and complex metronome conditions. Additionally, at 100% of movement completion in both the primary and secondary axes, no sound conditions had a lower mean marker position compared to both the simple and complex metronome conditions. This mirrors the results of Experiment 1, and supports the hypothesis that the additional auditory information allows the participant to avoid adopting the worst case scenario strategy of time and energy conservation (Elliott et al., 1999, 2009, 2004; Engelbrecht et al., 2003; Lyons et al., 2006).

There were no significant interactions between vision and auditory conditions. As previously mentioned, the no vision conditions were included to create a controlled model of disrupted sensory feedback. In Experiment 2, participants always had vision prior to movement initiation during movement planning in both simple and complex metronome conditions. Therefore, they received the most amount of sensory information during movement planning, which could have led to a more stable movement plan. There may have been a learning or carry over effect due to auditory information being available before movement initiation in eight out of the ten conditions.

Following Experiment 1, two hypotheses for performance improvements seen with the rhythmic auditory stimuli heard before movement initiation included improved temporal aspects of the movement plan (Elliott et al., 2010; Hatfield et al., 2010; Ladwig et al., 2016) and a shift towards an external focus of attention (Wulf, 2007). The lack of significant effects for rhythmic complexity in Experiment 2 lends support to the focus of attention hypothesis over the improved movement plan hypothesis. Additionally, there could be a ceiling effect where performance effects taper off when the metronome provides enough of a stimulus. Therefore, increasing rhythmic complexity would not induce further performance benefits.

Based on similar performance in simple and complex metronome conditions from the rhythmic complexity analysis, both complexities are able to elicit reaching performance benefits in terms of reaction time and movement trajectory.

Auditory Enjoyability

Results

Likert Scale – Descriptive Results.

The Likert scale ranged from 1 to 7, with 1 being very unpleasant and 7 being very pleasant. In no sound conditions, the mean participant rating was 3.19 (SD=1.13). In the simple metronome conditions, participants reported a mean of 2.67 (SD=1.00) and complex metronome mean was 2.71 (SD=1.15). For the simple drum condition, participants reported a mean of 3.43 (SD=0.77) and complex drum resulted in a mean of 3.81 (SD=0.92) (Figure 17).

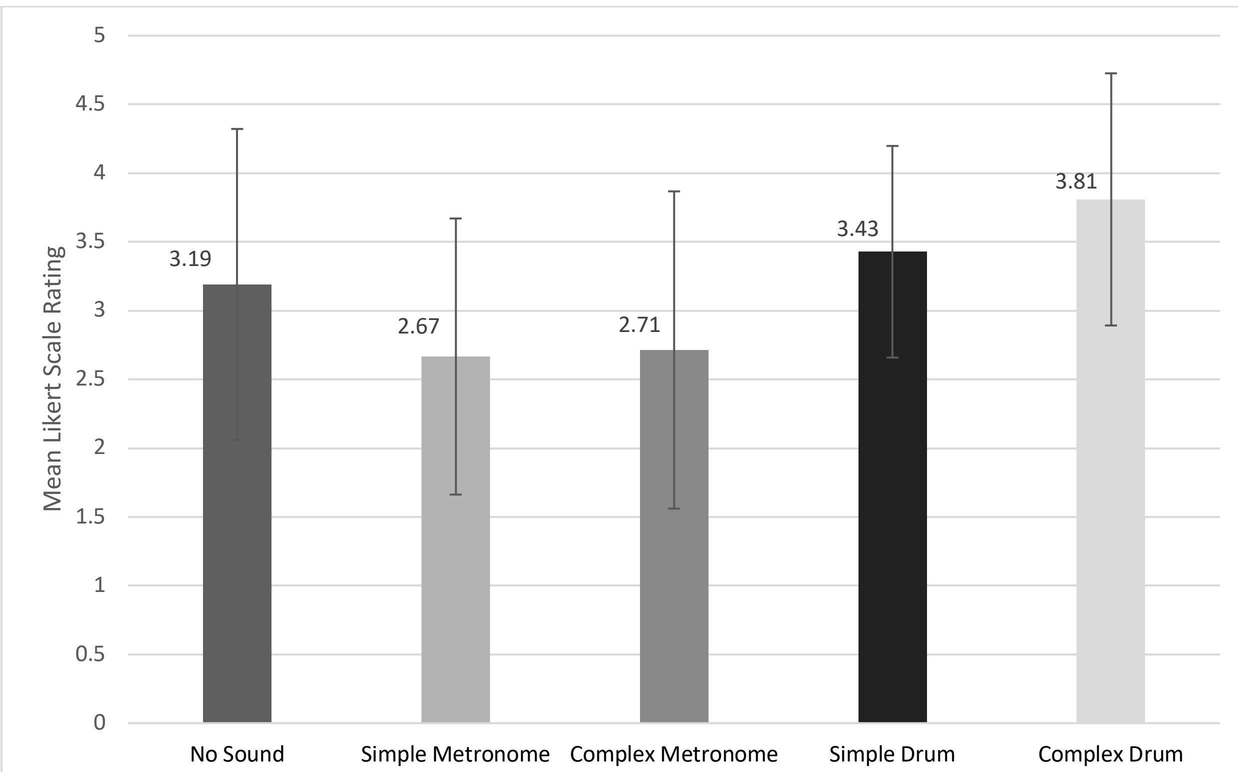


Figure 17. Mean Likert scale rating for each condition. Error bars represent standard deviation.

Collapsed across rhythmic complexity, no sound conditions had a mean rating of 3.19 (SD=1.31), metronome conditions had a mean of 2.69 (SD=1.07), and drum conditions had a mean of 3.62 (SD=0.86) (Figure 18).

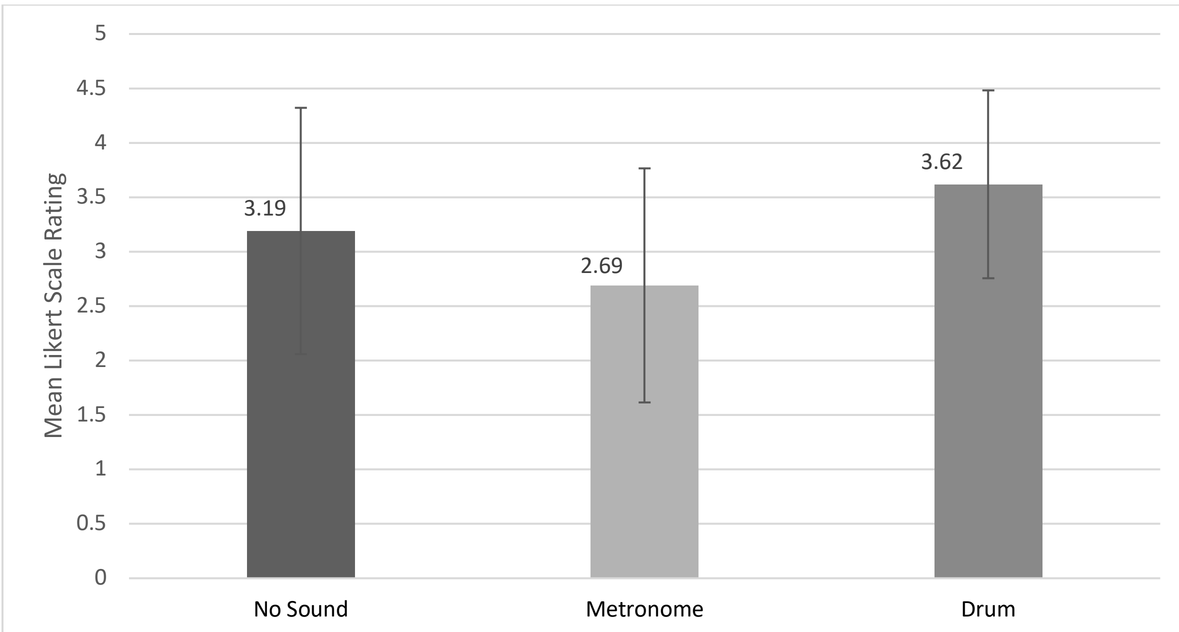


Figure 18. Mean Likert scale rating for each auditory condition, collapsed across rhythmic complexity. Error bars represent standard deviation.

Drum to Metronome Comparison.

For mean reaction time, there was a significant effect for vision ($F(1, 20)=10.57$, $p=0.004$) and auditory source (uncorrected: $F(2, 40)=101.06$, $p<0.01$, corrected: $F(1.37, 27.47)=101.06$, $p<0.01$). No vision conditions had significantly increased mean reaction times at 272ms compared to vision conditions (260ms). Post hoc analysis with Tukey's HSD revealed that no sound conditions had an increased mean reaction times (324ms) compared to both metronome (242ms) and drum (233ms) conditions. There was no significant interaction between vision and auditory source $F(2, 40)=2.34$, $p=0.10$.

In terms of reaction time variability (standard deviation), there was no significant effect for vision ($F(1, 20)=2.21$, $p=0.12$). There was a significant effect for auditory source ($F(2, 40)=4.71$, $p=0.02$). Post hoc analysis revealed that metronome (34ms) conditions had significantly less RT variability than no sound (38ms) and drum (39ms) conditions. There was no significant interaction between vision and auditory source ($F(2, 40)=2.09$, $p=0.14$).

For movement time, there was a significant effect for vision ($F(1, 20)=22.21$, $p<0.01$). No vision conditions (437ms) had a significantly shorter mean MT compared to full vision conditions (458ms). There was no significant effect for auditory source ($F(2, 40)=0.91$, $p=0.41$), or vision by auditory source interaction ($F(2, 40)=0.02$, $p=0.98$).

For movement time variability (standard deviation) there were no significant effects for vision ($F(1, 20)=2.32$, $p=0.14$)), auditory source (uncorrected: $F(2, 40)=0.30$, $p=0.74$, corrected: $F(1.47, 29.49)=0.30$, $p=0.68$), or vision by auditory source interaction ($F(2, 40)=1.08$, $p=0.35$).

For peak velocity in the primary axis, there was a significant effect for vision ($F(1, 20)=23.35$, $p<0.01$) and auditory source ($F(2, 40)=3.65$, $p=0.04$). The no vision condition (1474mm/s) reached higher peak velocities compared to the vision condition (1425mm/s). Post hoc analysis with Tukey's HSD revealed that metronome condition (1429mm/s) reached lower peak velocities compared to the drum condition (1465mm/s). There was no significant interaction between vision and auditory source ($F(2, 40)=0.03$, $p=0.97$).

For peak velocity in the secondary axis, there was a significant effect for vision ($F(1, 20)=12.0$, $p=0.002$), with no vision conditions (891mm/s) reaching higher peak velocities compared to vision conditions (856mm/s). There was no significant effect for auditory source ($F(2, 40)=0.79$, $p=0.46$), or vision by auditory source interaction ($F(2, 40)=0.30$, $p=0.74$).

For the ratio of time to peak velocity to movement time, there was a significant effect for vision ($F(1, 20)=4.82$, $p=0.04$) and auditory source ($F(2, 40)=4.46$, $p=0.02$). No vision conditions (0.41) reached peak velocity significantly later in the movement compared to vision conditions (0.40). Post hoc analysis with Tukey's HSD revealed that the no sound condition (0.42) reached peak velocity significantly later in the movement time compared to the metronome (0.41) and drum (0.41) conditions. There was no significant interaction between vision and auditory source ($F(2, 40)=0.28$, $p=0.76$).

In both the primary ($F(1, 20)=71.64$, $p<0.01$) and secondary ($F(1, 20)=70.91$, $p<0.01$) axes, no vision conditions (primary: 9mm, secondary: 9mm) had significantly more endpoint variable error compared to full vision conditions (primary: 6mm, secondary: 6mm). There were no significant effects for auditory source (primary: $F(2, 40)=1.41$, $p=0.26$, secondary: $F(2, 40)=1.20$, $p=0.31$), or vision by auditory source interaction (primary: $F(2, 40)=1.06$, $p=0.35$, secondary: $F(2, 40)=1.11$, $p=0.34$).

For endpoint constant error, there was a significant effect for vision in the secondary axis ($F(1, 20)=5.64$, $p=0.03$), but not the primary axis ($F(1, 20)=1.60$, $p=0.22$). In secondary axis, no vision conditions had a larger target undershoot of -2mm compared to vision conditions (-0.3mm). There were no significant effects for auditory source (primary= uncorrected: $F(2, 40)=0.80$, $p=0.46$, corrected: $F(1.49, 29.71)=0.80$, $p=0.42$, secondary= $F(2, 40)=1.39$, $p=0.26$) or vision by auditory source interactions (primary= uncorrected: $F(2, 40)=0.10$, $p=0.90$, corrected: $F(1.50, 30.07)=0.10$, $p=0.85$, secondary= $F(2, 40)=1.42$, $p=0.25$).

For endpoint absolute error, there was a significant effect for vision in both the primary ($F(1, 20)=82.79$, $p<0.01$) and secondary ($F(1, 20)=83.04$, $p<0.01$) axes. No vision conditions (primary: 8mm, secondary: 8mm) had significantly more endpoint error compared to vision condition (primary: 5mm, secondary: 5mm). There was no significant effect for auditory source (primary= $F(2, 40)=1.05$, $p=0.36$, secondary= uncorrected: $F(2, 40)=1.02$, $p=0.37$, corrected: $F(1.32, 26.30)=1.03$, $p=0.34$), or vision by auditory source interaction (primary= $F(2, 40)=1.84$, $p=0.17$, secondary= $F(2, 40)=1.62$, $p=0.21$).

For marker trajectory variability (standard deviation) in the primary axis at 20, 40, 60, 80 and 100 percent of movement completion, there were no significant effects for vision ($F(1, 20)=0.95$, $p=0.34$) or auditory source ($F(2, 40)=1.56$, $p=0.22$). There was a significant interaction between condition and position ($F(8, 160)=9.60$, $p<0.01$). Post hoc analysis with Tukey's HSD revealed that at 20 percent of movement completion the no sound condition had less marker variability than the drum condition, at 40 and 60 percent of movement completion, the no sound, drum and metronome conditions were all significantly different from one another, with drum conditions having the most variability and no sound conditions the least. At 80 and 100 percent of movement completion, the no sound condition had significantly more marker variability compared to both the drum and metronome conditions (Figure 19).

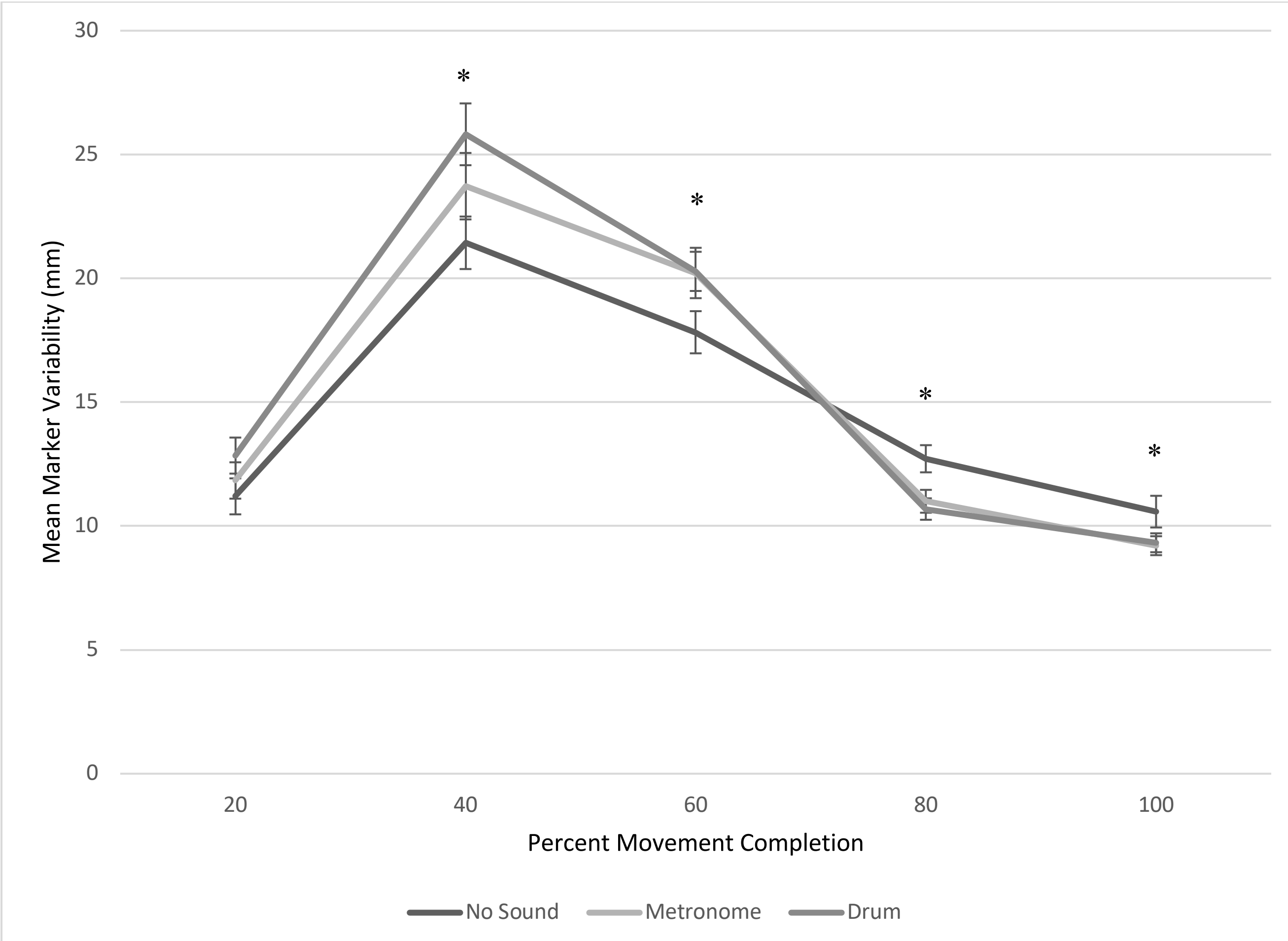


Figure 19. Marker trajectory variability in the primary axis. Interaction between auditory condition and position. Measured in millimeters. Error bars represent standard error.

There was also a significant interaction between vision and percent movement completion ($F(4, 80)=20.05$, $p<0.01$) for marker trajectory variability in the primary axis. Post hoc analysis with Tukey's HSD revealed that vision conditions had more marker variability at 40 percent of movement completion, while no vision conditions had more marker variability at 80 and 100 percent completion (Figure 20).

