VISUAL PERTURBATIONS IN MANUAL OBSTACLE AVOIDANCE

THE EFFECTS OF AN UNEXPECTED VISUAL PERTURBATION ON HAND PATH TRAJECTORIES IN MANUAL OBSTACLE AVOIDANCE

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LAY ABSTRACT

It is well known that individuals are able to successfully aim to targets in environments that are both predictable and unpredictable. Additionally, these trajectories are successfully modified in the presence of an expected obstacle resulting in a change to the optimal movement to incorporate the location of the obstacle. What is less understood, however, is how individuals respond to the sudden onset of an obstacle along the optimal trajectory. This thesis characterizes these behaviours using a manual obstacle avoidance task wherein obstacles unexpectedly appear to obstruct the preferred movement pathway. The behavioural response to this perturbation is indicative of the performance of more cautious movements, adapted for the worst-case scenario. On average, individuals compromise between the biomechanical and computational demands of the task to execute wide trajectories that do not need to be updated during movement execution, a response that is potentially identified in an autism spectrum population.

ABSTRACT

Perturbations to the upper limb in aiming tasks act to force individuals to modify their movements using online control processes. Individuals are able to successfully counteract these mechanical and perceptual perturbations to accurately acquire a specific target goal. What is less well understood is how individuals self-initiate a change to their trajectory during obstacle avoidance. A series of two studies were conducted to better understand the effects of a visual perturbation when performing two-dimensional sliding aiming movements during a manual obstacle avoidance task when a second set of obstacles appeared unexpectedly along the preferred, optimal trajectory. On each trial, a planned obstacle appeared at 25%, 50% or 75% of the movement amplitude. On some trials, a second set of obstacles appeared early or late in the movement to force participants to make online corrections or adapt their preferred trajectory to successfully reach the specified target. Results revealed that the mere possibility of the unexpected second obstacles influenced the overall trajectory and movement kinematics (i.e., whether that second obstacles appeared or not). Despite performing the movement in the same amount of time, participants executed a more lateral avoidance trajectory and reached higher accelerations later and further into the movement. We suggest that this pattern of behaviour is indicative of an optimal movement strategy such that the potential for an online correction resulted in individuals planning for the worst-case scenario.

The presentation of a case-study for an individual with autism spectrum disorder (ASD) provides insight into potential differences in obstacle avoidance tasks when compared to a matched control. Despite relative differences in execution behaviour, the

individual with an ASD successfully completed the task. This provides potential support for the sparing of motor execution processes within this population.

Taken together, we suggest that optimal movement strategies may be better defined on a more individual basis. That is, what is optimal for one population might not be optimal for another.

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LIST OF ABBREVIATIONS

ANOVA:	Analysis of variance
ASD:	Autism spectrum disorder
BAPQ:	Broader Autism Phenotype Questionnaire
CNS:	Central nervous system
DE:	Distal early
DL:	Distal late
DO:	Distal obstacle
HSD:	Honestly significant difference
L:	Leftwards
LB:	Left between
ME:	Middle early
ML:	Middle late
MO:	Middle obstacle
MT:	Movement time
NO:	No obstacle
PA:	Peak acceleration
PE:	Proximal early
PL:	Proximal late
PO:	Proximal obstacle
PV:	Peak velocity
R:	Rightwards
RB:	Right between
S1:	Study 1
S2:	Study 2
SD:	Standard deviation
TAPA:	Time after peak acceleration
TAPV:	Time after peak velocity
TD:	Typically developing
TTPV:	Time to peak velocity

DECLARATION OF ACADEMIC ACHIEVEMENT

This thesis is the original work of Jessica Skultety, who was responsible for the collection and analyses of data, as well as manuscript preparation. As the M.Sc. supervisor, Dr. Jim Lyons was involved in the conceptualization of the experimental idea, study design, and editing and reviewing all chapters.

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CHAPTER 1: LITERATURE REVIEW

1.1 GOAL-DIRECTED MOVEMENTS

1.1.1 The two-component model of aiming

The study of goal-directed aiming movements provides important insight into how the central nervous system (CNS) utilizes and integrates multiple sources of sensory stimuli to perform successful goal-directed movements. Seminal work by Woodworth (1899) found that the execution of an aiming movement consisted of individual components related to different aspects of limb control. He interpreted these results to suggest that the entire, global movement is in fact a serially executed combination of two distinct components (i.e., the first iteration of a two-component model of manual aiming). By fragmenting such a movement into its specific “constituent” components, or submovements, a more detailed picture regarding the control and execution processes involved in its performance emerges.