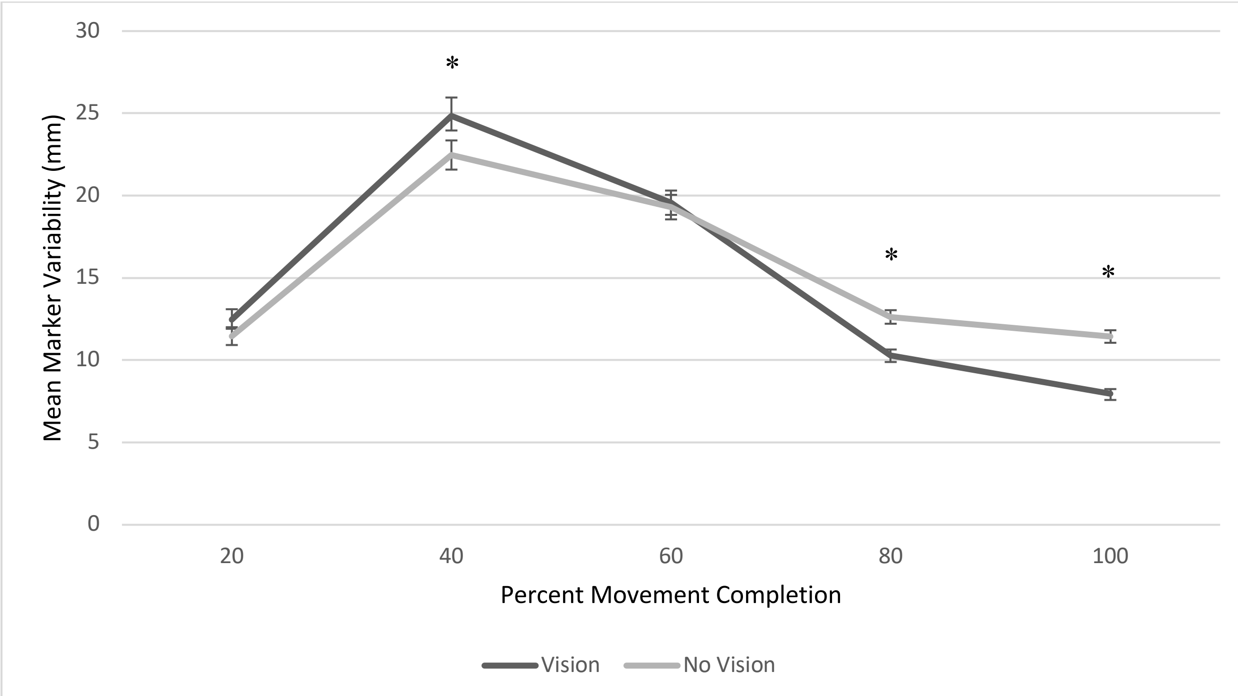


Figure 20. Mean marker trajectory in the primary axis. Interaction between vision and position. Measured in millimeters. Error bars represent standard error.

There was a three way interaction between auditory condition, vision and percent movement completion (F(8, 160)=2.37, p=0.02). Post hoc analysis with Tukey's HSD revealed that in vision conditions, at 40 percent of movement completion, the drum had more marker variability compared to both the metronome and no sound conditions, however at 80 percent of movement completion, the no sound condition had significantly more variability than both the drum and metronome conditions (Figure 21). In no vision conditions, at 40 and 60 percent of movement completion, the no sound condition had significantly less marker variability than metronome and drum conditions. At 100 percent of movement completion, the no sound condition had significantly more marker variability compared to both the metronome and drum conditions (Figure 22).

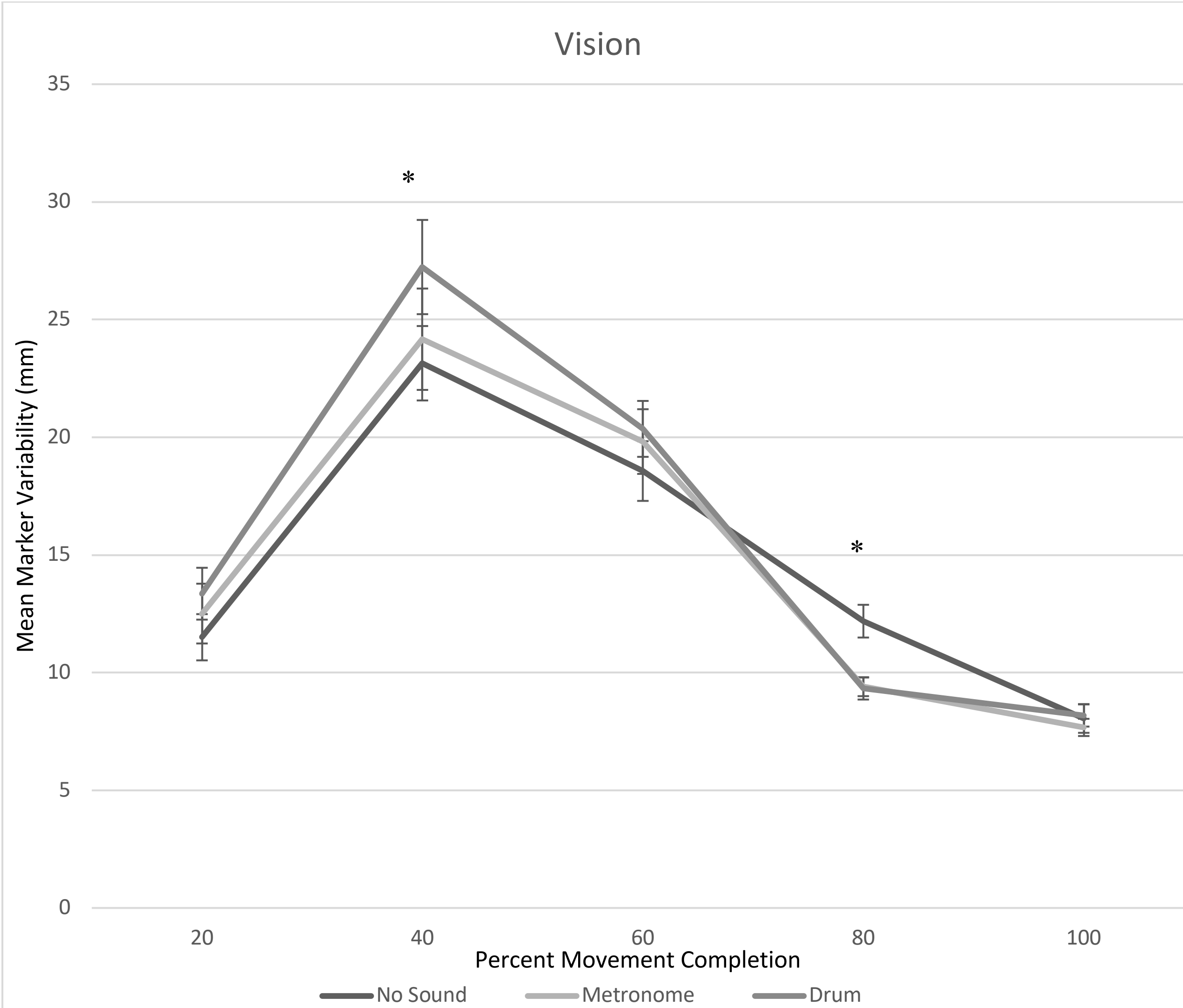


Figure 21. Mean marker variability by condition in the primary axis in vision conditions. Measured in millimeters. Error bars represent standard error.

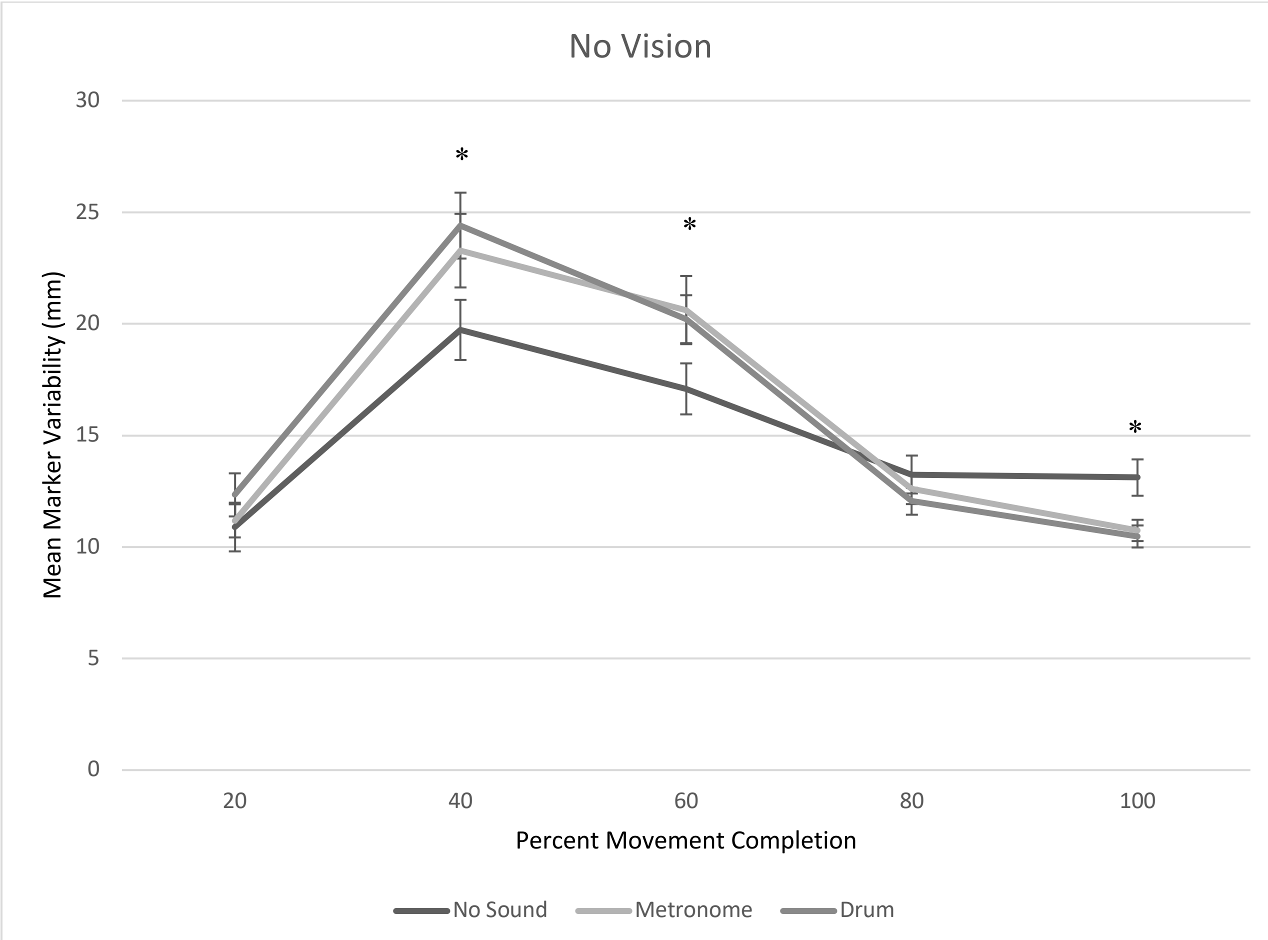


Figure 22. Mean marker variability by condition in the primary axis in no vision conditions. Measured in millimeters. Error bars represent standard error.

In the secondary axis, there was a significant interaction between vision and position ($F(4, 80)=36.26$, $p<0.01$) for marker trajectory variability at 20, 40, 60, 80 and 100 percent of movement completion. Post hoc analysis with Tukey's HSD revealed that vision conditions had significantly more marker variability at 40 and 60 percent of movement completion, while no vision conditions had more marker variability at 80 and 100 percent of movement completion (Figure 23).

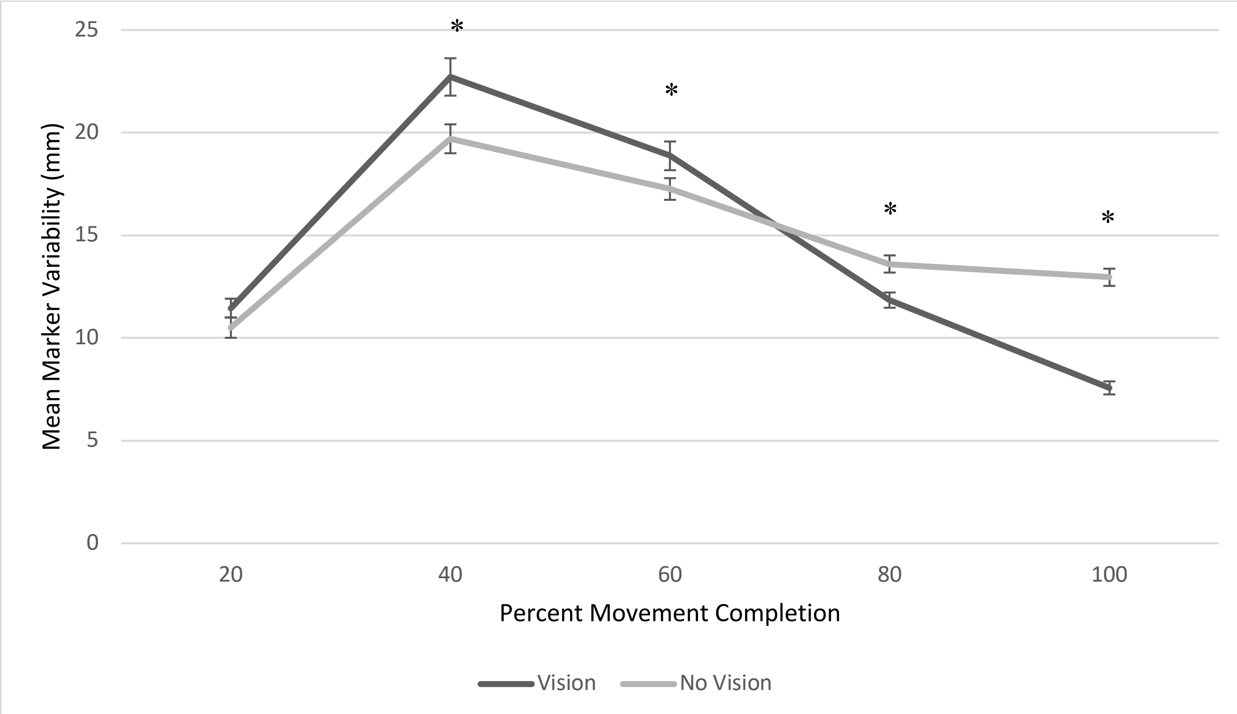


Figure 23. Mean marker variability in the secondary axis. Interaction between vision and position. Measured in millimeters. Error bars represent standard error.

For mean marker position at 20, 40, 60 80 and 100 percent of movement completion in the primary axis, there was a significant effect for vision ($F(1, 20)=4.45$, $p=0.05$), with no vision having a lower mean marker position compared to vision conditions. The main effect was superseded by an interaction between vision and position ($F(4, 80)=2.89$, $p=0.03$). Following post hoc with Tukey's HSD, there were no significant differences between auditory conditions. There was also a significant interaction between vision and position ($F(4, 80)=3.31$, $p=0.01$). Post hoc analysis with Tukey's HSD revealed that no vision conditions had a significantly lower mean marker position at 40 and 60 percent of movement completion compared to vision positions (Figure 24).

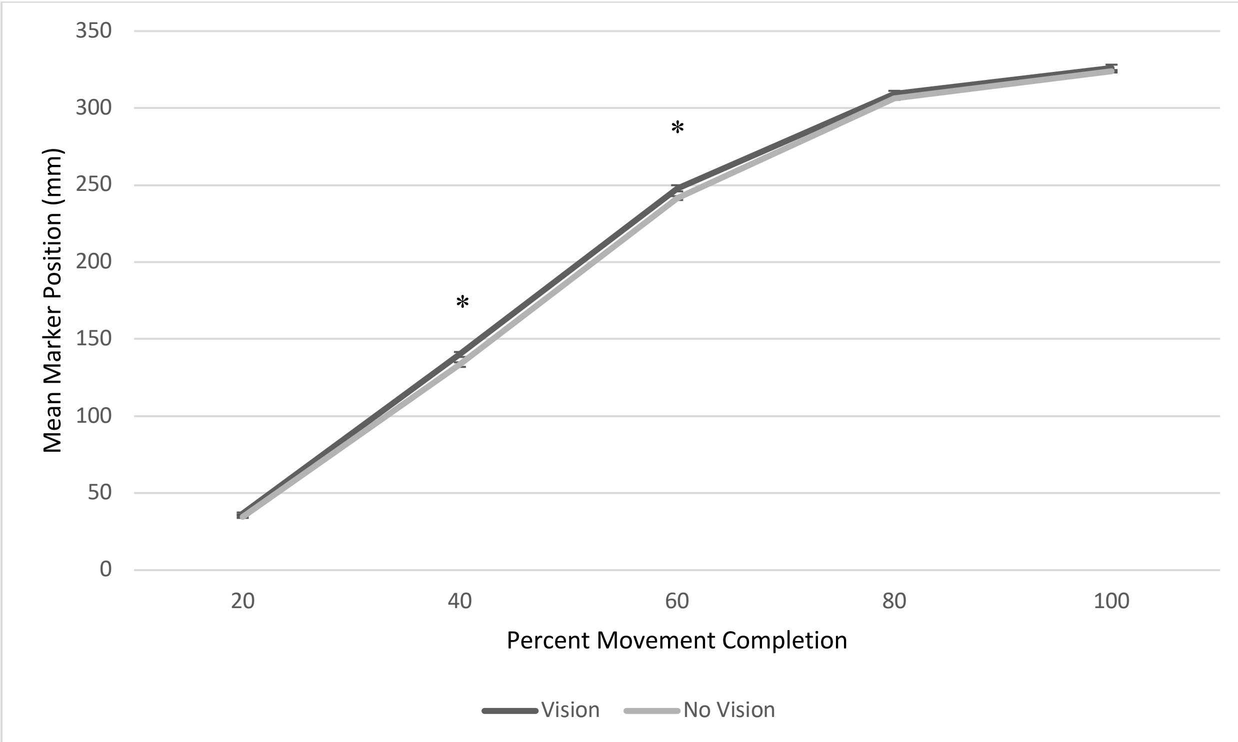


Figure 24. Mean marker position in the primary axis. Interaction between vision and position. Measured in millimeters. Error bars represent standard error.

For mean marker position in the secondary axis, there was a significant interaction between auditory source and position (percent movement completion) ($F(8, 160)=3.85$, $p<0.01$). Post hoc analysis with Tukey's HSD revealed that at 100 percent of movement completion no sound conditions had a significantly lower mean marker position compared to the metronome condition (Figure 25).

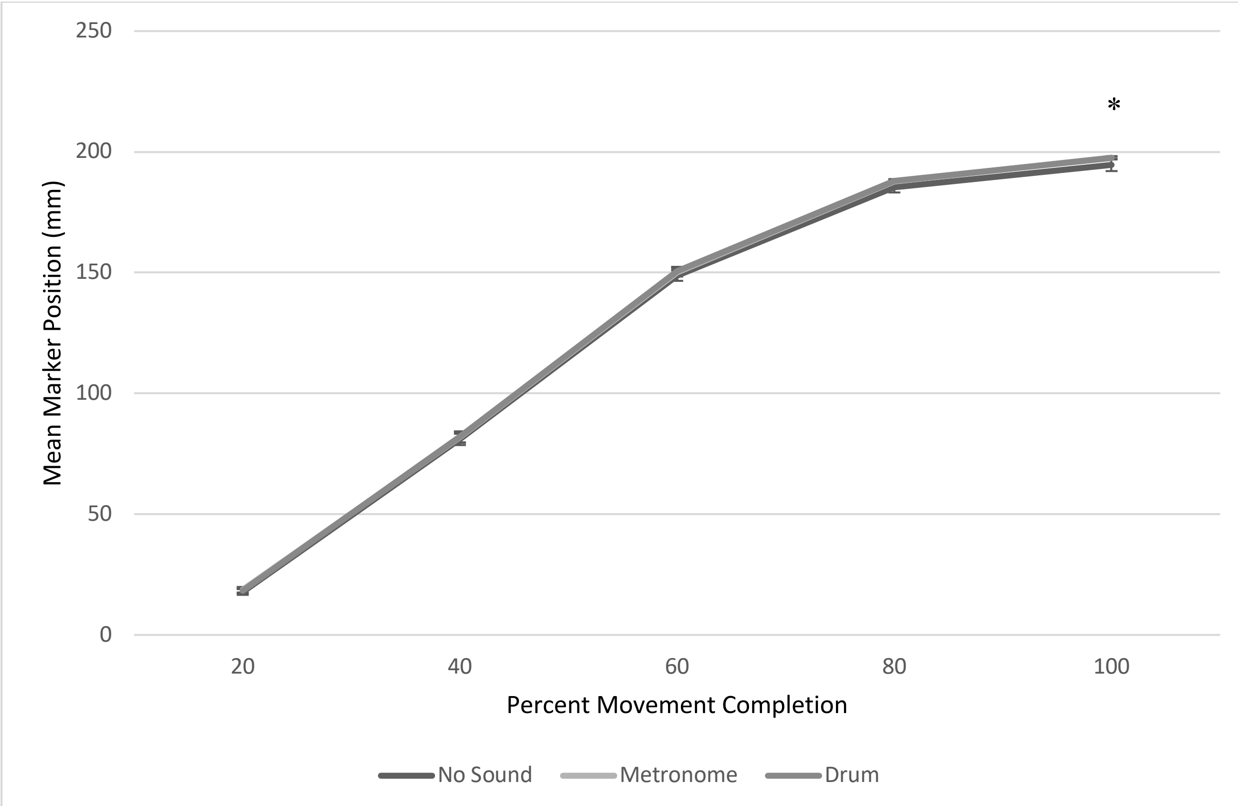


Figure 25. Mean marker position in the secondary axis. Interaction between auditory condition and position. Error bars represent standard error.

Correlations.

Spearman's correlation coefficient was calculated with the difference in Likert scores between drum and metronome conditions, and differences in performance between drum and metronome conditions. The correlation in mean reaction time between drum and metronome conditions and Likert scale ratings was -0.45, indicating a moderate negative correlation. RT variability (standard deviation) had a correlation coefficient of -0.23, representing a weak correlation. Movement time had a correlation coefficient of -0.13, representing a very weak correlation. The ratio of time to peak velocity to movement time had a correlation of 0.12, indicating a very weak correlation. Variable error in the primary axis had a correlation coefficient of 0.11, indicating a very weak correlation There were no other correlations between performance and enjoyment ratings with Spearman's correlation coefficients ranging from -0.087 to 0.082.

Discussion

This section of analysis examined the subjective ratings on the Likert scale for each auditory condition, comparisons between no sound, metronome and drum conditions, and correlations between subjective ratings and performance. Overall, participants tended to like the drum conditions over the metronome conditions. Effects for vision were consistent with existing literature and Experiment 1. There were few differences between metronome and drum conditions, however, in these conditions participants tended to perform better compared to the no sound conditions. There were also some moderate and weak correlations between performance and Likert scale ratings between the auditory conditions.

Vision.

Effects for vision were consistent with Experiment 1, rhythmic complexity results, and existing literature. In no vision conditions, reaction times were increased, while movement times were decreased. No vision conditions also reached higher peak velocities and reached them earlier in the movement compared to vision conditions. Vision conditions had less endpoint error and had less of a target undershoot in the secondary axis compared to no vision conditions. Effects of vision were also evident throughout movement trajectory with no vision conditions having more trajectory variability near the end of the movement and undershooting the movement throughout the trajectory. Results for vision support previous conclusions of the influence of vision of goal-directed reaching movements including; differences in movement planning based on the available sensory information (Elliott et al., 2010; Hansen et al., 2006;

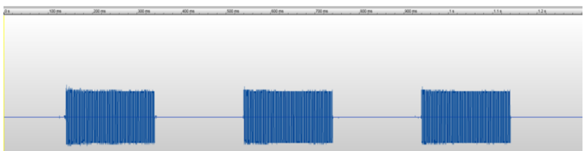
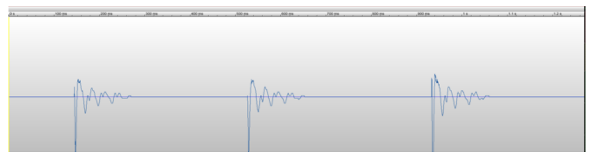
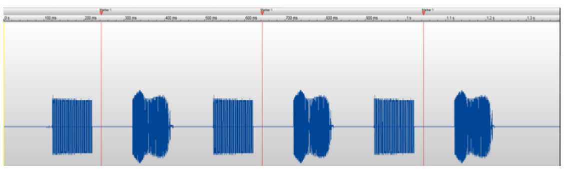
Khan, Elliott, Coull, Chua, & Lyons, 2002) and error corrections near the movement endpoint based on visual feedback (Carson et al., 1990; Chua & Elliott, 1993; Elliott et al., 2010).

Auditory Source.

Contrary to predictions, there were few significant differences between drum and metronome conditions. I expected that based on improved subjective ratings of enjoyability in drum conditions, there would be associated improvements compared to the less enjoyable metronome conditions. There were some key differences between metronome and drum conditions in RT variability, peak velocity, and movement trajectory that offer some preliminary evidence about the role of enjoyability in movement performance.

As expected, no sound conditions had longer reaction times compared to both the metronome and drum conditions. This was expected based on results from Experiment 1 and existing literature regarding the ability of an auditory stimulus to function as a precue to elicit faster reaction times (Eversheim & Bock, 2002). The metronome condition elicited less variable reaction times compared to both the drum and no sound conditions. In Experiment 1 sound before elicited less variable reaction times, and in the auditory complexity analysis there was no effect for rhythmic complexity for reaction time variability. In this experiment the metronome beat was produced by a computer, resulting in extremely precise timing intervals. The drum beat was produced by a human, and while the timing was very precise, there is some inherent variability associated with a human derived beat that may have led to increased reaction time variability. Additionally, the metronome beat has a very distinct start and stop, while the drum beat has a less finite end (Table 5).

Table 4. Auditory rhythms.

Simple Metronome 	Simple Drum 
Complex Metronome 	Complex Drum 

There were no significant effects for movement time or movement time variability. This was anticipated based on the lack of significant effects seen in Experiment 1 and the analysis for rhythmic complexity. In the primary axis, drum conditions reached higher peak velocities compared to metronome conditions. This effect was also seen in the ratio of time to peak velocity to movement time, where no sound conditions reached peak velocity significantly later in the movement compared to both metronome and drum conditions. The increased peak velocity in drum conditions and larger ratio of time to peak velocity to movement time in no sound conditions provides some evidence that the metronome heard before movement initiation impacts movement execution through changes in movement planning. Additionally, higher peak velocities in the drum condition compared to metronome and no sound conditions provides some initial evidence that different sources of auditory information elicit differences in movement planning. Reaching peak velocity earlier in the movement could be a result of changes to the initial impulse made during movement planning (McKay & Weir, 2004). Reaching peak velocity earlier in the movement also allows more time near the end of the movement to make corrections to reach the target (Chua & Elliott, 1993). Attaining peak velocity earlier in the movement is typically seen when vision is available throughout the task as participants are able to make corrections based on visual feedback (Chua & Elliott, 1993). In this experiment, participants reached peak velocity earlier in the movement when sound was heard before movement initiation, which could indicate that this additional information was influencing their ability to make error corrections later in the movement.

Paralleling the rhythmic complexity analysis, there were no effects for auditory source for endpoint error. Based on reductions in endpoint variable error with sound before movement initiation in Experiment 1, I expected to see less endpoint error in both the drum and metronome conditions compared to no sound conditions. In this protocol, 8 out of 10 experimental conditions had sound before movement initiation. With a large proportion of conditions having the sound before, it is possible that there was a learning effect across the blocks, which could have resulted in improved performance in no sound conditions if they were later in the experiment.

There was a significant effect for auditory source for trajectory variability in the primary axis. At 20, 40 and 60 percent of movement completion, the no sound condition had significantly less marker variability than metronome and drum conditions and the drum had significantly more variability than the metronome at 40 percent of movement completion. At 80 and 100 percent of movement completion, the no sound condition had more marker variability than both drum and metronome conditions. There was also a three-way interaction between auditory condition, vision and position. In no vision conditions, no sound had less trajectory variability at 40 and 60 percent of movement completion, but more variability near the movement endpoint. This provides some preliminary evidence that sound before the movement impacts movement execution, especially when vision is unavailable.

There was also an effect for auditory source for mean marker position throughout movement trajectory in the secondary axis. At 100 percent of movement completion, the no sound condition undershot the target significantly more than the metronome condition. This mirrors the effect seen in Experiment 1 where no sound conditions had significantly larger undershoots at the target endpoint and throughout movement trajectory. This could be representative of a more conservative movement strategy (Elliott et al., 1999, 2009, 2004; Engelbrecht et al., 2003; Lyons et al., 2006) in no sound conditions.

Correlation

Differences between performance in drum versus metronome conditions in terms of reaction time were moderately correlated with differences in Likert scale ratings. When participants rated the drum condition higher than the metronome condition, this correlated to faster (decreased) reaction times in drum conditions compared to metronome conditions. This provides some preliminary evidence that subjective enjoyment of an auditory stimulus can influence performance. There were other weak and very weak correlations between enjoyment and performance in reaction time variability, movement time, the ratio of time to peak velocity to movement time, and variable error in the Y axis. A follow up experiment should further examine these relationships with a larger sample size. Given the relatively small difference in enjoyability ratings between the metronome and drum conditions, it is possible that there would be a stronger correlation with auditory conditions that had a larger spectrum of enjoyability, such as music. Past experiments that have seen improved performance in response to emotion eliciting auditory information used both music and metronome conditions (Magennis et al., 2019; Park et al., 2019;

Styns et al., 2007). Future experiments should examine reaching performance with self-selected music, or distorted music to create a wider spectrum of emotion eliciting auditory information.

General Discussion

The objective of Experiment 1 was to determine when during a movement do rhythmic auditory stimuli benefit reaching performance. Participants had improved performance in terms of reaction time and endpoint error when sound was heard before movement initiation. There were also some interactions between auditory onset and vision in endpoint error, providing preliminary support that auditory information may supplement the movement plan when other sensory input is removed. Experiment 2 considered the role of rhythmic complexity and enjoyability in reaching performance. Both the complex and simple metronome conditions resulted in improved performance compared to the no sound control indicating that rhythmic complexity may not play a role in inducing performance benefits. Participants tended to like the drum beat over the metronome beat, which was moderately correlated to improved performance in reaction time.

Throughout Experiments 1 and 2 effects of vision were consistent with existing literature. No vision conditions had longer reaction times and shorter movement times compared to full vision conditions. Current literature has attributed longer reaction times in no vision conditions to participants strengthening memory representations of the target location (Hansen et al., 2006; Khan et al., 2002). In vision conditions participants had shorter reaction times, as they were able to use visual feedback to make online corrections to reach the target, in turn resulting in increased movement times (Elliott et al., 2010; Khan et al., 2002). In no vision conditions, participants may have exhibited faster movement times to prevent the decay of memory representations of the target location (Binsted et al., 2006). In the present experiments, no vision conditions had increased trajectory variability near the movement end (80 and 100% of MT), increased endpoint error, and movement undershoots throughout the trajectory. Increases in trajectory variability near the endpoint of the movement and endpoint error were expected as participants were unable to make online corrections based on visual feedback (Carson et al., 1990; Chua & Elliott, 1993). Undershoots throughout movement trajectory compared to vision conditions were expected based on time and energy conserving strategies typically seen in no vision reaching tasks (Elliott et al., 2014).

An overarching hypothesis for Experiments 1 and 2 was that when visual input was removed during movement execution, typically developing participants would rely more on the auditory information. Interactions between auditory condition and vision in endpoint absolute error and constant error in Experiment 1 provide some evidence to support this hypothesis.

In Experiment 1, movement performance improvements elicited by rhythmic auditory stimuli heard before movement initiation were evident in both spatial and temporal measures, including endpoint constant error, endpoint variable error, endpoint absolute error, mean position location and reaction time. The improvements in spatial aspects of performance contradicts the modality appropriateness hypothesis proposed by Welch & Warren (1980). Welch & Warren (1980) hypothesized that performers would weigh the importance of available sensory modalities depending on specific task requirements. While each sensory modality is capable of a range of functions (Freides, 1974), O'Connor & Hermelin (1972) hypothesize that certain modalities are best suited to specific characteristics of a movement. For example, vision is best suited to controlling spatial characteristics, while audition is best suited to control temporal aspects (O'Connor & Hermelin, 1972). In the present experiment, the inclusion of auditory information impacted a spatial outcome, which contrasts with the modality appropriateness hypothesis. In the following section two possible reasons for this discrepancy are suggested.

The inclusion of rhythmic auditory stimuli may have encouraged participants to use an external focus of attention, which has consistently been found to result in improved performance (Wulf, 2007, 2013; Wulf, Höß, & Prinz, 1998; Wulf, Shea, & Park, 2001b). There is consistent research that shows improved performance on motor tasks when participants adopt an external focus of attention (Wulf, 2007). Additionally, the auditory information heard before movement initiation could encourage performers to sustain attention to the visual target, resulting in reaction time benefits (Eversheim & Bock, 2002). The directed attention hypothesis proposed by Welch & Warren (1980) suggests that auditory information may be more attention eliciting than visual stimuli. With this hypothesis in mind, it is reasonable to assume that the auditory stimulus may have had attention capturing properties, instigating an external focus of attention, and in turn eliciting performance improvements. Davis & Green (1969) hypothesize that improvements in RT with auditory warning signals could be the result of faster central arrival compared to vision. In the experiment by Whitall et al., (2000) the authors hypothesized that the auditory cue elicited performance improvements in part, by functioning as an attentional cue (Whitall & Waller, 2013). In addition to eliciting an external focus of attention, auditory information heard before movement initiation could allow the performer to engage in some movement planning earlier, in turn saving time during before movement initiation (Rosenbaum, 1980). This effect is evident in terms of the observed reaction time benefit; however one hypothesis is that improved temporal stability of the movement plan, resulted in improvements in movement execution, evidenced by improvements in endpoint consistency.

Another possible explanation is that the auditory information heard before movement initiation increased the temporal stability of the movement plan, resulting in improved movement execution. The multiple-process model of limb control proposes that goal-directed movements are controlled by an initial ballistic movement and overlapping methods of online control (Elliott et al., 2010). There is inherent variability associated with the initial submovement due to noise in the motor system and errors in motor recruitment associated with increased force (Schmidt et al., 1979). The auditory information before movement initiation may have benefited performance in terms of endpoint error by reducing the inherent temporal variability associated with the movement plan. Additionally, having auditory information before movement initiation may have allowed participants to dedicate less attentional resources on anticipating the go signal and more resources on the targets, reducing endpoint error.

Based on the hypothesis from Experiment 1 that rhythmic auditory stimuli improve reaching performance due to improved temporal stability of the movement, I predicted that increasing rhythmic complexity would result in improved performance. In Experiment 2, both simple and complex metronome conditions outperformed the no sound control, however there were no significant differences between metronome complexities. The lack performance differences between conditions could be a result of a ceiling effect, where any rhythmic auditory information prior to movement initiation is able to act as a precue (Eversheim & Bock, 2002). It is possible that any amount of rhythmic auditory information provides the performer with enough additional information to elicit performance benefits.

The lack of significant effect for rhythmic complexity may also support the attention eliciting hypothesis, that the rhythmic auditory stimuli elicit an external focus of attention, which in turn results in performance improvements (Wulf, 2007). Sound heard before movement initiation may also encourage participants to pay increased attention to the target and the imminent go signal, which could result in improved performance by solidifying memory representations (Binsted et al., 2006).

Overall, drum conditions were rated higher than metronome conditions, however this was only moderately correlated to improved performance in reaction time. This provides some preliminary evidence that more enjoyable rhythmic auditory stimuli may contribute to improved performance. Existing literature has found performance improvements in gait with music compared to metronome conditions (Wittwer et al., 2013), smoother gait kinematics with stimuli that elicit anger and joy (Kang & Gross, 2015, 2016), increased gait velocity associated with subjective ratings of musical enjoyment in people with Parkinson's Disease (Park et al., 2019)and, smoother circle tracing with pleasant and unpleasant auditory information (Magennis et al., 2019). Some of these experiments used music to induce an emotional response (Park et al., 2019; Wittwer et al., 2013), which could explain why they found more significant effects for improved performance with different emotion eliciting stimuli. Salimpoor, Benovoy, Larcher, Dagher, & Zatorre, (2011) examined dopamine release in response to musical enjoyment, which could mediate improved performance. Considering the full spectrum of sources of rhythmic auditory information, from a simple metronome to a complex piece of music, the difference in enjoyability between a metronome beat and a drum beat is relatively small. Despite this, there was still a moderate correlation between enjoyability and performance in terms of reaction time.