According to Woodworth, the first phase of a manual aiming movement, typically termed the ‘initial impulse’ or ‘ballistic phase’, is characterized by a rapid, stereotyped movement that propels the limb close to the vicinity of the target (Woodworth, 1899). This is typically marked by the first discontinuity, identified as a zero-crossing in an acceleration trace (Brooks, 1974), and is termed the primary submovement. This initial, ballistic, portion of the movement is thought to fall under central, feed-forward control such that this portion of the movement is pre-programmed based upon specific task constraints as well as the available visual information prior to movement onset. At the time, this ballistic phase of the movement was thought to unfold uninfluenced by changes in visual information due to the delay in processing visual feedback (Woodworth, 1899).

The second phase of the movement, termed by Woodworth as the ‘current control phase’ or now more commonly the ‘homing phase’, is characterized by a slower movement that contains potentially numerous discontinuities, or secondary submovements (Woodworth, 1899; Elliott, Helson, & Chua, 2001). This portion of the movement falls under feedback-based control and the discontinuities are indicative of potentially numerous submovements that allow the effector to accurately land within the bounds of the target. These latter, smaller submovements provide important information regarding the use of online control through visual and proprioceptive feedback as a comparison between the location of the limb in space, relative to the target location, is computed and corrections to the movement are made (Woodworth, 1899; Elliott et al., 2001). For example, a movement that contains many secondary submovements within the homing phase is interpreted as utilizing continuously processed response-produced feedback to guide the movement to an accurate termination. This inference is built upon the idea that the secondary accelerations or movement reversals comprising the submovements(s) serve to correct for an initially suboptimal ballistic burst that would otherwise fall short (or too far) of the intended target. Conversely, a movement with few or no such corrective submovements is considered to have unfolded with minimal concurrent corrections to the original movement plan.

Such analyses of goal-directed movements typically employ important performance and kinematic measures that provide valuable information for the processes of movement regulation. A complete movement, that is, the time from the signal to move until the end of the movement, has traditionally been broken down into two time intervals. The first of these intervals is known as the reaction time (RT), or the time between the signal to move and the onset of the movement. During this time, individuals pre-plan a movement trajectory by generating a motor program that effectively allows them to reach the end target. This measure provides valuable information regarding planning processes, such that longer RTs are typically associated with greater planning demands.

The second interval, known as the movement time (MT) is considered to be the time between the movement onset and the movement offset. The ballistic and homing phases of the movement comprise this interval, and it is from this portion of the trajectory that the integrity and execution processes of the movement can be inferred (Woodworth, 1899). The distinct phases of the two-component model can be partitioned using measures of peak velocity (PV) and its derivative, peak acceleration (PA). Specifically, the time from movement onset until PV is reached is termed the time to peak velocity (TTPV). The time from PV until target acquisition is termed the time after peak velocity (TAPV). The TTPV and the TAPV correspond to Woodworth's ballistic and homing phases, respectively. Additionally, PA provides information into the pre-planned phase of the movement and endpoint accuracy allows for comparisons of terminal endpoint errors.

1.1.2 Adaptations to the two-component model

In the years following the development of the two-component model (Woodworth, 1899), numerous studies continued to explore the interaction of these dual processes to explain the commonly found speed-accuracy trade-off (Fitts, 1954). Fitts' Law (Fitts, 1954), used to describe this trade-off, states that a relationship between the

MT and spatial accuracy exists in goal-directed aiming movements. Specifically, MTs are found to increase linearly when aiming to smaller targets, and vice versa.

In an effort to explain the processes governing this speed-accuracy trade-off, numerous models were developed to characterize the phases of limb control. The iterative corrections model (Keele, 1968; Crossman & Goodeve, 1983) proposed that the initial portion of the movement unfolds through the use of a motor program, or a set of structured muscle commands that allow for movement execution without the need for peripheral feedback. However, in accordance with visual processing time, it was suggested that a second motor program is actually engaged earlier than previously believed, at around 200ms (Keele & Posner, 1968) to correct for errors associated with the first motor program. Following the initial phase of the movement, each correction was a submovement that proportionally minimized errors using feedback from the preceding submovement until the end target was acquired. Specifically, this model attributed longer MTs to a greater number of absolute corrections to the movement, resulting in less error. Around the same time, Beggs & Howarth (1970) proposed the single correction model, postulating that a ballistic movement did in fact bring the limb close to the target but was followed only by a single correction at approximately 290ms, based on visual feedback. Longer movements thus allow the limb to be closer to the target prior to the single correction; however, shorter, more rapid movements, do not provide enough time for a correction to be made. Inconsistencies in both of these models in explaining a lack of multiple corrections in aiming movements, and faster visual processing times than previously believed (Carlton, 1992), led to the development of a more refined model to explain the distribution of primary submovement endpoints.