Implications

Experiments 1 and 2 help inform current models of movement control and provide insight into the features of rhythmic auditory stimuli that should be considered in a rehabilitation context.

Results from Experiment 1 demonstrate that sound heard before movement initiation may contribute to improved movement planning resulting in improved movement execution (Elliott et al., 2010). In these conditions participants had visual and auditory information during movement planning, which resulted in improved performance in temporal and spatial outcomes. In Experiment 1 when visual input was removed during movement execution, inclusion of rhythmic auditory stimuli before movement initiation resulted in improved endpoint error. This provides some preliminary evidence that auditory information can supplement the motor system when visual input is removed.

Results from the rhythmic complexity analysis in Experiment 2 did not provide explicit support for improved movement planning, due to the lack of performance improvements with more precise temporal intervals. This lends some support towards changes in attentional focus, which may result in performance benefits (Wulf, 2007). Experiment 2 offered some preliminary evidence that subjective enjoyability of auditory information may benefit reaching performance.

Results from Experiments 1 and 2 provide some preliminary support for the Optimal Theory of Motor Learning (Wulf & Lewthwaite, 2016) which postulates that external foci of attention, increased motivation, and autonomy supporting paradigms support motor learning and control. Future work could consider the role of autonomy and motivation in the selection of rhythmic auditory stimuli to cue reaching movements.

Rhythmic auditory cueing has been investigated as a tool to facilitate performance improvements in populations with sensorimotor impairments (Johansson et al., 2012; Johansson et al., 2014; Ladwig et al., 2016; Thaut et al., 2002; Whitall & Waller, 2013; Whitall et al., 2000). Experiment 1 demonstrates that rhythm can elicit performance improvements when heard before a goal-directed reaching movement. Experiment 2 provides some evidence that practitioners should consider the source of the auditory information and customize the source to the participants likes and dislikes. This set of experiments tested typically developing adults, more work should be done in populations with sensorimotor impairments.

Future Directions

Future projects could further examine the role of rhythmic auditory stimuli during movement panning by altering visual feedback during movement planning rather than movement execution. The current project manipulated vision during movement execution, so it is possible that participants may use auditory information more when vision is altered in movement planning. For example, one could use a prism distortion to alter visual input during movement planning to see if participants may rely more on auditory information when visual input is altered during movement planning.

Given the use of music as a rhythmic auditory stimulus in existing literature, another experiment could consider a wider spectrum of types of rhythmic auditory information, including music. This would provide a wider array of subjective enjoyment ratings to examine how enjoyability impacts motor performance. This experiment could also have participants self-select music and use a yoked design to consider motivational contributions to reaching performance.

To differentiate between performance benefits due to improved temporal stability of the movement plan and enhanced attentional foci, a future project could compare performance with rhythmic auditory stimuli to non-rhythmic auditory stimuli. This experiment could parse out whether it is the rhythmic information or attention eliciting properties that benefit performance.

The current project considered evidence from populations with sensorimotor impairments and tested typically developing individuals with and without vision to create a controlled model of reduced sensory feedback. Future projects should test populations with sensorimotor impairments such as stroke and cerebral palsy to see whether effects of rhythmic auditory stimuli are consistent in these populations.

Limitations

When interpreting results from this project, it is important to consider the experimental limitations. In the sound during condition of Experiment 1, participants heard three metronome beats during movement execution. However, due to short movement times it is possible that participants did not hear the full rhythm before they reached the target. While participants would have heard at least two beats during the movement, there is significant debate as to whether that would constitute as a rhythm.

As previously mentioned, considering the large spectrum of enjoyability of rhythmic auditory information, Experiment 2 implemented a relatively narrow sample. This may explain why there were few correlations between subjective ratings of enjoyment and movement performance.

The current experiment aimed to create a model of disrupted sensory feedback by occluding vision during movement execution. Coupled with sound before movement initiation, this experimental design essentially created a situation where participants had the most amount of sensory information during movement planning. This may have influenced interactions between the vision and auditory conditions. While there were performance benefits when sound was heard before movement initiation, by uncoupling vision and audition during movement planning, it may be possible to further parse out the impact of rhythmic auditory information on movement planning.

Conclusion

The present thesis investigated features of rhythmic auditory stimuli that contribute to reaching performance improvements in a typically developing adult population. Experiment 1 found that sound before a movement benefits reaching performance in terms of reaction time and endpoint error. Experiment 2 examined different complexities and sources of rhythmic auditory stimuli and found that both simple and complex rhythms elicited performance improvements, and that participants tended to like the drum beat more than the metronome, which was moderately correlated to improved performance in reaction time. Improved movement planning and attentional foci are considered in their role in facilitating performance improvements, however future work should further examine their contributions. Overall, rhythmic auditory stimuli have the potential to benefit reaching performance when heard before reaching initiation, and there is preliminary evidence that the auditory source and subjective enjoyability have the potential to benefit performance.

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Appendix A

INFORMED CONSENT – Matched Group

Exploring Rhythm and Reach-Ability in adults with and without Cerebral Palsy

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

PURPOSE: We are interested in learning how individuals with and without Cerebral Palsy plan and execute reaching movements of varying complexities, and how their posture may or may not be impacted by the movement.

DESCRIPTION: During the study, you will be asked to make a series of pointing movements to target in front of you. An OPTOTRAK 3-D motion analysis system will be used to record your shoulder, arm, and hand movements of both arms. In some conditions, you will have full vision throughout the movement, while in others vision will be occluded for a portion of the movement with visual occlusion glasses. Prior to this task, you will be asked to fill out a brief demographics questionnaire that inquires about your age, gender, handedness, whether or not your vision and hearing are corrected (glasses, contact lenses, hearing aids), as well as the Waterloo Handedness Questionnaire. After each experimental condition, you will be asked to respond to a question, to scale how much you enjoyed the sound that you heard. The whole procedure will take 30-60 minutes to complete.

RISKS AND BENEFITS: There are minimal risks to taking part in this study (similar to everyday activities). The tasks you will perform may become repetitive and you may experience boredom and/or mild muscle fatigue in your arms. While this may be frustrating, the investigator with you will provide breaks throughout and you may request a break at anytime.

Your participation in this study will help us discover ways in which participants with cerebral palsy might use an external rhythm to improve control of arm movement, as well as broaden our understanding and perspective of how multisensory-motor integration changes with task difficulty.

COSTS AND PAYMENTS: There are no fees or charges to participate in this study. You will receive a Tim Hortens gift card thank you for donating your time. The amount will be proportional to the time duration of the study. Specifically, ten dollars per hour, rounded up to the nearest half hour. For example, if the protocol is 60 minutes then you will receive a $10 gift card.

CONFIDENTIALITY: Your information will be kept confidential. Once you begin the study your name, information, and results will be referred to by a code number. All files containing identifying information will be stored in a locked cabinet separate from data with your code number. Your files will only be accessible by the investigators and will be destroyed by Dr. Glazebrook seven years after the completion of the study (approximately June, 2025). As PI for the project Dr. Glazebrook may be present during testing in order to assist with the data collection process. All papers containing personal information will be shredded. All electronic files will be deleted. Any CDs or DVDs containing data will be physically destroyed. Only Dr. Cheryl Glazebrook and the student research assistants listed will have access to any lists that contain identifying information.

Results will be presented at academic conferences, invited presentations, and published in peer-reviewed academic journals. In almost all cases only group averages will be presented. In some cases a drawing of an individual movement path will be presented. This data contains no identifiable information and therefore your anonymity will be maintained.

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

VOLUNTARY CONSENT: If the participant *does not wish to participate* in the study or wishes withdraw from the study, you are free to leave without consequence at any point in time and we thank you for your consideration. If a person changes their mind and wishes to withdraw from the study they may do so by telling the researcher or by contacting Carrie Peters by email (petersc9@myumanitoba.ca) or phone (204-480-1487) to let her know that they no longer wish to participate. The participant can tell the researcher if they wish for any existing data to be included in the study or destroyed.

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

A copy of this consent form has been given to you to keep for your records and reference.
This research has been approved by the Education/Nursing Research Ethics Board. If you have any concerns or complaints about this project you may contact any of the above named persons or the Human Ethics Coordinator (HEC) 474-7122 or humanethics@umanitoba.ca.

INFORMED CONSENT – Matched Group

Research Study: Exploring Rhythm and Reach-Ability in adults with and without Cerebral Palsy

Signature of Participant____ Date ____________

Researcher/ Delegate's Signature __________________________________Date ___________

SUMMARY OF FINDINGS: Would you like to be contacted by a student research assistant with a summary of the overall findings of this study? ☐ YES ☐ NO
If yes, please complete the following:
Name: ____
Phone Number: ____
Email Address: ____

Appendix B

Demographics Questionnaire (matched group)

Participant Number: ______________________________

Age of Participant: _____________ Gender (check one): Male ☐ Female ☐

Dominant Hand (check one): Right ☐ Left ☐

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

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

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

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

Yes ☐ No ☐

Appendix C
Field Notes

Participant ID:					
Date:					
NDI Session Number:					
E-Prime Subject Number:					
Condition Order					
	Trial Number	Observation		Trial	Observation
Aiming Trials					
Home Position	1				
Left Target	2				
Right Target	3				
Collection Trials					
E-Prime Session Number:					
	4			35	
	5			36	
	6			37	
	7			38	
	8			39	
	9			40	
	10			41	
	11			42	
	12			43	
	13			44	
	14			45	
	15			46	
	16			47	
	17			48	
	18			49	
	19			50	
	20			51	
	21			52	
	22			53	
	23			54	
	24			55	
	25			56	
	26			57	
	27			58	
	28			59	
	29			60	
	30			61	
	31			62	
	32			63	
	33			64	
	34			65	

Condition:					
E-Prime Session Number:					
	Trial Number	Observation	Trial Number	Observation	
	66		108		
	67		109		
	68		110		
	69		111		
	70		112		
	71		113		
	72		114		
	73		115		
	74		116		
	75		117		
	76		118		
	77		119		
	78		120		
	79		121		
	80		122		
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	82		124		
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	93		135		
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	95		137		
	96		138		
	97		139		
	98		140		
	99		141		
	100		142		
	101		143		
	102		144		
	103		145		
	104		146		
	105		147		
	106		148		
	107		149		
	Other Notes:				

	Condition:				
	E-Prime Session Number:				
		Trial Number	Observation	Trial Number	Observation
		150		192	
		151		193	
		152		194	
		153		195	
		154		196	
		155		197	
		156		198	
		157		199	
		158		200	
		159		201	
		160		202	
		161		203	
		162		204	
		163		205	
		164		206	
		165		207	
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		170		212	
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		182		224	
		183		225	
		184		226	
		185		227	
		186		228	
		187		229	
		188		230	
		189		231	
		190		232	
		191		233	
		Other Notes:			

Appendix D
Likert Scale

Participant Number_________________
Please rate how much you liked the sound during the last condition (circle one).

Condition ___________________

Very Unpleasant	Somewhat Unpleasant	Neutral	Somewhat Pleasant	Very Pleasant

Condition ___________________

Very Unpleasant	Somewhat Unpleasant	Neutral	Somewhat Pleasant	Very Pleasant

Condition ___________________

Very Unpleasant	Somewhat Unpleasant	Neutral	Somewhat Pleasant	Very Pleasant

Condition ___________________

Very Unpleasant	Somewhat Unpleasant	Neutral	Somewhat Pleasant	Very Pleasant

Condition ___________________

Very Unpleasant	Somewhat Unpleasant	Neutral	Somewhat Pleasant	Very Pleasant

Condition ___________________

Very Unpleasant	Somewhat Unpleasant	Neutral	Somewhat Pleasant	Very Pleasant

Condition ___________________

Very Unpleasant	Somewhat Unpleasant	Neutral	Somewhat Pleasant	Very Pleasant

Condition ___________________

Very Unpleasant	Somewhat Unpleasant	Neutral	Somewhat Pleasant	Very Pleasant

Appendix E
Summary Tables – Experiment 1

Reaction Time (ms)

Participant	NoSound		SoundBefore		SoundDuring		Sound Throughout	
	Vision	NoVision	Vision	NoVision	Vision	NoVision	Vision	NoVision
P01	412	485	288	300	397	413	321	332
P02	302	298	231	244	305	279	205	257
P04	279	274	226	229	301	308	247	276
P05	263	292	257	278	258	267	235	272
P06	316	343	261	246	316	353	289	275
P07	357	364	213	238	351	328	190	223
P08	293	307	250	237	312	303	215	248
P10	246	278	208	218	267	260	190	220
P11	350	430	261	367	373	375	271	369
P12	288	357	245	268	328	349	219	252
P13	404	417	254	257	354	386	264	278
P14	305	382	216	239	392	389	295	274
P15	278	329	197	210	251	289	172	185
P16	467	438	272	355	357	442	264	342
P17	336	319	215	254	325	354	210	217
P18	297	298	220	270	299	289	263	292
P19	275	290	229	223	290	296	232	278
P20	264	256	192	215	241	271	223	198
P21	261	261	204	212	285	295	218	190
P22	252	238	204	236	256	229	182	177
P23	321	309	227	293	326	361	233	224

	Degrees of Freedom	F	p	Partial eta-squared
Auditory Condition	3	66.3963	*0.000000	0.768509
Error	60			
Vision	1	24.4449	*0.000078149	0.550005
Error	20			

A.C * Vis.	3	0.7132	0.547945	0.034432
Error	60			

Reaction Time Variability (SD) (ms)

	NoSound		**SoundBefore**		**SoundDuring**		**Sound Throughout**	
Participant	**Vision**	**NoVision**	**Vision**	**NoVision**	**Vision**	**NoVision**	**Vision**	**NoVision**
P01	57	61	52	27	62	59	51	36
P02	44	40	31	29	55	52	26	37
P04	24	36	22	26	45	37	29	33
P05	19	27	29	30	34	39	28	30
P06	39	41	42	26	41	45	56	50
P07	45	44	18	49	54	50	26	35
P08	31	42	34	41	46	65	36	31
P10	22	29	26	28	25	20	17	32
P11	32	68	31	80	36	62	39	56
P12	31	43	29	49	36	39	28	27
P13	34	61	27	41	71	93	34	36
P14	56	41	29	40	101	68	83	57
P15	27	42	43	31	35	39	30	31
P16	86	78	53	91	67	81	65	98
P17	41	40	15	24	53	31	20	36
P18	44	47	25	39	40	48	45	46
P19	23	28	18	28	34	41	35	45
P20	23	25	16	34	35	28	38	22
P21	19	25	20	21	43	35	23	36
P22	21	19	28	21	34	26	38	28
P23	44	44	25	67	42	88	47	50

	Degrees of Freedom	**F**	**p**	**Partial eta-squared**
Auditory Condition	3	11.0111	*0.0000007	0.355070
Error	60			
Vision	1	5.0388	*0.0362550	0.201239
Error	20			
A.C * Vis.	3	1.5217	0.218071	0.070706

Error	60			

Movement Time (ms)

	NoSound		SoundBefore		SoundDuring		Sound Throughout	
Participant	**Vision**	**NoVision**	**Vision**	**NoVision**	**Vision**	**NoVision**	**Vision**	**NoVision**
P01	760	714	727	712	737	762	820	798
P02	531	487	519	505	483	501	498	497
P04	491	487	484	486	531	490	499	474
P05	493	483	523	478	449	477	433	465
P06	564	584	559	573	534	576	544	642
P07	659	700	641	661	653	673	657	613
P08	603	621	593	606	600	647	595	643
P10	516	532	503	489	529	498	521	526
P11	506	512	528	485	484	521	504	483
P12	595	460	540	512	547	498	554	503
P13	544	438	567	492	486	505	500	463
P14	545	521	551	525	521	556	512	518
P15	420	381	423	431	468	424	495	425
P16	462	447	482	394	447	402	462	394
P17	509	479	456	435	461	467	461	444
P18	417	422	406	435	418	422	467	437
P19	453	413	449	471	440	473	456	491
P20	442	321	398	349	444	378	409	342
P21	563	554	632	502	600	460	612	519
P22	494	460	512	478	511	440	500	463
P23	391	356	335	377	381	377	345	366

	Degrees of Freedom	**F**	**p**	**Partial eta-squared**
Auditory Condition	3	0.1254	0.944715	0.006232
Error	60			
Vision	1	5.7220	*0.026690	0.222454
Error	20			
A.C * Vis.	3	1.2258	0.308218	0.057750
Error	60			

Movement Time Variability (SD) (ms)

	NoSound		SoundBefore		SoundDuring		Sound Throughout	
	Vision	NoVision	Vision	NoVision	Vision	NoVision	Vision	NoVision
P01	84	73	70	66	66	64	85	42
P02	64	66	53	77	54	71	50	85
P04	38	45	44	43	47	52	41	38
P05	67	54	50	70	48	94	46	71
P06	47	101	65	93	79	88	78	94
P07	60	74	48	76	73	83	57	86
P08	51	64	28	39	46	41	41	59
P10	58	51	50	56	55	56	49	56
P11	62	56	40	67	69	57	45	70
P12	61	61	74	72	81	91	73	62
P13	53	40	70	47	42	46	53	47
P14	84	74	92	79	63	65	84	62
P15	31	33	51	42	59	36	60	43
P16	44	68	50	34	61	49	58	35
P17	46	38	43	34	44	43	62	30
P18	34	40	54	46	38	44	53	45
P19	42	45	39	35	56	29	36	42
P20	40	26	41	28	33	40	26	23
P21	55	55	48	50	62	40	58	69
P22	53	58	46	58	48	53	45	52
P23	49	43	42	35	42	48	45	52

	Degrees of Freedom	F	p	Partial eta-squared
Auditory Condition	3	0.6411	0.591588	0.031057
Error	60			
Vision	1	0.3593	0.555650	0.017646
Error	20			
A.C * Vis.	3	0.0469	0.986410	0.002339
Error	60			