The optimized submovement model (Meyer, Abrams, Kornblum, Wright, & Smith, 1988) suggests that the inherent noise present in the motor system influences movement execution and the terminal location of the primary submovement. This results in a normally distributed, stochastic output of primary submovement endpoints, where the center of the distribution lies in the middle of the target. What this model failed to capture was that a bias towards target undershoots is commonly observed (see Elliott, Hansen, Mendoza, & Tremblay, 2004). In contrast to Meyer et al. (1988), Elliott et al. (2004) attributed this bias to the idea that primary submovement endpoint errors are not all equal. Specifically, that target overshoots are more costly than target undershoots, as overcoming an inertia of zero velocity, or a movement reversal, requires more time and energy to correct. Thus, a more relevant model in goal-directed aiming movements captures the optimization of both speed and energy such that over time the distribution of primary movement endpoint errors that overshoot the target is minimized (Elliott et al., 2004; Lyons, Hansen, Hurding, & Elliott, 2006). With practice, individuals become better able to plan movements, thus decreasing the variability in primary submovement endpoints, while still minimizing target overshoots. Specifically, over time, individuals become better able to regulate the muscular forces needed to propel the limb towards the target in the initial ballistic phase.

Though these dual-process models explain the mechanisms underlying the speed-accuracy trade-off differently, they all characterize the components of movements as discrete entities. A similar theme across these models is that they propose that the initial phase occurs uninfluenced by feedback, whereas the latter phase unfolds after sufficient time for visual processing to occur. Contrary to this, recent work suggests that the initial, ballistic phase of the movement is actually regulated by feedback-based processes, giving rise to a more continuous model of control (Elliott et al., 2010).

1.2 THE MULTIPLE-PROCESS MODEL

1.2.1 Rethinking the dichotomy of the ballistic and homing phases

To account for the very early corrections to movements, Elliott et al. (2010) proposed a multiple-process model for goal-directed behaviours. This framework maintains that while there are still two identifiable components in goal-directed aiming movements, the first distance-covering phase is not as exclusively ballistic and uninfluenced by feedback as once thought. Instead, during the initial phase of movement, early proprioceptive and visual information is compared to the expected sensory consequences, thus acting as a form of continuous control. This continuous processing results in decreases in the variability of primary submovement endpoints with practice (Elliott, Hansen, & Grierson, 2009). Contrary to the stochastic properties proposed by Meyer et al. (1988), this model suggests that primary endpoint variability arises from a consideration of the temporal and energy costs of overshooting and undershooting a target, resulting in a distribution that is centered short of the target (see Elliott et al., 2010).

1.2. Vision for online control

Continuous control refers to the idea that online processes are not limited to the second phase of the movement, but are in fact present throughout the entire duration (Elliott et al., 2010). Thus, the division between the two phases is not always as exclusive as previously believed (Elliott, Carson, Goodman, & Chua, 1991).

This finding was specifically highlighted in a study by Elliott et al. (1991) where individuals performed aiming movements in full vision, no vision, and delayed no vision tasks. In the no vision condition, the room lights were extinguished upon movement initiation, and in the delayed no vision task, the room lights were extinguished just prior to movement initiation, both resulting in the inability for participants to receive visual feedback regarding target or limb position throughout the execution of the movement. Despite being significantly more accurate in acquiring the target when full vision was available, submovements were observed in both tasks, however there was no difference in their frequency compared to when vision was occluded (Elliott et al., 1991; Khan, Elliott, Coull, Chua, & Lyons, 2002). The presence of these corrective submovements when visual information was removed conflicts with the initial reasoning that their presence occurs as a result of feedback-based control (Chua & Elliott, 1993). Instead, this finding lends support for the role of continuous control, such that online corrections are able to occur very early in the movement as a result of early visual and proprioceptive processes, prior to the influence of visual feedback. It is this multisensory integration of visual and proprioceptive information that facilitates accuracy corrections throughout the movement. Even when these sources of sensory information are in contrast to one another, these early control mechanisms are able to minimize errors within the system, supporting the use of continuous control (Grierson & Elliott, 2009), These corrections arise from internal, forward models of limb control that predict what is supposed to happen as the movement unfolds. Error reduction processes are then executed when there is a mismatch between the expected and the perceived sensory consequences, and these processes are seen to influence the movement prior to the effector reaching the vicinity of the target (see Elliott et al., 1991).

1.2.3 Vision as a dominant source of sensory information

Visual information plays an important role during goal-directed movements as it provides integral information regarding the behavioural context. That is, through a combination of feed-forward and feedback processes, visual information is taken in, interpreted, and representations of objects within the environment are created (see Gilbert & Li, 2013).

Interestingly, the availability of visual information can affect measures prior to movement execution. For example, when visual information is knowingly available throughout the movement, lower RTs are observed (Khan et al., 2002; Hansen, Glazebrook, Anson, Weeks, & Elliott, 2006). This is attributed to the notion that individuals spend less time planning a movement when visual-based feedback is available as they know they will be able to correct any errors as the movement unfolds. Additionally, the availability of vision during a movement typically results in asymmetric velocity profiles, supporting the notion that a larger proportion of the movement is spent in the TAPV (i.e. in the corrective phase of the movement) where visual feedback is used to optimize trajectory endpoint and reduce errors. It is suggested that individuals use this strategy to propel the limb as close to the target as possible to allow for more time in the latter, feedback-based portion of the movement (Hansen et al., 2006).

When vision is knowingly occluded during an action, increases in RT (Hansen et al., 2006), decreases in MT (Elliott et al., 1991; Chua & Elliott, 1993; Brière & Proteau, 2017), and a larger proportion of the movement being spent in the TTPV (Elliott et al., 1991; Chua & Elliott, 1993; Elliott et al., 1999; Khan et al., 2002) are observed. More symmetric velocity profiles with lower observed PVs (Hansen et al., 2006) are also noted. Taken together, these findings are interpreted to suggest that the removal of vision forces a more rapid movement, wherein participants develop a more feed-forward movement strategy. The longer RTs observed demonstrate a greater time spent planning a movement, contrary to when vision is available. Interestingly, when the availability of vision is unknown, individuals tend to plan for the worst-case scenario. That is, movements contain similar qualities to when vision is knowingly occluded (Hansen et al., 2006; Elliott et al., 2014).

It is evident that the availability of visual information is important for accuracy and performance optimization. Humans rely heavily on visual information, making it a dominant source of sensory information in goal-directed behaviour. As a result, vision is highly influential in one’s perceptual experience of the world. The two-visual systems hypothesis (Goodale & Milner, 1992) suggests that there is a functional division within the visual processing pathway. The ventral pathway is characterized by vision for perception, and the dorsal pathway is characterized by vision for action (Goodale &

Milner, 1992; Milner & Goodale, 2008). Specifically, the ventral stream is responsible for the planning of an action as it transforms visual information into mental representations, and identifies possible target objects. On the other hand, the dorsal stream is responsible for the online control of movements that form an action through the use of bottom-up information to specify movement parameters, for example the trajectory of a reach. Hence, Milner & Goodale (2008) argue that both pathways contribute to an action, but in different ways.

Numerous studies support this division between the dorsal and ventral processing streams, demonstrating that individuals incorrectly estimate the length of objects during perceptual illusions, despite correctly adjusting their grip aperture as they program their movement towards the object (Aglioti, DeSouza, & Goodale, 1995). Additionally, reaching and grasping behaviours are impacted in individuals with damage to the ventral stream such that they are still able to successfully navigate around objects (Schindler et al., 2004) and skilfully execute the necessary grasps, but are unable to identify where to grasp an object (Carey, Harvey, & Milner, 1996). Thus, it is evident that the dorsal pathway plays an important role in visual guidance for action.

1.3 PERTURBATIONS IN MANUAL AIMING

1.3.1 The importance of examining perturbations

Numerous study designs have explored the processes involved in propelling the limb to a constant, unchanging target (Carson, Goodman, Chua, & Elliott, 1993; Elliott et al., 1993; Elliott et al., 2004; Elliott & Hansen, 2010). It is however important to consider the implications of forcing individuals to adjust their movement to a new end goal. By changing the conditions of a movement, researchers are better able to understand the online control processes that underlie the modification of trajectories and the point at which corrections to movements can be made. This can be done through the use of perturbations, which afford researchers a deeper look at the processes that underlie the control of movements.

1.3.2 Types of perturbations

Perturbations to goal-directed movements result in a change in movement requirements. Through, for example, changes in target location, size or the forces required to move the limb, researchers are able to examine the dissociation of the different processes that underlie these aiming movements.

Studies examining the effects of perturbations on goal-directed aiming support the multiple-process model (Elliott et al., 2010) and the ability for continuous control throughout the movement. Early portions of the movement have been found to be regulated by early proprioceptive and visual information. By manipulating these early control processes, Grierson & Elliott (2009) induced a mismatch between the expected and perceived velocity of the limb. Despite this incongruency, individuals were still able to rapidly adjust the early stages of their movement, demonstrating the use of early, continuous control.