Ratio of time to peak velocity to movement time

	NoSound		SoundBefore		SoundDuring		Sound Throughout	
	Vision	NoVision	Vision	NoVision	Vision	NoVision	Vision	NoVision
P01	0.34	0.36	0.36	0.36	0.37	0.35	0.36	0.39
P02	0.37	0.38	0.34	0.34	0.35	0.36	0.33	0.34
P04	0.34	0.31	0.32	0.33	0.31	0.32	0.32	0.34
P05	0.32	0.29	0.32	0.28	0.29	0.27	0.29	0.29
P06	0.36	0.30	0.35	0.33	0.32	0.30	0.33	0.30
P07	0.38	0.37	0.42	0.39	0.41	0.36	0.41	0.40
P08	0.36	0.31	0.27	0.28	0.31	0.31	0.30	0.29
P10	0.32	0.30	0.30	0.24	0.34	0.31	0.31	0.28
P11	0.33	0.28	0.31	0.33	0.27	0.34	0.29	0.27
P12	0.33	0.29	0.30	0.32	0.31	0.32	0.29	0.35
P13	0.40	0.41	0.43	0.44	0.41	0.49	0.41	0.41
P14	0.37	0.43	0.41	0.40	0.43	0.38	0.43	0.40
P15	0.43	0.44	0.38	0.34	0.41	0.41	0.43	0.38
P16	0.36	0.42	0.38	0.38	0.40	0.39	0.40	0.40
P17	0.34	0.38	0.34	0.36	0.35	0.34	0.36	0.37
P18	0.42	0.44	0.38	0.40	0.39	0.40	0.38	0.42
P19	0.45	0.41	0.46	0.44	0.40	0.43	0.44	0.43
P20	0.33	0.37	0.34	0.36	0.28	0.34	0.30	0.34
P21	0.44	0.50	0.41	0.44	0.41	0.46	0.41	0.44
P22	0.40	0.43	0.34	0.38	0.39	0.44	0.39	0.45
P23	0.43	0.39	0.39	0.39	0.37	0.40	0.39	0.39

	Degrees of Freedom	F	p	Partial eta-squared
Auditory Condition	3	2.291	0.087332	0.102769
Error	60			
Vision	1	0.511	0.482874	0.024924
Error	20			
A.C * Vis.	3	0.742	0.531431	0.035755
Error	60			

Peak Velocity – Primary Axis (mm/s)

Y	NoSound		SoundBefore		SoundDuring		Sound Throughout	
	Vision	**NoVision**	**Vision**	**NoVision**	**Vision**	**NoVision**	**Vision**	**NoVision**
P01	1004	974	998	994	978	1004	897	842
P02	1561	1631	1518	1570	1706	1692	1572	1667
P04	1705	1706	1681	1696	1665	1749	1702	1763
P05	1614	1881	1468	2031	2067	2135	2155	1906
P06	1556	1671	1410	1586	1639	1663	1617	1607
P07	1091	1072	1004	1032	1059	1108	1032	1136
P08	1293	1288	1329	1371	1331	1309	1285	1347
P10	1530	1613	1725	1797	1509	1698	1607	1680
P11	1619	1576	1401	1729	1710	1554	1525	1691
P12	1345	1684	1466	1542	1431	1551	1423	1472
P13	1281	1320	1222	1334	1278	1212	1319	1381
P14	1204	1230	1323	1208	1386	1062	1330	1221
P15	1390	1549	1501	1480	1306	1447	1275	1451
P16	1369	1368	1314	1539	1433	1597	1358	1566
P17	1287	1238	1375	1336	1314	1295	1306	1348
P18	1377	1401	1520	1387	1373	1393	1336	1349
P19	1319	1418	1340	1304	1409	1265	1286	1270
P20	1330	1652	1437	1516	1372	1511	1449	1569
P21	1189	1176	1067	1252	1224	1338	1150	1213
P22	1201	1262	1139	1201	1263	1283	1266	1306
P23	1621	1787	1912	1636	1608	1703	1862	1768

	Degrees of Freedom	**F**	**p**	**Partial eta-squared**
Auditory Condition	3	0.9525	0.421125	0.045459
Error	60			
Vision	1	9.7475	*0.00536881	0.327674
Error	20			
A.C * Vis.	3	0.8112	0.492687	0.038977
Error	60			

Peak Velocity – Secondary Axis (mm/s)

X	NoSound		SoundBefore		SoundDuring		Sound Throughout	
	Vision	**NoVision**	**Vision**	**NoVision**	**Vision**	**NoVision**	**Vision**	**NoVision**
P01	508	534	544	575	567	571	508	500
P02	882	925	879	980	1013	937	891	975
P04	1024	1094	988	1039	1035	1075	1001	1108
P05	1082	1143	972	1128	1157	1334	1178	1056
P06	857	994	862	955	989	1013	942	971
P07	667	646	633	652	645	686	629	696
P08	719	754	711	731	733	727	648	719
P10	1036	988	1028	1084	939	1028	945	1100
P11	974	912	911	1099	992	974	940	968
P12	814	957	872	920	830	896	843	890
P13	674	741	547	746	685	600	715	735
P14	723	724	817	676	772	583	815	708
P15	923	1004	922	875	836	879	815	919
P16	911	882	854	1041	958	1000	873	989
P17	828	747	862	867	852	834	864	848
P18	957	921	942	898	923	911	860	857
P19	730	870	780	727	820	784	766	799
P20	881	1036	1002	961	876	1070	936	1093
P21	717	714	637	788	738	848	647	705
P22	849	856	834	897	809	887	862	817
P23	1016	1126	1224	1043	1005	1090	1166	1057

	Degrees of Freedom	F	p	Partial eta-squared
Auditory Condition	3	0.6147	0.608122	0.029820
Error	60			
Vision	1	10.1046	*0.00471927	0.335649
Error	20			
A.C * Vis.	3	0.1323	0.940503	0.006569
Error	60			

Endpoint Constant Error – Primary Axis (mm)

Y	NoSound		SoundBefore		SoundDuring		Sound Throughout	
	Vision	NoVision	Vision	NoVision	Vision	NoVision	Vision	NoVision
P01	0.7	5.8	1.0	3.3	1.6	4.7	1.7	2.4
P02	0.9	0.0	-1.4	-5.9	-0.1	-2.9	-0.9	-2.9
P04	0.1	-0.7	1.1	1.5	-0.5	1.8	0.9	-0.4
P05	1.3	3.9	-1.4	-1.7	-0.8	0.6	-1.1	0.2
P06	-2.7	0.1	-1.9	0.8	-1.1	-2.1	-0.7	1.1
P07	2.5	2.3	-1.2	2.1	-1.0	6.8	-0.5	2.4
P08	1.5	-2.3	1.7	2.9	2.2	3.2	2.6	-0.2
P10	-0.1	2.9	-0.3	0.4	0.4	1.1	-0.6	5.1
P11	-3.2	1.3	2.0	1.5	-1.0	2.1	0.1	-0.4
P12	1.3	3.7	0.5	1.6	1.4	1.5	0.9	1.9
P13	-5.5	-4.4	-3.5	-1.0	-4.1	-8.7	-1.6	-2.8
P14	2.7	7.3	1.4	1.6	1.7	-0.5	-0.5	-2.4
P15	-0.3	-3.7	-1.2	1.7	-0.2	1.3	-2.9	-3.7
P16	-1.6	-1.6	-3.3	-1.3	-3.4	-1.3	1.0	0.2
P17	0.2	-2.1	1.2	-1.7	-0.6	4.3	2.0	-1.6
P18	-0.1	-5.4	0.2	-1.3	1.7	-0.2	-2.0	1.1
P19	2.5	4.5	5.8	4.7	2.6	1.1	2.5	0.8
P20	-3.4	-1.0	-2.4	-2.2	-1.0	-1.9	-2.1	-1.8
P21	-1.7	1.2	-0.2	0.6	-0.2	-0.5	-1.9	-0.6
P22	0.7	2.5	1.6	-3.7	2.5	-3.3	1.9	1.4
P23	-0.4	-1.5	-1.0	2.7	-0.5	-4.0	-3.6	0.0

	Degrees of Freedom	F	p	Partial eta-squared
Auditory Condition	3	0.187200	0.904710	0.009273
Error	60			
Vision	1	1.240919	0.278503	0.058421
Error	20			
A.C * Vis.	3	0.287393	0.834317	0.014166
Error	60			

Endpoint Constant Error – Secondary Axis (mm)

X	NoSound		SoundBefore		SoundDuring		Sound Throughout	
	Vision	NoVision	Vision	NoVision	Vision	NoVision	Vision	NoVision
P01	0.9	-5.2	1.7	-2.5	1.0	1.4	1.5	-3.4
P02	0.9	0.1	-0.2	7.3	-0.1	-4.2	0.8	6.7
P04	1.8	4.9	1.6	0.1	0.9	5.8	0.7	4.0
P05	-1.2	-9.5	-1.7	-6.9	0.6	-5.5	-0.9	-5.0
P06	-0.6	-4.1	-0.4	0.3	-1.0	-0.6	-0.7	-1.2
P07	0.1	0.1	-0.7	7.2	-0.4	4.4	-0.5	7.8
P08	-0.8	4.3	1.2	1.6	0.3	1.8	0.4	3.2
P10	-2.4	-9.1	-0.4	-2.9	-0.3	-4.3	-1.3	-0.5
P11	0.5	-5.6	1.0	-1.2	0.2	-0.1	0.8	-2.3
P12	-0.6	-4.4	-0.9	5.7	-0.4	-1.4	-2.3	2.4
P13	2.0	-0.9	-1.0	-4.7	-0.1	-9.6	-0.8	1.5
P14	-0.4	-9.2	-2.9	-4.1	0.8	-1.9	-0.5	-1.9
P15	-2.5	-8.1	0.7	-0.5	-1.9	-0.6	-0.5	0.4
P16	0.7	-2.3	-0.5	-1.4	0.1	-1.8	0.5	-3.9
P17	0.0	-4.4	1.2	-2.6	-1.8	-1.4	-0.5	-3.6
P18	1.5	-5.7	2.1	-4.2	0.4	-1.8	-0.5	-2.8
P19	1.6	0.7	1.2	0.2	0.0	-1.3	3.6	1.0
P20	-3.0	-2.2	-2.0	0.7	-0.6	-1.6	-1.6	-5.7
P21	0.0	1.3	-2.0	3.5	-1.2	3.1	-1.2	1.9
P22	1.5	0.1	0.2	2.6	1.6	2.7	2.0	-2.3
P23	-2.5	-1.5	-2.1	1.1	1.4	0.4	0.0	-1.2

	Degrees of Freedom	F	p	Partial eta-squared
Auditory Condition	3	4.421535	*0.00710912	0.181051
Error	60			
Vision	1	1.919779	0.181140	0.087582
Error	20			
A.C * Vis.	3	4.440115	*0.006958	0.181673
Error	60			

Endpoint Variable Error – Primary Axis (mm)

Y	**NoSound**		**SoundBefore**		**SoundDuring**		**Sound Throughout**	
	Vision	**NoVision**	**Vision**	**NoVision**	**Vision**	**NoVision**	**Vision**	**NoVision**
P01	2.8	6.6	2.8	4.0	3.0	9.1	4.3	7.0
P02	4.3	8.3	5.0	7.5	6.5	8.1	4.6	7.1
P04	5.2	8.6	4.9	9.4	4.6	11.7	6.0	8.8
P05	4.2	8.8	4.3	5.4	4.5	8.9	4.7	8.3
P06	5.1	5.7	4.1	7.3	5.4	6.4	4.2	6.5
P07	3.3	8.9	3.4	6.6	5.1	7.5	4.1	7.9
P08	3.5	6.9	3.6	5.1	4.6	9.1	4.2	7.4
P10	3.6	4.2	3.5	5.5	3.0	6.3	3.0	5.8
P11	6.4	10.9	4.5	7.5	5.4	7.3	4.9	8.4
P12	3.2	8.5	3.4	7.2	3.8	7.4	3.5	7.0
P13	10.9	7.9	4.6	8.4	9.3	8.3	5.0	8.9
P14	6.8	10.6	6.2	8.4	7.1	13.1	6.4	6.4
P15	6.6	13.5	6.8	6.0	5.9	9.3	4.7	5.8
P16	5.9	8.9	5.3	7.6	6.8	10.8	5.0	9.3
P17	3.8	6.6	5.5	7.5	3.8	8.8	4.8	9.3
P18	9.6	9.5	5.6	7.0	7.1	6.0	6.6	9.3
P19	6.3	10.8	5.4	7.0	4.0	6.8	7.0	9.0
P20	5.1	7.2	6.5	8.0	5.6	8.4	5.6	6.7
P21	3.8	7.4	4.3	6.8	2.3	7.7	4.6	6.9
P22	5.9	15.0	6.4	8.8	6.8	8.2	6.7	9.7
P23	7.2	9.0	7.4	4.9	8.1	8.4	7.6	10.5

	Degrees of Freedom	**F**	**p**	**Partial eta-squared**
Auditory Condition	3	5.6399	*0.00179472	0.219966
Error	60			
Vision	1	138.0049	*<0.00001	0.873422
Error	20			
A.C * Vis.	3	2.0189	0.120841	0.091688
Error	60			

Endpoint Variable Error – Secondary Axis (mm)

X	NoSound		SoundBefore		SoundDuring		Sound Throughout	
	Vision	NoVision	Vision	NoVision	Vision	NoVision	Vision	NoVision
P01	3.3	11.8	3.4	6.8	2.1	7.6	2.3	9.0
P02	5.3	9.5	2.6	8.4	3.8	9.7	4.0	7.7
P04	7.3	17.4	6.7	19.3	8.5	19.0	8.6	18.3
P05	1.8	10.0	3.4	9.1	2.8	7.3	3.0	12.1
P06	4.9	6.0	3.9	8.0	3.7	5.7	4.3	6.8
P07	2.4	13.3	1.7	7.3	3.6	8.4	3.5	8.5
P08	3.9	8.7	5.2	8.8	4.2	8.3	3.4	8.7
P10	2.7	7.7	5.0	8.6	3.1	5.4	3.7	6.3
P11	4.1	10.0	4.0	8.0	4.0	8.8	5.0	9.8
P12	3.0	8.2	3.3	9.7	3.2	9.3	2.3	8.7
P13	6.9	11.5	5.0	10.4	5.1	7.4	3.5	7.9
P14	6.7	11.4	4.6	10.4	5.4	11.9	7.9	9.1
P15	5.4	11.7	5.6	8.0	4.7	8.5	4.1	5.8
P16	7.5	8.0	9.1	13.1	6.7	11.8	8.8	8.2
P17	3.6	10.7	4.0	12.5	3.9	6.9	5.2	10.1
P18	4.5	7.4	5.0	7.9	4.5	8.2	4.8	9.7
P19	5.9	9.7	8.0	6.2	6.5	8.0	3.5	5.7
P20	6.2	9.0	5.5	8.1	3.4	9.4	4.0	12.3
P21	4.6	9.3	4.0	9.8	3.7	6.7	4.4	9.7
P22	3.3	16.5	4.9	7.5	4.2	8.4	4.2	8.7
P23	5.8	9.5	8.5	8.5	6.0	12.2	6.3	8.1

	Degrees of Freedom	F	p	Partial eta-squared
Auditory Condition	3	2.5937	0.060825	0.114797
Error	60			
Vision	1	116.7624	*<0.00001	0.853761
Error	20			
A.C * Vis.	3	1.5266	0.216822	0.070916
Error	60			

Endpoint Absolute Error – Primary Axis (mm)

Y	NoSound		SoundBefore		SoundDuring		Sound Throughout	
	Vision	NoVision	Vision	NoVision	Vision	NoVision	Vision	NoVision
P01	2.1	7.0	2.3	4.4	2.7	9.2	4.0	5.5
P02	3.4	6.9	4.3	8.2	5.2	7.5	3.5	6.1
P04	3.8	6.9	3.7	8.0	3.6	9.1	4.9	7.5
P05	3.8	8.2	3.3	4.3	3.6	6.8	3.7	6.6
P06	4.2	4.7	3.5	5.8	4.4	5.1	3.1	4.7
P07	3.3	6.7	3.0	5.2	4.2	8.3	3.5	6.6
P08	2.9	6.4	3.0	4.5	3.8	7.7	3.9	6.3
P10	2.9	4.2	2.9	4.4	2.2	4.7	2.4	6.0
P11	5.7	9.7	3.7	6.1	4.2	5.5	4.0	6.7
P12	2.6	7.3	2.7	5.9	3.3	5.5	3.0	6.4
P13	9.7	7.2	4.7	7.5	8.8	9.7	4.3	7.7
P14	4.9	10.8	5.1	6.7	6.0	10.1	5.1	5.4
P15	5.0	11.8	5.5	4.3	4.5	7.5	4.6	5.4
P16	5.1	6.7	4.9	5.4	6.2	9.0	4.1	7.2
P17	2.9	5.1	4.5	6.5	2.9	8.3	4.0	6.3
P18	7.8	8.8	4.1	5.1	4.9	4.8	5.2	7.0
P19	5.3	10.5	6.7	6.5	3.7	5.4	5.6	8.0
P20	4.7	5.8	5.6	6.6	4.4	7.1	5.2	5.0
P21	3.0	6.2	3.0	5.6	2.0	6.4	4.0	5.1
P22	4.6	9.4	5.5	6.8	5.6	6.9	4.8	7.9
P23	5.9	7.5	5.9	4.7	6.7	7.9	6.8	8.3

	Degrees of Freedom	F	p	Partial eta-squared
Auditory Condition	3	4.8249	*0.0044828	0.194358
Error	60			
Vision	1	146.6101	*<0.000001	0.879959
Error	20			
A.C * Vis.	3	3.3775	*0.023989	0.144477
Error	60			

Endpoint Absolute Error – Secondary Axis (mm)

X	NoSound		SoundBefore		SoundDuring		Sound Throughout	
	Vision	NoVision	Vision	NoVision	Vision	NoVision	Vision	NoVision
P01	2.7	11.2	3.4	5.5	1.7	5.2	2.3	7.5
P02	4.3	7.1	2.0	8.6	3.0	9.1	3.2	8.0
P04	6.3	14.2	6.1	16.3	6.9	16.3	7.4	15.1
P05	1.7	12.1	3.2	8.3	2.3	6.8	2.3	10.7
P06	3.9	5.5	3.2	6.3	2.9	3.9	3.4	5.3
P07	1.9	10.0	1.6	8.0	2.9	8.2	2.9	9.8
P08	3.3	8.5	4.0	7.5	3.4	6.8	2.9	7.2
P10	3.1	9.5	3.7	6.3	2.6	5.2	3.3	4.9
P11	3.1	10.1	3.0	6.8	3.2	6.9	3.8	7.7
P12	2.4	8.1	2.6	9.4	2.5	7.2	2.7	6.6
P13	5.8	8.8	4.0	9.4	3.6	10.1	2.9	6.3
P14	4.7	11.0	4.1	9.3	4.5	10.0	6.4	7.0
P15	4.8	10.0	4.6	5.6	4.2	7.1	3.4	4.6
P16	6.0	6.4	7.3	9.0	5.2	10.0	7.5	7.0
P17	3.1	9.0	3.3	11.2	3.2	5.9	3.9	7.7
P18	3.6	7.2	3.8	7.7	3.7	6.4	3.8	8.2
P19	4.7	7.8	6.6	4.9	5.4	6.4	3.9	4.6
P20	5.0	6.4	4.1	6.1	2.7	8.2	3.2	10.8
P21	3.6	7.2	3.3	6.8	2.9	5.5	3.7	7.2
P22	2.8	11.3	3.9	6.1	3.3	7.5	3.5	5.9
P23	5.4	8.1	6.9	6.8	4.8	9.4	4.9	6.3

	Degrees of Freedom	F	p	Partial eta-squared
Auditory Condition	3	4.6492	*0.0054764	0.188616
Error	60			
Vision	1	102.2232	*<0.000001	0.836365
Error	20			
A.C * Vis.	3	2.3748	0.078990	0.106138
Error	60			

Trajectory Variability – Primary Axis (mm)

Summary table of participants means too large – available upon request.