The latter, corrective component is also involved in updating and correcting an aiming movement using online control. Unexpected changes in target size (Heath, Hodges, Chua, & Elliott, 1998; Hansen & Elliott, 2009) or target location (Elliott, Lyons, Chua, Goodman, & Carson, 1995), wherein the target appears to 'jump' after movement onset force individuals to adjust their movement during movement execution to successfully acquire the end target. When the target size changes, the initial portion of the movement, or the TTPV, remains relatively unchanged and contains characteristics of the trajectory towards the initial target size or amplitude. Instead, it is the TAPV that reflects characteristics of the final target size (Heath et al., 1998; Hansen & Elliott, 2009). The importance of the corrective component of the movement is demonstrated when the target changes location. Movements performed with the dominant hand are less variable and performed more rapidly, suggesting that the advantage is associated with the ability to complete the TAPV, or homing phase, of the movement more efficiently rather than the ability to execute an initial corrective movement more rapidly (Elliott et al., 1993). Taken together, these studies suggest that individuals are better able to regulate the corrective impulses of submovements more effectively with the dominant hand, and that the available visual information in the latter part of the movement is incorporated into a new trajectory thereby reflecting online regulation of the movements.

Manipulations of gain, or the force required to move the limb towards a target, have also been used to explore the corrective processes during aiming movements (Elliott et al., 1999). Unexpected increases or decreases in the magnetic attraction between a metal stylus and the home plate allowed for increases or decreases in the gain respectively. When a greater amount of force was needed to move the stylus from the home position, increases in the TAPV, or the homing phase, were found as more adjustments were needed to correct for the increase in force necessary to propel the limb forward. Despite the need for a longer proportion of the movement to be spent in the

TAPV, participants were still able to adjust the corrective component of their movement to successfully land on the target.

When evaluating the characteristics of aiming movements of the upper limb, the multiple-process model (Elliott et al., 2010) provides a valuable framework for understanding the processes involved in the movement. Even when a movement is perturbed and individuals are forced to make corrections, the separate phases of the movement remain clear with adjustments being made in both the early and late phases. Though continuous control is observed throughout the movement, changes to the relative proportion of time spent in each of these phases effectively allow individuals to reach the end target, implicating the critical role of the corrective phase of the movement in regulating the online control of target acquisition.

These observed behaviours occur in goal-directed aiming tasks, or tasks in which the trajectory remains unobstructed. While studies invoking perturbations provide important information regarding the online control processes that govern movement execution, it is unclear what happens when an obstruction prevents an individual from executing such a direct trajectory. Thus, the impact of an obstacle within the direct movement context must be explored.

1.4 OBSTACLE AVOIDANCE

1.4.1 Obstacles acting as a perturbation

The multiple-process model as an explanation of aiming movements has been well documented in the literature (Elliott et al., 2010). However, it is less well-defined when an obstacle is presented along the movement pathway. Here we suggest that obstacle avoidance tasks act as a special class of movement perturbation such that individuals are forced to potentially modify their trajectory to successfully complete the task.

By definition, an obstacle acts as a barrier, falling directly within the movement pathway of the effector. In contrast to distractors, which act to draw attention away from the task (Welsh, Elliott, & Weeks, 1999), individuals must actively pay attention to the specific location of an obstacle and deviate around it to successfully acquire the end target and complete the task. Thus, while distractors are objects within the environment that are to be ignored, obstacles are objects within the environment that must be dealt with.

In accordance with aiming tasks, straight hand paths are often observed in trials when an obstacle is not present (Dean & Brüwer, 1994, 1997; Nashed, Crevecoeur, & Scott, 2014). In contrast, the addition of a two-dimensional obstacle along the movement pathway reliably forces a curved trajectory (Dean & Brüwer, 1994, 1997; Jax & Rosenbaum, 2007). That is, individuals are able to successfully alter their trajectory (i.e., the original movement plan) to account for the location of the obstacle within the movement context, by deviating around it. While this finding is to be expected, what is interesting is how individuals alter their movement behaviours as a result.

When an obstacle is placed along the movement pathway, the direct trajectory of the movement is disturbed, resulting in increases in both planning and execution demands. These results are found across studies using virtual, two-dimensional obstacles (Chapman & Goodale, 2010), and those using physical, three-dimensional obstacles (Saling, Alberts, Stelmach, & Bloedel, 1998; Tuitert et al., 2017). MT is found to be highly correlated with path curvature, such that increases in path curvature lead to slower movements (Lacquaniti, Terzuolo, & Viviani, 1983; Jax & Rosenbaum, 2007). This is attributed to the added consequence an obstacle imposes. Simply the potential for a collision imposes a consequence to the movement resulting in the execution of more cautious movements (Chapman & Goodale, 2010). Additionally, this turn of the deviation typically occurs once the obstacle has been cleared as individuals begin to return their trajectory towards the end target (Dean & Brüwer, 1994).