	Degrees of Freedom	F	p	Partial eta-squared
Auditory Condition	3	0.4820	0.696049	0.023532
Error	60			
Vision	1	0.8219	0.375405	0.039475
Error	20			
Position	4	91.9996	*<0.000001	0.821428
Error	80			
A.C * Vis.	3	0.0603	0.980406	0.003008
Error	60			
Pos. * A.C.	12	1.3317	0.201035	0.062429
Error	240			
Pos. * Vis.	4	6.6118	*0.00011944	0.248455
Error	80			
A.C. * Vis. * Pos.	12	1.2788	0.231666	0.060096
Error	240			

Trajectory Variability – Secondary Axis (mm)
Summary table of participant means too large – available upon request.

	Degrees of Freedom	F	p	Partial eta-squared
Auditory Condition	3	0.0712	0.975136	0.003547
Error	60			
Vision	1	6.7941	*0.016885	0.253568
Error	20			
Position	4	87.4102	*<0.00001	0.813798
Error	80			
A.C * Vis.	3	0.1149	0.951030	0.005714
Error	60			
Pos. * A.C.	12	0.7033	0.747773	0.033968
Error	240			
Pos. * Vis.	4	35.1307	*<0.00001	0.637226
Error	80			
A.C. * Vis. * Pos.	12	0.7499	0.701522	0.036139
Error	240			

Trajectory Position – Primary Axis (mm)

Summary table of participants too large – available upon request.

	Degrees of Freedom	F	p	Partial eta-squared
Auditory Condition	3	5.339	0.002509	0.210714
Error	60			
Vision	1	0.715	0.407806	0.034514
Error	20			
Position	4	1621.571	*<0.000001	0.987817
Error	80			
Loc.	1	0.366	0.551900	0.017980
Error	20			
A.C * Vis.	3	0.304	0.822351	0.014974
Error	60			
A.C. * Pos.	12	3.123	*0.000384072	0.135072
Error	240			
Vis. * Pos.	4	0.667	0.616525	0.032290
Error	80			
A.C. * Loc.	3	0.752	0.525482	0.036239
Error	60			
Vis. * Loc.	1	2.226	0.151296	0.100160
Error	20			
Pos. * Loc.	4	71.108	*<0.000001	0.780480
Error	80			
A.C. * Vis. * Pos.	12	0.813	0.636737	0.039072
Error	240			
A.C. * Vis. * Loc.	3	0.211	0.888601	0.010426
Error	60			
A.C. * Pos. * Loc.	12	0.721	0.730664	0.034782
Error	240			
Vis. * Pos. * Loc.	4	5.395	*0.0006745	0.212437
Error	80			
A.C * Vis. * Pos. * Loc.	12	0.468	0.932203	0.022844
Error	240			

Trajectory Position – Secondary Axis (mm)
Summary table of participants too large – available upon request.

	Degrees of Freedom	F	p	Partial eta-squared
Auditory Condition	3	0.786	0.506403	0.037816
Error	60			
Vision	1	27.712	*0.000037552	0.580822
Error	20			
Position	4	3.051	*0.0215076	0.132357
Error	80			
Loc.	1	4516.318	*<0.000001	0.995591
Error	20			
A.C * Vis.	3	0.235	0.871465	0.011625
Error	60			
A.C. * Pos.	12	1.041	0.411767	0.049479
Error	240			
Vis. * Pos.	4	3.983	*0.0053523	0.166064
Error	80			
A.C. * Loc.	3	4.591	*0.0058567	0.186678
Error	60			
Vis. * Loc.	1	4.249	*0.05251840	0.175218
Error	20			
Pos. * Loc.	4	1715.430	*<0.000001	0.988475
Error	80			
A.C. * Vis. * Pos.	12	0.904	0.544095	0.043224
Error	240			
A.C. * Vis. * Loc.	3	2.373	0.079187	0.106055
Error	60			
A.C. * Pos. * Loc.	12	1.208	0.278324	0.056938
Error	240			
Vis. * Pos. * Loc.	4	1.485	0.214488	0.069126
Error	80			
A.C * Vis. * Pos. * Loc.	12	0.790	0.660263	0.038016
Error	240			

Appendix F
Summary Tables – Experiment 2

Reaction Time (ms)

	NoSound		SimpleMetronome		ComplexMetronome	
Participant	**Vision**	**NoVision**	**Vision**	**NoVision**	**Vision**	**NoVision**
P01	285	288	213	235	213	244
P02	362	362	261	254	234	230
P03	282	299	240	253	248	213
P04	293	314	212	233	211	224
P05	287	275	245	223	204	207
P06	337	336	263	215	238	250
P07	273	273	215	215	202	213
P08	424	464	305	291	344	264
P09	274	273	225	234	249	249
P11	292	305	228	229	234	220
P12	430	422	256	240	244	217
P13	346	426	259	328	254	268
P14	367	334	249	261	247	282
P16	323	317	245	256	267	258
P17	299	310	215	266	266	293
P18	266	329	245	281	230	249
P19	259	259	189	202	209	218
P20	278	304	204	256	209	196
P21	289	277	183	233	198	227
P22	399	379	249	251	269	259
P24	321	361	278	267	297	284

	Degrees of Freedom	**F**	**p**	**Partial eta-squared**
Auditory Condition	2	82.137	*<0.0000001	0.804185
Error	40			
Vision	1	3.209	0.088383	0.138263
Error	20			
A.C * Vis.	2	1.465	0.243320	0.068230
Error	40			

Participant	NoSound		Metronome		Drum	
	Vision	NoVision	Vision	NoVision	Vision	NoVision
P01	285	288	213	240	214	216
P02	362	362	248	242	234	241
P03	282	299	244	233	203	217
P04	293	314	211	229	235	261
P05	287	275	225	215	194	201
P06	337	336	250	232	200	216
P07	273	273	208	214	212	232
P08	424	464	325	278	270	354
P09	274	273	237	242	237	239
P11	292	305	231	224	219	228
P12	430	422	250	229	260	231
P13	346	426	256	298	205	266
P14	367	334	248	271	242	272
P16	323	317	256	257	235	252
P17	299	310	240	280	222	260
P18	266	329	237	265	206	217
P19	259	259	199	210	192	225
P20	278	304	207	226	212	238
P21	289	277	190	230	196	180
P22	399	379	259	255	254	269
P24	321	361	288	275	234	286

	Degrees of Freedom	F	p	Partial eta-squared
Auditory Condition	2	101.063	*<0.00000001	0.834797
Error	40			
Vision	1	10.566	*0.0040061	0.345671
Error	20			
A.C * Vis.	2	2.340	0.109344	0.104760
Error	40			

Reaction Time Variability (SD) (ms)

Participant	NoSound		SimpleMetronome		ComplexMetronome	
	Vision	NoVision	Vision	NoVision	Vision	NoVision
P01	26	31	38	24	29	38
P02	24	38	28	42	31	30
P03	37	34	21	26	30	19
P04	32	47	45	31	34	55
P05	22	25	25	17	17	33
P06	47	44	60	47	48	32
P07	29	39	23	30	29	22
P08	68	58	50	47	34	36
P09	40	52	28	36	44	35
P11	33	27	22	31	27	27
P12	69	60	46	45	42	41
P13	26	39	20	28	28	32
P14	36	48	20	42	35	57
P16	17	34	33	38	26	36
P17	24	39	36	35	36	37
P18	27	37	35	41	32	49
P19	25	18	22	21	35	14
P20	36	37	28	35	41	28
P21	38	41	33	33	62	27
P22	45	54	39	36	50	51
P24	38	42	42	35	41	27

	Degrees of Freedom	F	p	Partial eta-squared
Auditory Condition	2	2.5775	0.088531	0.114161
Error	40			
Vision	1	0.9628	0.338211	0.045928
Error	20			
A.C * Vis.	2	2.1176	0.133613	0.095742
Error	40			

Participant	NoSound		Metronome		Drum	
	Vision	NoVision	Vision	NoVision	Vision	NoVision
P01	26	31	34	31	30	30
P02	24	38	30	36	39	42
P03	37	34	26	22	27	33
P04	32	47	40	43	46	48
P05	22	25	21	25	27	27
P06	47	44	54	39	53	53
P07	29	39	26	26	29	25
P08	68	58	42	42	51	55
P09	40	52	36	35	38	35
P11	33	27	24	29	20	28
P12	69	60	44	43	63	42
P13	26	39	24	30	24	49
P14	36	48	28	49	48	48
P16	17	34	29	37	30	36
P17	24	39	36	36	28	41
P18	27	37	34	45	33	30
P19	25	18	28	18	34	31
P20	36	37	34	31	36	47
P21	38	41	47	30	44	38
P22	45	54	45	44	63	41
P24	38	42	42	31	36	52

	Degrees of Freedom	F	p	Partial eta-squared
Auditory Condition	2	4.7083	*0.014579520	0.190555
Error	40			
Vision	1	2.2093	0.152776	0.099476
Error	20			
A.C * Vis.	2	2.0895	0.137049	0.094593
Error	40			

Movement Time (ms)

	NoSound		SimpleMetronome		ComplexMetronome	
Participant	**Vision**	**NoVision**	**Vision**	**NoVision**	**Vision**	**NoVision**
P01	422	338	481	379	471	406
P02	527	572	552	573	552	536
P03	471	440	534	503	464	459
P04	307	326	335	278	360	385
P05	417	349	405	358	390	351
P06	515	494	507	480	524	465
P07	346	305	315	319	346	337
P08	675	680	763	640	734	642
P09	391	388	379	369	382	384
P11	454	453	466	438	469	439
P12	534	506	522	518	501	540
P13	477	418	467	464	471	395
P14	546	534	492	523	571	517
P16	306	297	283	298	285	291
P17	355	349	369	361	328	331
P18	614	597	554	523	567	538
P19	301	309	320	307	312	324
P20	430	434	421	453	436	419
P21	491	424	475	458	496	424
P22	585	532	610	521	579	575
P24	469	447	438	476	460	455

	Degrees of Freedom	**F**	**p**	**Partial eta-squared**
Auditory Condition	2	0.1028	0.902571	0.005112
Error	40			
Vision	1	13.0994	*0.0017098	0.395760
Error	20			
A.C * Vis.	2	0.0321	0.968468	0.001601
Error	40			

Participant	NoSound		Metronome		Drum	
	Vision	NoVision	Vision	NoVision	Vision	NoVision
P01	422	338	476	393	411	387
P02	527	572	552	554	553	544
P03	471	440	499	481	458	445
P04	307	326	348	331	327	313
P05	417	349	397	354	371	332
P06	515	494	515	472	467	468
P07	346	305	331	328	335	352
P08	675	680	748	641	721	695
P09	391	388	381	376	393	376
P11	454	453	468	438	455	443
P12	534	506	511	529	501	484
P13	477	418	469	430	432	429
P14	546	534	531	520	539	552
P16	306	297	284	295	277	281
P17	355	349	348	346	389	362
P18	614	597	560	530	571	549
P19	301	309	316	316	335	298
P20	430	434	429	436	457	425
P21	491	424	485	441	477	444
P22	585	532	594	548	589	515
P24	469	447	449	466	492	425

	Degrees of Freedom	F	p	Partial eta-squared
Auditory Condition	2	0.9122	0.409823	0.043621
Error	40			
Vision	1	22.2072	*0.00013350	0.526148
Error	20			
A.C * Vis.	2	0.0242	0.976092	0.001209
Error	40			

Movement Time Variability (SD) (ms)

	NoSound		SimpleMetronome		ComplexMetronome	
Participant	**Vision**	**NoVision**	**Vision**	**NoVision**	**Vision**	**NoVision**
P01	85	49	94	49	77	54
P02	44	66	48	43	41	55
P03	68	52	46	57	64	48
P04	23	41	37	25	46	47
P05	31	28	39	39	38	40
P06	51	36	41	50	52	60
P07	29	22	21	34	33	30
P08	49	56	61	67	44	44
P09	40	46	39	31	34	47
P11	45	45	34	31	42	35
P12	47	51	76	55	48	80
P13	34	39	47	32	47	34
P14	44	48	43	53	54	52
P16	37	23	20	30	15	26
P17	24	39	44	33	28	31
P18	32	50	34	49	40	40
P19	41	56	51	48	37	54
P20	54	39	42	39	57	50
P21	72	57	48	42	63	38
P22	92	75	63	55	80	66
P24	56	42	49	39	39	48

	Degrees of Freedom	**F**	**p**	**Partial eta-squared**
Auditory Condition	2	0.5991	0.554175	0.029082
Error	40			
Vision	1	0.6394	0.433312	0.030981
Error	20			
A.C * Vis.	2	0.4365	0.649322	0.021360
Error	40			

Participant	NoSound		Metronome		Drum	
	Vision	NoVision	Vision	NoVision	Vision	NoVision
P01	85	49	85	52	68	61
P02	44	66	45	49	49	55
P03	68	52	55	53	53	53
P04	23	41	42	36	44	34
P05	31	28	38	40	37	28
P06	51	36	46	55	62	48
P07	29	22	27	32	31	27
P08	49	56	53	55	62	46
P09	40	46	36	39	37	46
P11	45	45	38	33	49	40
P12	47	51	62	67	58	62
P13	34	39	47	33	38	30
P14	44	48	49	53	45	60
P16	37	23	17	28	21	14
P17	24	39	36	32	39	41
P18	32	50	37	44	37	41
P19	41	56	44	51	59	46
P20	54	39	50	44	49	30
P21	72	57	56	40	52	48
P22	92	75	71	61	80	54
P24	56	42	44	44	47	33

	Degrees of Freedom	F	p	Partial eta-squared
Auditory Condition	2	0.2994	0.742874	0.014752
Error	40			
Vision	1	2.3187	0.143478	0.103892
Error	20			
A.C * Vis.	2	1.0788	0.349688	0.051180
Error	40			

Peak Velocity – Primary Axis (mm/s)

	NoSound		SimpleMetronome		ComplexMetronome	
Participant	**Vision**	**NoVision**	**Vision**	**NoVision**	**Vision**	**NoVision**
P01	1650	1948	1428	1620	1558	1700
P02	1164	1098	1081	1028	1069	1116
P03	1387	1409	1284	1316	1396	1357
P04	2148	1899	2043	2450	1786	1590
P05	1659	1840	1709	1749	1708	1788
P06	1327	1380	1266	1364	1205	1338
P07	1760	1958	1860	1984	1844	1875
P08	896	953	882	942	789	937
P09	1560	1581	1560	1573	1482	1533
P11	1417	1381	1364	1376	1359	1437
P12	1200	1255	1247	1227	1272	1279
P13	1417	1526	1308	1288	1278	1676
P14	1078	1097	1178	1141	1026	1157
P16	1877	2063	2088	1957	2019	2023
P17	1551	1568	1520	1490	1688	1643
P18	1111	1114	1176	1277	1137	1159
P19	1858	1830	1732	1771	1765	1793
P20	1284	1324	1312	1311	1309	1326
P21	1280	1349	1190	1241	1193	1374
P22	1139	1213	1152	1219	1166	1151
P24	1250	1329	1368	1174	1244	1274

	Degrees of Freedom	**F**	**p**	**Partial eta-squared**
Auditory Condition	2	0.8090	0.452447	0.038878
Error	40			
Vision	1	12.5625	*0.00203486	0.385796
Error	20			
A.C * Vis.	2	0.2156	0.806950	0.010667
Error	40			

Participant	NoSound		Metronome		Drum	
	Vision	NoVision	Vision	NoVision	Vision	NoVision
P01	1650	1948	1493	1660	1719	1782
P02	1164	1098	1075	1072	1086	1095
P03	1387	1409	1340	1337	1409	1449
P04	2148	1899	1915	2020	2099	2157
P05	1659	1840	1708	1768	1804	1882
P06	1327	1380	1235	1351	1339	1395
P07	1760	1958	1852	1930	1814	1768
P08	896	953	836	939	901	895
P09	1560	1581	1521	1553	1554	1576
P11	1417	1381	1361	1407	1431	1452
P12	1200	1255	1259	1253	1242	1295
P13	1417	1526	1293	1482	1495	1502
P14	1078	1097	1102	1149	1072	1085
P16	1877	2063	2054	1990	2064	2100
P17	1551	1568	1604	1566	1512	1528
P18	1111	1114	1156	1218	1161	1162
P19	1858	1830	1749	1782	1698	1887
P20	1284	1324	1311	1318	1302	1372
P21	1280	1349	1192	1308	1266	1286
P22	1139	1213	1159	1185	1134	1273
P24	1250	1329	1306	1224	1165	1316

	Degrees of Freedom	F	p	Partial eta-squared
Auditory Condition	2	3.6487	*0.0350320	0.154286
Error	40			
Vision	1	23.3518	*0.00010114	0.538658
Error	20			
A.C * Vis.	2	0.0289	0.971531	0.001443
Error	40			

Peak Velocity – Secondary Axis (mm/s)