An examination of the movement kinematics supports a more cautious approach to avoidance movements. As opposed to the smooth, asymmetrical velocity profile observed when an obstacle is not present, the addition of an obstacle causes a more biphasic profile, corresponding to the path curvature (Dean & Brüwer, 1994). Specifically, movement velocity increases as individuals begin their movement, followed by decreases in velocity as the hand approaches the obstacle. After deviating around it, individuals increase their velocity a second time to propel the limb towards the target, resulting in this biphasic velocity profile. In contrast, when successful task completion necessitates an avoidance behaviour over a physical obstacle, a single peak in the velocity profile is observed, such that PV occurs earlier in the movement (Tuitert et al., 2017).

However, these contrasting velocity profiles may actually be due to the nature of the task. When performing a two-dimensional, virtual task along the horizontal plane, the force of gravity is constant throughout the movement. Thus, to limit the risk of collision, more time can be spent deviating around the obstacle as it can be made up for after the obstacle has been successfully cleared, on the way to the target. In contrast, when the movement occurs in a three-dimensional context, one must overcome the initial force of gravity to lift the effector off and away from the starting surface, and then decelerate and counteract the force of gravity to smoothly land on the end target. In this latter instance, a biphasic velocity profile would be inefficient given the nature of the task.

In addition to a more cautious approach to movements when an obstacle is presented within the movement context, as evidenced by the kinematics of the movement, consecutive trial performance is also affected. Specifically, the presence of an obstacle on a previous trial can affect the trajectory of the subsequent trial (Jax & Rosenbaum, 2007; van der Wel, Fleckenstein, Jax & Rosenbaum, 2007). This phenomenon, termed ‘hand path priming’, occurs when the presence of an obstacle is unpredictable. It results in increases in hand path curvature on trials when an obstacle is not present to exceed those of trials in which obstacles knowingly never appear (Jax & Rosenbaum, 2007). These carry-over effects are hypothesized to occur as a result of the dorsal stream retaining an abstractly defined hand pathway in working memory that can be applied to different conditions. Thus, even when the most biomechanically efficient route to the target is a straight trajectory, individuals plan for the worst-case scenario and compromise biomechanical and computational efficiency (Jax & Rosenbaum, 2007; van der Wel et al., 2007; Cohen, Biddle, & Rosenbaum, 2010). Specifically, individuals develop these abstract spatiotemporal forms to help eliminate the need for planning on each trial. By not prioritizing biomechanical efficiency over computational load, individuals are able to control movements in an efficient manner, when task conditions are uncertain. This spatiotemporal form can be used from one movement to another, thus conserving computational resources by limiting changes in the movement plan when only slight differences are required.

1.4.2 The effects of mechanical perturbations during obstacle avoidance

The way in which humans perform movements is controlled by the coordination of potentially numerous degrees of freedom within the body. As a result, there are an infinite number of ways a movement can be performed. This redundancy within the motor system highlights the many ways in which the same behavioural goal can be accomplished, such that when an obstacle lies within the path of a movement, multiple potential trajectories are available to overcome its displacement.

In an attempt to understand the chosen trajectories when an obstacle is present along the movement pathway, alternative explanations for the use of feedback have been proposed. One such theory, the theory of optimal control, resolves this redundancy dilemma by suggesting that movements are predicted, and ultimately executed, by optimizing motor commands for a particular aspect of motor performance, such as minimizing movement time (see Scott, 2004; Todorov, 2004). Optimal feedback control stipulates that optimal performance is achieved through the use of all available information at each time point of the movement. This moment-to-moment calculation produces an optimal trajectory, with the lowest accumulated cost, that is the best action under the circumstances in which it is performed (Todorov & Jordan, 2002).

Studies examining the effects of a mechanical perturbation, or an unexpected force that displaces the limb from its original intended trajectory, have found that rapid motor responses are able to adapt to the disturbance by either correcting for the perturbation, or altering the trajectory to continue in the direction of the perturbation to a new end goal (Nashed, Crevecoeur, & Scott, 2012, 2014). Specifically, when the mechanical disruption to the trajectory is small, the system is able to rapidly correct for the disturbance and pass between two horizontally aligned obstacles. When the mechanical disruption is large, the hand deviates completely around the two obstacles prior to returning to the target position. Interestingly, medium perturbations contain a mixture of both trajectory types. The selection of which strategy is used is primarily attributed to the location of the hand in space when it is perturbed (Nashed et al., 2014). These findings are in line with theories of optimal control, suggesting that the optimal trajectory is that with the lowest accumulated cost (see Todorov, 2004). In accordance with this model of optimal control, when a perturbation disrupts a trajectory, another path or end goal may become more favourable, demonstrating the flexibility of trajectory planning (Nashed et al., 2014).