	NoSound		SimpleMetronome		ComplexMetronome	
Participant	**Vision**	**NoVision**	**Vision**	**NoVision**	**Vision**	**NoVision**
P01	1114	1414	792	1031	949	966
P02	711	708	672	659	694	698
P03	882	903	778	829	877	865
P04	1301	1239	1134	1320	1024	988
P05	975	1045	1006	1088	1045	1166
P06	807	888	777	864	710	863
P07	1096	1205	1168	1283	1113	1244
P08	514	537	456	471	409	652
P09	1053	1131	1080	1017	1103	984
P11	849	829	839	853	876	862
P12	617	628	706	614	678	655
P13	883	932	762	742	763	1000
P14	602	647	765	665	639	691
P16	1127	1258	1250	1220	1224	1227
P17	945	888	979	883	995	1091
P18	697	635	704	713	675	702
P19	920	959	795	924	930	813
P20	834	787	819	805	780	793
P21	804	896	884	818	765	933
P22	627	675	756	701	698	669
P24	746	803	787	692	811	747

	Degrees of Freedom	**F**	**p**	**Partial eta-squared**
Auditory Condition	2	0.7940	0.459031	0.038184
Error	40			
Vision	1	5.9220	*0.02445685	0.228453
Error	20			
A.C * Vis.	2	0.7444	0.481507	0.035882
Error	40			

Participant	NoSound		Metronome		Drum	
	Vision	NoVision	Vision	NoVision	Vision	NoVision
P01	1114	1414	870	999	998	1112
P02	711	708	683	678	676	699
P03	882	903	828	847	886	897
P04	1301	1239	1079	1154	1189	1223
P05	975	1045	1025	1127	1112	1105
P06	807	888	744	864	836	906
P07	1096	1205	1140	1263	1080	1102
P08	514	537	432	562	472	462
P09	1053	1131	1091	1001	940	1002
P11	849	829	857	857	875	878
P12	617	628	692	635	698	739
P13	883	932	763	871	957	881
P14	602	647	702	678	652	666
P16	1127	1258	1237	1224	1309	1272
P17	945	888	987	987	936	944
P18	697	635	689	707	667	648
P19	920	959	863	869	715	962
P20	834	787	799	799	766	851
P21	804	896	825	875	826	864
P22	627	675	727	685	654	716
P24	746	803	799	720	733	819

	Degrees of Freedom	F	p	Partial eta-squared
Auditory Condition	2	0.7885	0.461450	0.037931
Error	40			
Vision	1	12.0033	*0.00244774	0.375064
Error	20			
A.C * Vis.	2	0.2981	0.743860	0.014686
Error	40			

Ratio of time to peak velocity to movement time

Participant	NoSound		SimpleMetronome		ComplexMetronome	
	Vision	NoVision	Vision	NoVision	Vision	NoVision
P01	0.35	0.35	0.32	0.32	0.32	0.35
P02	0.39	0.40	0.40	0.42	0.37	0.40
P03	0.39	0.40	0.38	0.41	0.39	0.40
P04	0.41	0.42	0.37	0.40	0.38	0.38
P05	0.42	0.51	0.41	0.42	0.37	0.44
P06	0.45	0.40	0.43	0.45	0.46	0.40
P07	0.45	0.44	0.40	0.42	0.43	0.46
P08	0.41	0.45	0.38	0.38	0.39	0.46
P09	0.41	0.41	0.44	0.47	0.45	0.42
P11	0.39	0.37	0.37	0.36	0.35	0.35
P12	0.47	0.51	0.44	0.51	0.49	0.51
P13	0.36	0.38	0.43	0.41	0.42	0.33
P14	0.45	0.40	0.36	0.40	0.44	0.43
P16	0.41	0.38	0.38	0.36	0.37	0.37
P17	0.41	0.45	0.39	0.40	0.44	0.33
P18	0.41	0.47	0.38	0.44	0.40	0.43
P19	0.37	0.34	0.36	0.39	0.38	0.35
P20	0.41	0.45	0.44	0.40	0.44	0.46
P21	0.40	0.42	0.39	0.46	0.39	0.45
P22	0.44	0.45	0.46	0.44	0.40	0.46
P24	0.47	0.43	0.38	0.43	0.42	0.41

	Degrees of Freedom	F	p	Partial eta-squared
Auditory Condition	2	2.645	0.083393	0.116805
Error	40			
Vision	1	3.564	0.073632	0.151257
Error	20			
A.C * Vis.	2	0.633	0.536168	0.030685
Error	40			

Participant	NoSound		Metronome		Drum	
	Vision	NoVision	Vision	NoVision	Vision	NoVision
P01	0.35	0.35	0.32	0.33	0.33	0.36
P02	0.39	0.40	0.39	0.41	0.40	0.41
P03	0.39	0.40	0.39	0.40	0.39	0.41
P04	0.41	0.42	0.38	0.39	0.39	0.37
P05	0.42	0.51	0.39	0.43	0.39	0.46
P06	0.45	0.40	0.45	0.42	0.44	0.41
P07	0.45	0.44	0.41	0.44	0.42	0.40
P08	0.41	0.45	0.39	0.42	0.40	0.42
P09	0.41	0.41	0.44	0.44	0.38	0.40
P11	0.39	0.37	0.36	0.35	0.36	0.37
P12	0.47	0.51	0.46	0.51	0.48	0.50
P13	0.36	0.38	0.42	0.37	0.35	0.35
P14	0.45	0.40	0.40	0.42	0.41	0.41
P16	0.41	0.38	0.38	0.37	0.40	0.38
P17	0.41	0.45	0.41	0.37	0.41	0.43
P18	0.41	0.47	0.39	0.43	0.41	0.43
P19	0.37	0.34	0.37	0.37	0.35	0.39
P20	0.41	0.45	0.44	0.43	0.41	0.44
P21	0.40	0.42	0.39	0.46	0.41	0.41
P22	0.44	0.45	0.43	0.45	0.43	0.47
P24	0.47	0.43	0.40	0.42	0.43	0.42

	Degrees of Freedom	F	p	Partial eta-squared
Auditory Condition	2	4.4585	*0.017864	0.182290
Error	40			
Vision	1	4.8214	*0.040071	0.194245
Error	20			
A.C * Vis.	2	0.2757	0.760474	0.013597
Error	40			

Endpoint Variable Error – Primary Axis (mm)

	NoSound		SimpleMetronome		ComplexMetronome	
Participant	**Vision**	**NoVision**	**Vision**	**NoVision**	**Vision**	**NoVision**
P01	9.0	13.4	10.3	14.5	5.5	8.4
P02	5.8	4.7	5.5	5.8	4.6	7.9
P03	5.6	11.2	9.4	11.0	8.7	11.9
P04	7.9	8.0	4.5	11.5	5.9	7.9
P05	4.0	10.8	5.0	10.6	5.4	6.8
P06	6.9	9.1	5.8	6.7	6.3	11.6
P07	8.5	10.6	9.4	9.0	7.7	7.4
P08	3.8	5.0	3.9	4.9	4.4	2.9
P09	10.1	12.7	9.6	8.4	10.8	12.5
P11	4.9	6.0	4.2	7.0	3.6	7.6
P12	6.2	9.2	6.2	11.9	7.1	10.7
P13	3.7	7.3	5.3	7.5	5.3	6.0
P14	4.8	10.2	4.9	11.6	4.1	5.8
P16	7.4	14.4	9.6	7.5	8.3	7.6
P17	9.2	13.5	8.1	10.7	9.4	13.0
P18	3.5	4.1	3.3	4.6	4.3	5.0
P19	8.1	9.0	6.0	10.7	7.5	9.4
P20	6.6	9.9	5.4	10.1	4.4	6.7
P21	5.4	5.5	4.7	7.6	5.4	7.7
P22	5.6	6.1	4.1	4.5	3.9	5.3
P24	6.4	7.2	5.8	7.4	5.0	8.2

	Degrees of Freedom	**F**	**p**	**Partial eta-squared**
Auditory Condition	2	1.440	0.248872	0.067178
Error	40			
Vision	1	62.338	*<0.000001	0.757098
Error	20			
A.C * Vis.	2	0.419	0.660546	0.020521
Error	40			

Participant	NoSound		Metronome		Drum	
	Vision	NoVision	Vision	NoVision	Vision	NoVision
P01	9.0	13.4	7.9	11.4	11.1	10.4
P02	5.8	4.7	5.0	6.9	4.6	7.3
P03	5.6	11.2	9.0	11.5	7.6	11.5
P04	7.9	8.0	5.2	9.7	8.2	6.3
P05	4.0	10.8	5.2	8.7	5.8	8.3
P06	6.9	9.1	6.0	9.1	6.7	9.2
P07	8.5	10.6	8.6	8.2	7.5	9.8
P08	3.8	5.0	4.2	3.9	3.7	5.7
P09	10.1	12.7	10.2	10.4	11.8	10.9
P11	4.9	6.0	3.9	7.3	4.7	5.7
P12	6.2	9.2	6.7	11.3	7.6	10.2
P13	3.7	7.3	5.3	6.8	4.2	7.0
P14	4.8	10.2	4.5	8.7	10.6	7.6
P16	7.4	14.4	9.0	7.5	6.0	8.5
P17	9.2	13.5	8.7	11.8	6.8	13.3
P18	3.5	4.1	3.8	4.8	2.9	3.7
P19	8.1	9.0	6.7	10.1	6.3	10.2
P20	6.6	9.9	4.9	8.4	6.4	7.4
P21	5.4	5.5	5.1	7.6	5.1	7.5
P22	5.6	6.1	4.0	4.9	5.1	6.0
P24	6.4	7.2	5.4	7.8	5.8	7.1

	Degrees of Freedom	F	p	Partial eta-squared
Auditory Condition	2	1.4088	0.256296	0.065806
Error	40			
Vision	1	71.6402	*<0.000001	0.781755
Error	20			
A.C * Vis.	2	1.0640	0.354634	0.050513
Error	40			

Endpoint Variable Error – Secondary Axis (mm)

Participant	NoSound		SimpleMetronome		ComplexMetronome	
	Vision	NoVision	Vision	NoVision	Vision	NoVision
P01	7.8	9.6	5.9	10.6	8.4	12.0
P02	5.4	8.0	4.1	5.9	3.1	7.0
P03	3.5	9.8	3.4	9.3	3.8	9.9
P04	10.1	8.9	5.3	7.0	6.8	10.0
P05	3.9	10.6	6.2	17.6	5.8	13.4
P06	4.4	10.6	4.4	9.6	4.7	8.1
P07	7.5	8.4	7.3	9.7	6.5	3.9
P08	3.6	8.6	4.6	6.1	3.5	7.9
P09	5.1	9.9	5.1	10.1	7.1	12.2
P11	4.2	9.3	3.0	7.3	2.6	8.6
P12	5.0	13.3	6.1	12.8	6.6	9.4
P13	4.2	6.9	4.7	7.1	5.4	6.4
P14	5.4	10.5	4.5	8.4	3.9	10.0
P16	8.2	7.0	4.9	6.4	5.2	7.7
P17	5.0	8.7	5.7	9.1	5.5	8.8
P18	3.6	7.8	3.0	7.3	4.1	7.8
P19	7.7	11.4	7.3	10.3	4.7	8.9
P20	6.9	11.1	3.9	9.1	7.0	10.2
P21	7.8	11.1	11.1	9.8	8.0	10.2
P22	1.9	9.0	3.2	7.3	6.7	9.2
P24	7.2	12.8	5.1	7.9	4.4	7.5

	Degrees of Freedom	F	p	Partial eta-squared
Auditory Condition	2	1.342	0.272813	0.062884
Error	40			
Vision	1	79.205	*<0.0000001	0.798398
Error	20			
A.C * Vis.	2	0.427	0.655198	0.020919
Error	40			

Participant	NoSound		Metronome		Drum	
	Vision	NoVision	Vision	NoVision	Vision	NoVision
P01	7.8	9.6	7.1	11.3	8.8	8.7
P02	5.4	8.0	3.6	6.5	3.2	5.9
P03	3.5	9.8	3.6	9.6	4.3	12.1
P04	10.1	8.9	6.0	8.5	9.3	11.1
P05	3.9	10.6	6.0	15.5	5.7	14.6
P06	4.4	10.6	4.5	8.9	4.5	8.8
P07	7.5	8.4	6.9	6.8	7.1	7.0
P08	3.6	8.6	4.0	7.0	4.7	9.1
P09	5.1	9.9	6.1	11.2	5.2	8.7
P11	4.2	9.3	2.8	7.9	3.3	6.4
P12	5.0	13.3	6.3	11.1	5.4	11.7
P13	4.2	6.9	5.1	6.7	4.9	8.3
P14	5.4	10.5	4.2	9.2	13.2	11.6
P16	8.2	7.0	5.0	7.1	8.2	9.3
P17	5.0	8.7	5.6	9.0	4.7	9.5
P18	3.6	7.8	3.5	7.5	3.7	7.0
P19	7.7	11.4	6.0	9.6	8.3	7.9
P20	6.9	11.1	5.5	9.7	4.7	7.9
P21	7.8	11.1	9.5	10.0	7.4	12.5
P22	1.9	9.0	5.0	8.2	3.4	8.5
P24	7.2	12.8	4.8	7.7	5.1	8.3

	Degrees of Freedom	F	p	Partial eta-squared
Auditory Condition	2	1.1991	0.312065	0.056564
Error	40			
Vision	1	70.9101	*<0.0000001	0.780002
Error	20			
A.C * Vis.	2	1.1114	0.339051	0.052644
Error	40			

Endpoint Constant Error – Primary Axis (mm)

Participant	NoSound		SimpleMetronome		ComplexMetronome	
	Vision	NoVision	Vision	NoVision	Vision	NoVision
P01	0.4	-0.8	-0.2	-6.4	-2.9	0.7
P02	0.6	-7.2	-0.7	-5.9	-1.7	-3.7
P03	-1.1	-0.4	-2.8	-2.6	-4.7	-1.4
P04	-0.3	-4.3	-0.9	3.3	-1.5	1.4
P05	-2.0	2.1	1.5	0.5	0.1	3.2
P06	-0.1	3.7	1.0	2.9	0.9	-3.7
P07	-3.3	-1.4	-2.4	-3.0	-2.8	-2.4
P08	-2.5	-3.1	-1.2	-0.7	-1.3	2.7
P09	0.3	2.7	0.2	-4.7	-0.9	-4.2
P11	-0.2	-2.0	0.6	-1.4	-0.3	-2.4
P12	-1.3	3.2	-1.2	-1.7	-2.7	-2.0
P13	-1.7	0.3	-0.4	3.0	-0.9	-1.3
P14	-3.2	-5.7	-4.1	-5.2	-2.7	-6.9
P16	-5.7	-13.8	-5.1	-10.1	-5.3	-2.4
P17	-1.3	-1.7	-1.6	0.5	1.9	0.7
P18	2.1	0.4	0.7	0.4	1.7	3.0
P19	0.2	3.4	0.8	0.8	-0.6	-2.0
P20	-1.5	3.2	-1.3	-1.1	-1.7	-5.5
P21	-1.1	-3.8	-0.1	-0.7	0.5	-1.1
P22	1.1	1.2	4.3	0.8	3.5	3.3
P24	0.6	-2.3	0.9	0.7	0.2	-1.7

	Degrees of Freedom	F	p	Partial eta-squared
Auditory Condition	2	0.022	0.978246	0.001099
Error	40			
Vision	1	1.323	0.263583	0.062055
Error	20			
A.C * Vis.	2	0.333	0.718793	0.016374
Error	40			

Participant	NoSound		Metronome		Drum	
	Vision	NoVision	Vision	NoVision	Vision	NoVision
P01	0.4	-0.8	-1.5	-2.9	1.5	-2.4
P02	0.6	-7.2	-1.2	-4.8	-0.6	-2.8
P03	-1.1	-0.4	-3.7	-2.0	-3.6	-3.7
P04	-0.3	-4.3	-1.2	2.4	-1.9	-0.1
P05	-2.0	2.1	0.8	1.9	1.8	-1.4
P06	-0.1	3.7	0.9	-0.4	2.0	-1.3
P07	-3.3	-1.4	-2.6	-2.7	-1.8	-2.8
P08	-2.5	-3.1	-1.3	1.0	-2.0	0.6
P09	0.3	2.7	-0.4	-4.5	1.2	-1.2
P11	-0.2	-2.0	0.2	-1.9	-0.7	0.1
P12	-1.3	3.2	-1.9	-1.8	-2.5	0.2
P13	-1.7	0.3	-0.6	0.9	-0.8	0.9
P14	-3.2	-5.7	-3.4	-6.1	-0.4	-7.1
P16	-5.7	-13.8	-5.2	-6.2	-8.2	-4.2
P17	-1.3	-1.7	0.2	0.6	3.8	-0.4
P18	2.1	0.4	1.2	1.7	2.3	1.5
P19	0.2	3.4	0.1	-0.6	2.9	3.7
P20	-1.5	3.2	-1.5	-3.3	-3.2	-1.0
P21	-1.1	-3.8	0.2	-0.9	0.3	-1.1
P22	1.1	1.2	3.9	2.1	3.1	0.3
P24	0.6	-2.3	0.5	-0.5	-0.1	1.4

	Degrees of Freedom	F	p	Partial eta-squared
Auditory Condition	2	0.8019	0.455543	0.038551
Error	40			
Vision	1	1.6046	0.219801	0.074273
Error	20			
A.C * Vis.	2	0.1034	0.902040	0.005142
Error	40			

Endpoint Constant Error – Secondary Axis (mm)

Participant	NoSound		SimpleMetronome		ComplexMetronome	
	Vision	NoVision	Vision	NoVision	Vision	NoVision
P01	3.6	2.1	-1.2	2.7	1.7	-5.2
P02	-0.6	-0.8	-2.1	-2.7	-0.8	-3.4
P03	-0.2	-2.1	-1.5	-2.7	1.2	-3.5
P04	-4.9	1.8	1.0	3.0	2.6	-2.6
P05	0.4	2.5	0.4	2.5	0.1	4.6
P06	1.1	-4.4	0.8	3.1	0.9	-0.9
P07	-0.9	-4.0	-0.2	-0.1	1.2	-1.5
P08	0.1	-4.7	-6.4	-7.4	-3.7	3.7
P09	1.3	1.9	0.1	-1.1	0.4	0.7
P11	1.6	-6.7	-1.3	-2.9	0.2	-2.2
P12	-1.9	-10.4	4.1	-0.1	-0.4	-7.3
P13	-1.8	-4.0	-1.9	-8.1	-1.8	-3.2
P14	-1.5	-1.1	-2.3	-1.7	-1.4	-3.7
P16	-1.5	5.2	1.6	5.6	-1.8	-1.8
P17	-0.1	-3.3	1.0	2.1	-0.5	3.7
P18	0.3	-5.5	0.9	-5.1	0.4	-2.0
P19	1.7	1.7	-1.7	0.7	1.5	0.3
P20	-1.6	-8.1	-2.6	-2.2	0.0	-8.5
P21	-1.2	-5.9	-3.8	2.1	2.5	-0.6
P22	1.7	-2.0	0.3	3.0	-0.7	-1.1
P24	-2.8	-4.2	0.7	-5.7	-3.1	-4.7

	Degrees of Freedom	F	p	Partial eta-squared
Auditory Condition	2	0.803	0.455223	0.038584
Error	40			
Vision	1	5.673	*0.0272668	0.220985
Error	20			
A.C * Vis.	2	2.258	0.117696	0.101458
Error	40			

Participant	NoSound		Metronome		Drum	
	Vision	NoVision	Vision	NoVision	Vision	NoVision
P01	3.6	2.1	0.2	-1.2	2.1	4.6
P02	-0.6	-0.8	-1.4	-3.1	-1.3	0.5
P03	-0.2	-2.1	-0.2	-3.1	0.6	-5.5
P04	-4.9	1.8	1.8	0.2	-1.0	1.6
P05	0.4	2.5	0.2	3.6	-0.3	-0.2
P06	1.1	-4.4	0.8	1.1	1.1	-1.1
P07	-0.9	-4.0	0.5	-0.8	-0.3	-0.9
P08	0.1	-4.7	-5.1	-1.9	-4.4	-1.8
P09	1.3	1.9	0.2	-0.2	1.3	-0.8
P11	1.6	-6.7	-0.5	-2.5	-0.9	-0.3
P12	-1.9	-10.4	1.9	-3.7	-0.3	-7.8
P13	-1.8	-4.0	-1.9	-5.7	-1.7	-3.1
P14	-1.5	-1.1	-1.8	-2.7	1.5	-0.8
P16	-1.5	5.2	-0.1	1.9	0.2	0.6
P17	-0.1	-3.3	0.3	2.9	-1.3	1.2
P18	0.3	-5.5	0.7	-3.5	0.7	-6.5
P19	1.7	1.7	-0.1	0.5	0.7	2.3
P20	-1.6	-8.1	-1.3	-5.3	-1.4	-2.7
P21	-1.2	-5.9	-0.6	0.7	-0.6	1.8
P22	1.7	-2.0	-0.2	1.0	1.1	-3.6
P24	-2.8	-4.2	-1.2	-5.2	-2.8	-5.3

	Degrees of Freedom	F	p	Partial eta-squared
Auditory Condition	2	1.3904	0.260754	0.065000
Error	40			
Vision	1	5.6390	*0.0276845	0.219938
Error	20			
A.C * Vis.	2	1.4241	0.252678	0.066470
Error	40			

Endpoint Absolute Error – Primary Axis (mm)

	NoSound		SimpleMetronome		ComplexMetronome	
Participant	**Vision**	**NoVision**	**Vision**	**NoVision**	**Vision**	**NoVision**
P01	5.7	8.5	5.0	8.0	6.5	9.6
P02	4.3	6.6	3.4	5.3	2.4	6.1
P03	2.8	7.6	3.1	7.6	3.2	8.3
P04	8.2	7.3	4.1	6.3	5.7	8.7
P05	3.2	8.7	4.9	14.8	4.4	11.9
P06	3.5	9.9	3.5	8.1	3.9	6.2
P07	6.0	7.2	6.3	7.6	5.0	3.1
P08	4.5	7.1	6.6	9.1	4.5	9.0
P09	3.9	8.6	3.9	8.1	5.3	10.2
P11	3.6	9.0	2.7	6.1	2.1	6.9
P12	4.4	13.1	6.1	10.1	5.1	9.5
P13	3.7	6.6	4.2	8.7	4.4	5.8
P14	4.4	9.1	3.7	6.5	3.2	8.5
P16	6.6	7.6	4.1	7.5	3.3	6.5
P17	3.9	7.5	4.7	7.6	4.3	7.4
P18	2.6	7.5	2.4	6.9	3.4	6.9
P19	6.3	9.4	6.0	7.4	3.8	7.3
P20	5.3	11.5	3.7	7.3	5.4	10.3
P21	7.0	10.3	9.9	7.7	7.4	9.0
P22	2.1	7.1	2.6	6.0	4.6	8.0
P24	4.5	8.9	4.0	7.7	4.4	6.9

	Degrees of Freedom	**F**	**p**	**Partial eta-squared**
Auditory Condition	2	1.045	0.361043	0.049662
Error	40			
Vision	1	97.877	*<0.0000001	0.830332
Error	20			
A.C * Vis.	2	0.971	0.387524	0.046293
Error	40			

Participant	NoSound		Metronome		Drum	
	Vision	NoVision	Vision	NoVision	Vision	NoVision
P01	5.7	8.5	5.8	8.8	7.0	7.7
P02	4.3	6.6	2.9	5.7	2.8	4.3
P03	2.8	7.6	3.2	7.9	3.6	10.7
P04	8.2	7.3	4.9	7.5	7.1	8.8
P05	3.2	8.7	4.7	13.4	4.4	11.8
P06	3.5	9.9	3.7	7.2	3.8	7.4
P07	6.0	7.2	5.7	5.3	5.6	5.2
P08	4.5	7.1	5.5	9.0	5.9	7.2
P09	3.9	8.6	4.6	9.1	4.5	7.0
P11	3.6	9.0	2.4	6.5	2.7	5.2
P12	4.4	13.1	5.6	9.8	4.7	11.0
P13	3.7	6.6	4.3	7.2	4.4	6.8
P14	4.4	9.1	3.4	7.5	7.1	9.3
P16	6.6	7.6	3.7	7.0	6.9	8.2
P17	3.9	7.5	4.5	7.5	3.9	8.3
P18	2.6	7.5	2.9	6.9	3.0	9.1
P19	6.3	9.4	4.9	7.3	6.6	6.5
P20	5.3	11.5	4.6	8.8	3.8	8.0
P21	7.0	10.3	8.6	8.4	5.9	9.1
P22	2.1	7.1	3.6	7.0	2.7	6.7
P24	4.5	8.9	4.2	7.3	4.0	8.8

	Degrees of Freedom	F	p	Partial eta-squared
Auditory Condition	2	1.0522	0.358632	0.049981
Error	40			
Vision	1	82.7864	*<0.0000001	0.805422
Error	20			
A.C * Vis.	2	1.8376	0.172379	0.084150
Error	40			

Endpoint Absolute Error – Secondary Axis (mm)

Participant	NoSound		SimpleMetronome		ComplexMetronome	
	Vision	NoVision	Vision	NoVision	Vision	NoVision
P01	7.3	10.3	7.5	12.5	5.0	6.7
P02	4.9	7.3	4.7	7.0	3.8	6.6
P03	4.8	9.2	8.5	9.7	7.8	10.1
P04	5.9	7.4	3.5	9.4	5.0	6.4
P05	3.5	9.3	4.5	8.7	3.8	5.4
P06	5.8	7.5	4.4	5.8	4.9	10.5
P07	7.1	9.2	8.3	8.0	7.0	6.2
P08	3.2	5.1	3.0	7.2	3.0	5.6
P09	7.9	10.8	8.0	7.6	9.2	10.0
P11	3.8	5.2	3.5	5.8	2.8	6.9
P12	4.6	8.0	5.2	9.8	6.3	8.9
P13	3.3	5.4	4.0	6.8	4.4	5.2
P14	4.9	9.2	4.6	10.3	3.9	7.5
P16	8.0	18.0	9.5	10.1	7.8	6.5
P17	7.4	12.1	6.2	9.1	8.5	10.7
P18	3.4	3.4	2.6	3.4	3.8	4.7
P19	6.2	6.9	3.8	7.9	5.7	7.8
P20	5.4	8.2	4.6	7.5	4.1	7.0
P21	4.2	5.2	3.7	6.0	4.2	5.8
P22	4.7	5.0	5.0	3.8	4.3	5.1
P24	5.1	5.5	4.3	6.4	3.7	7.3

	Degrees of Freedom	F	p	Partial eta-squared
Auditory Condition	2	1.006	0.374834	0.047879
Error	40			
Vision	1	87.244	*<0.0000001	0.813509
Error	20			
A.C * Vis.	2	0.747	0.480325	0.036001
Error	40			

Participant	NoSound		Metronome		Drum	
	Vision	**NoVision**	**Vision**	**NoVision**	**Vision**	**NoVision**
P01	7.3	10.3	6.2	9.6	9.5	8.7
P02	4.9	7.3	4.3	6.8	3.6	7.7
P03	4.8	9.2	8.2	9.9	6.8	10.0
P04	5.9	7.4	4.3	7.9	6.5	5.3
P05	3.5	9.3	4.1	7.0	5.0	7.2
P06	5.8	7.5	4.7	8.1	6.3	7.6
P07	7.1	9.2	7.7	7.1	6.3	8.7
P08	3.2	5.1	3.0	6.4	3.3	7.2
P09	7.9	10.8	8.6	8.8	10.2	8.8
P11	3.8	5.2	3.2	6.3	3.5	4.6
P12	4.6	8.0	5.7	9.3	6.5	8.4
P13	3.3	5.4	4.2	6.0	3.3	5.9
P14	4.9	9.2	4.2	8.9	7.6	8.6
P16	8.0	18.0	8.6	8.3	8.7	8.8
P17	7.4	12.1	7.3	9.9	6.2	11.7
P18	3.4	3.4	3.2	4.0	3.0	3.6
P19	6.2	6.9	4.7	7.9	4.6	8.2
P20	5.4	8.2	4.4	7.2	5.4	6.7
P21	4.2	5.2	3.9	5.9	4.1	6.3
P22	4.7	5.0	4.7	4.4	5.0	4.9
P24	5.1	5.5	4.0	6.9	4.5	5.9

	Degrees of Freedom	F	p	Partial eta-squared
Auditory Condition	2	1.0247	0.368118	0.048740
Error	40			
Vision	1	83.0406	*<0.0000001	0.805902
Error	20			
A.C * Vis.	2	1.6240	0.209834	0.075102
Error	40			

Trajectory Variability – Primary Axis (mm)
Table of participant means too large for table – available upon request.

Complexity	**Degrees of Freedom**	**F**	**p**	**Partial eta-squared**
Auditory Condition	2	1.9335	0.157921	0.088153
Error	40			
Vision	1	0.0001	0.994041	0.000003
Error	20			
Position	4	11.1114	*<0.0000001	0.357149
Error	80			
A.C * Vis.	2	2.9269	0.065119	0.127661
Error	40			
Pos. * A.C.	8	2.3663	*0.01961837	0.105799
Error	160			
Pos. * Vis.	4	9.7796	*<0.0000001	0.328400
Error	80			
A.C. * Vis. * Pos.	8	1.3409	0.226920	0.062833
Error	160			

Source	**Degrees of Freedom**	**F**	**p**	**Partial eta-squared**
Auditory Condition	2	1.5574	0.223190	0.072244
Error	40			
Vision	1	0.9463	0.342280	0.045178
Error	20			
Position	4	113.9128	*<0.0000001	0.850649
Error	80			
A.C * Vis.	2	0.4707	0.627995	0.022993
Error	40			
Pos. * A.C.	8	9.6038	*<0.0000001	0.324411
Error	160			
Pos. * Vis.	4	20.0462	*<0.0000001	0.500577
Error	80			
A.C. * Vis. * Pos.	8	2.3707	*0.0193989	0.105973
Error	160			

Trajectory Variability – Secondary Axis (mm)
Table of participant means too large for table – available upon request.

Complexity	**Degrees of Freedom**	**F**	**p**	**Partial eta-squared**
Auditory Condition	2	0.1380	0.871541	0.006851
Error	40			
Vision	1	0.2939	0.593709	0.014483
Error	20			
Position	4	94.0584	*<0.000001	0.824651
Error	80			
A.C * Vis.	2	0.0800	0.923220	0.003986
Error	40			
Pos. * A.C.	8	0.7811	0.619918	0.037588
Error	160			
Pos. * Vis.	4	34.1899	*<0.000001	0.630928
Error	80			
A.C. * Vis. * Pos.	8	0.6070	0.771061	0.029457
Error	160			

Source	**Degrees of Freedom**	**F**	**p**	**Partial eta-squared**
Auditory Condition	2	0.0883	0.915657	0.004396
Error	40			
Vision	1	0.3305	0.571778	0.016256
Error	20			
Position	4	101.0097	*<0.000001	0.834724
Error	80			
A.C * Vis.	2	0.0788	0.924362	0.003925
Error	40			
Pos. * A.C.	8	0.6434	0.740320	0.031166
Error	160			
Pos. * Vis.	4	36.2622	*<0.000001	0.644522
Error	80			
A.C. * Vis. * Pos.	8	0.7689	0.630650	0.037021
Error	160			

Trajectory Position – Primary Axis (mm)
Table of participant means too large for table – available upon request.

Complexity	**Degrees of Freedom**	**F**	**p**	**Partial eta-squared**
Auditory Condition	2	0.121	0.886066	0.006030
Error	40			
Vision	1	4.092	0.056671	0.169837
Error	20			
Position	4	6331.764	*<0.000001	0.996851
Error	80			
Loc.	1	18.258	*0.00037165	0.477231
Error	20			
A.C * Vis.	2	0.695	0.505026	0.033581
Error	40			
A.C. * Pos.	8	2.435	*0.0164233	0.108532
Error	160			
Vis. * Pos.	4	3.143	*0.0187401	0.135808
Error	80			
A.C. * Loc.	2	0.754	0.477265	0.036309
Error	40			
Vis. * Loc.	1	2.963	0.100596	0.129052
Error	20			
Pos. * Loc.	4	28.519	*<0.000001	0.587788
Error	80			
A.C. * Vis. * Pos.	8	0.987	0.448258	0.047026
Error	160			
A.C. * Vis. * Loc.	2	0.601	0.553341	0.029156
Error	40			
A.C. * Pos. * Loc.	8	0.976	0.456565	0.046540
Error	160			
Vis. * Pos. * Loc.	4	1.220	0.308862	0.057500
Error	80			
A.C * Vis. * Pos. * Loc.	8	0.703	0.688755	0.033947
Error	160			

Source	**Degrees of Freedom**	**F**	**p**	**Partial eta-squared**
Auditory Condition	2	4.445	0.047812	0.181842
Error	40			
Vision	1	6543.687	*<0.00001	0.996953
Error	20			
Position	4	20.724	*0.0001936	0.508887
Error	80			
Loc.	1	0.678	0.513156	0.032809
Error	20			
A.C * Vis.	2	3.004	*0.0036269	0.130587
Error	40			
A.C. * Pos.	8	3.310	*0.01460471	0.141987
Error	160			
Vis. * Pos.	4	0.686	0.509258	0.033177
Error	80			
A.C. * Loc.	2	2.623	0.120977	0.115950
Error	40			
Vis. * Loc.	1	27.419	*<0.00001	0.578231
Error	20			
Pos. * Loc.	4	1.251	0.273227	0.058850
Error	80			
A.C. * Vis. * Pos.	8	0.703	0.501196	0.033948
Error	160			
A.C. * Vis. * Loc.	2	1.224	0.288014	0.057683
Error	40			
A.C. * Pos. * Loc.	8	0.902	0.466894	0.043155
Error	160			
Vis. * Pos. * Loc.	4	1.043	0.406170	0.049564
Error	80			
A.C * Vis. * Pos. * Loc.	8	0.703	0.688755	0.033947
Error	160			

Trajectory Position – Secondary Axis (mm)
Table of participant means too large for table – available upon request.

Complexity	**Degrees of Freedom**	**F**	**p**	**Partial eta-squared**
Auditory Condition	2	0.429	0.653848	0.021020
Error	40			
Vision	1	0.150	0.703054	0.007422
Error	20			
Position	4	11.114	*<0.000001	0.357197
Error	80			
Loc.	1	6393.122	*<0.000001	0.996881
Error	20			
A.C * Vis.	2	2.638	0.083949	0.116512
Error	40			
A.C. * Pos.	8	3.726	*0.0005057	0.157057
Error	160			
Vis. * Pos.	4	0.254	0.906650	0.012523
Error	80			
A.C. * Loc.	2	0.901	0.414065	0.043129
Error	40			
Vis. * Loc.	1	2.300	0.145042	0.103129
Error	20			
Pos. * Loc.	4	3171.217	*<0.000001	0.993733
Error	80			
A.C. * Vis. * Pos.	8	1.304	0.245133	0.061200
Error	160			
A.C. * Vis. * Loc.	2	0.413	0.664227	0.020249
Error	40			
A.C. * Pos. * Loc.	8	0.577	0.795715	0.028043
Error	160			
Vis. * Pos. * Loc.	4	1.479	0.216410	0.068850
Error	80			
A.C * Vis. * Pos. * Loc.	8	0.345	0.946879	0.016968
Error	160			

Source	Degrees of Freedom	F	p	Partial eta-squared
Auditory Condition	2	0.523	0.596478	0.025505
Error	40			
Vision	1	0.226	0.639590	0.011178
Error	20			
Position	4	12.331	*<0.000001	0.381394
Error	80			
Loc.	1	6637.330	*<0.000001	0.996996
Error	20			
A.C * Vis.	2	1.609	0.212677	0.074480
Error	40			
A.C. * Pos.	8	3.849	*0.000361	0.161396
Error	160			
Vis. * Pos.	4	0.279	0.890861	0.013750
Error	80			
A.C. * Loc.	2	1.029	0.366725	0.048920
Error	40			
Vis. * Loc.	1	2.806	0.109473	0.123041
Error	20			
Pos. * Loc.	4	3201.326	*<0.000001	0.993791
Error	80			
A.C. * Vis. * Pos.	8	1.042	0.406917	0.049518
Error	160			
A.C. * Vis. * Loc.	2	0.510	0.604571	0.024848
Error	40			
A.C. * Pos. * Loc.	8	0.883	0.532077	0.042291
Error	160			
Vis. * Pos. * Loc.	4	1.733	0.150775	0.079758
Error	80			
A.C * Vis. * Pos. * Loc.	8	0.415	0.910665	0.020333
Error	160			