1.4.3 Top-down versus bottom-up processing

Obstacle avoidance tasks provide an alternative way of viewing perturbations to movements. Optimal feedback control suggests that specific behaviours emerge from environmental changes primarily through a proprioceptively driven, “bottom-up” fashion.

For example, if an individual reaches towards a mug of tea and their arm is perturbed by an unanticipated force, this perturbation to the musculature results in a change within the proprioceptive system. These mechanical changes in lower-level aspects of control are then utilized to guide behaviours to produce an optimal control output, such that another aspect of the mug might become more favourable to grasp (Nashed et al., 2014). In contrast, traditional information processing based models of aiming and reaching behaviours would suggest that the visual context (e.g., the current position of the moving limb relative to the target goal) is incorporated continuously into the original movement plan and that this information is utilized to rapidly update and correct the original motor plan in response to the perturbation based on the properties of the mug. While both theoretical frameworks result in optimal trajectories, it is the computation of these trajectories that differ.

1.5 NEUROATYPICAL POPULATIONS

1.5.1 The importance of understanding atypical visual-motor control

The studies and movement contexts reported here assume that all of the underlying perceptual and action-related processes are subserved by an intact or otherwise uncompromised perceptual motor system. It is known, however, that some populations are challenged in this regard. For example, it has been found that individuals with Down syndrome and Williams syndrome demonstrate compromised aiming movements. Compared to matched controls, movement kinematics show a greater number of discontinuities, resulting in longer movement times across these populations (Elliott, Welsh, Lyons, Hansen, & Wu, 2006; Hodges, Cunningham, Lyons, Kerr, & Elliott, 1995). In line with the multiple component model, discrete corrections to the movement are typical, thus a larger number of corrections is thought to represent errors in planning and feed-forward control. Therefore, deficits in the initial planning stages of movement likely result in a greater reliance on discrete control, however the presence of corrections demonstrates that visual, feedback-driven online control remains intact.

1.5.2 Autism spectrum disorder

Recently, a considerable amount of work has examined motor tasks in those with an autism spectrum disorder (ASD). These individuals have been shown to plan and execute movements differently compared to a typically developing (TD) population (e.g. Glazebrook, Elliott, & Lyons, 2006). Those with an ASD demonstrate specific difficulties in integrating visual information into the online control of goal-directed movements (Spencer et al., 2000). Thus, unexpected stimuli or changes to the movement context typically highlight the differences observed between TD and ASD populations. By characterizing these differences in individuals with a compromised perceptual-motor system, researchers are better able to understand how an intact system allows for efficient movement control, while adopting potential interventions that target these deficiencies in the compromised population.

1.6 SUMMARY AND STUDY OBJECTIVES

1.6.1 Summary of the literature

Goal-directed behaviours include both aiming and obstacle avoidance movements. It is clear that underlying performance and kinematic measures provide important information regarding the integrity of these movements, specifically in how they are prepared and executed. During aiming tasks, online control processes allow for rapid and reliable adjustments to the movement following a perturbation (e.g. Hansen & Elliott, 2009). The multiple process model suggests that these control processes exist throughout the duration of the movement and that prior to visual feedback, early sensory feedback is utilized to correct movements (Grierson & Elliott, 2009; Elliott et al., 2010). While responses to mechanical perturbations in avoidance tasks have demonstrated the flexibility of the sensorimotor system in choosing optimal trajectories (Nashed et al., 2014) it is unknown how individuals update their movements in response to unexpected perceptual obstacles. Unlike mechanical perturbations that push the limb off of the initial trajectory path, these obstacles require self-initiated changes to the movement.

1.6.2 Study objectives

A series of two studies were conducted that collectively serve to characterize differences in movement planning and avoidance strategies. The first study is used to define the preferred movement pathway taken to avoid an expected obstacle. This obstacle is presented prior to movement onset, thus allowing participants to incorporate its location into their initial movement plan. Though these trajectories have been well documented in the literature (e.g. Dean & Brüwer, 1994), the aim of this study was to calculate the optimal trajectory given the specific experimental setup of the task. This was conducted to understand whether a preferred trajectory existed within each condition, and if so, to allow for its calculation. In effect, our primary objective in this study was to create a participant-driven, quantifiable instantiation of a specific "optimum control" parameter (optimal trajectory). This information was necessary for the experimental setup and hypotheses of the second study which aimed to perturb this preferred, optimal avoidance trajectory. The second study then placed a second set of unexpected obstacles along the previously identified movement pathway to understand how avoidance behaviours were influenced when an online correction was potentially needed. By manipulating the timing of the onset of the second set of obstacles, we examined how these avoidance behaviours changed when an early or late correction to the trajectory was needed.

In addition, a single case study is presented to provide insight into the hypothesized differences in motor behaviours in a population with known challenges in integrating visual information into the online control of movements (ASD). From these data, we seek to compare and contrast relative differences in avoidance behaviours of a participant on the autism spectrum with a matched participant from the TD sample.

1.6.3 Hypotheses

In the first study it is hypothesized that the presentation of an obstacle during the planning phase of the movement will allow for individuals to successfully incorporate its location into their motor program. Additionally, this unchanging visual environment will result in low trajectory variability across participants, as avoidance behaviours are found to be fairly consistent (Nashed et al., 2012). In line with previous findings (i.e. Dean & Brüwer, 1994), it is hypothesized that straight hand paths will be observed when an obstacle is not present.

In the second study, it is hypothesized that the use of continuous control in goal-directed movements will allow for individuals to successfully update their movement plan to avoid a second, unexpected obstacle regardless of its onset time. By manipulating the onset timing of these second obstacles, different components of the movements are perturbed. Consistent with the multiple process model, it is hypothesized that both the early and late onsets of these unexpected obstacles will allow for enough time to incorporate their spatial location to successfully deviate around them, resulting in fewer collisions. If this hypothesis were not supported, the behaviours would be more indicative of a ballistically-driven system that does not incorporate feedback into the initial movement phase..

If these hypotheses are supported, this work will contribute to literatures in manual obstacle avoidance, as well as provide support for the multiple process model. Specifically, it will demonstrate that individuals are able to self-initiate corrections to movements during movement execution as a result of a changing visual environment.

CHAPTER TWO: STUDY ONE

The purpose of Study 1 was to calculate the preferred movement pathway that a typically developing (TD) population uses to avoid an expected obstacle.

2.1 METHODS

2.1.1 Participants

Consistent with previous work, a total of twelve participants (5 males), between the ages of 20-40 years were recruited from the McMaster University population to participate in this study. All participants were identified as TD, and presented with no self-reported upper limb musculoskeletal impairments and normal or corrected-to-normal vision. Prior to participation, individuals signed the informed consent form which outlined the nature of the study and the experimental protocol. Participants completed the Edinburgh Handedness Inventory (Oldfield, 1971), which provided a negative or positive laterality index (LI) score that corresponded with either left- or right-hand dominance, respectively. Results from this questionnaire show that three left-hand dominant, and nine right-hand dominant individuals completed the task. Participants also completed the Broader Autism Phenotype Questionnaire (BAPQ) (Hurley, Losh, Parlier, Reznick & Piven, 2007). This questionnaire has been shown to be a reliable measure of assessing personality and language characteristics of the broader autism phenotype, including repetitive behaviours, language skills, and social deficits. These data were collected to assess whether participants potentially possessed characteristics of the phenotype that could influence their performance on the task. The cut-off points for the BAPQ are presented based on subscale characteristic and sex (M/F): Aloof (3.25/3.00), Pragmatic language (2.95/2.70), Rigidity (3.65/3.25) and Total score (3.35/3.25) (see Hurley et al., 2007).

A summary of participant characteristics can be found in Table 2.1, including results pertaining to handedness and BAPQ scores. Upon completion of the study, participants received financial compensation in the amount of $5 for their time.

2.1.2 Instrumentation and Data Acquisition

Positional data were collected using a Wacom PTK1240 Intuos 4 tablet and stylus (Wacom, Kazo, Japan). The spatial coordinate system was measured relative to the participant; anterior-posterior movements in the vertical direction represented movements in the X direction, or primary movement axis, whereas medial-lateral movements in the horizontal direction resulted in changes in the Y direction, or secondary movement axis. Relative to the participant, the origin (0,0) was set to the bottom left of the computer monitor.

The computer mouse, represented by a red circle measuring 0.5cm in diameter, was controlled by movements of the stylus on the graphics tablet. Relative to the participant, anterior-posterior and medial-lateral movements of the stylus resulted in a visual representation of the mouse moving upward and downward, and leftward and rightward on the monitor, respectively. The computer monitor (ASUS VP247H-P, Taipei, Taiwan) refresh rate was set at 60Hz and custom E-Prime® software (Version 2.0, Psychology Software Tools Inc., Sharpsburg, PA) was used to run the experiment. Data were collected for three seconds at a collection frequency of 500Hz.

2.1.3 Experimental Procedures and Protocol

Participants sat at a table centrally facing a vertically oriented computer monitor (57cm x 34cm, 1080 x 1920 pixels) affixed to a custom-built apparatus positioned posterior to the tablet (Figure 2.1). All movements were made by sliding the stylus along the tablet with their previously identified dominant hand. Participants were instructed to move as quickly and accurately as possible while avoiding any obstacles along the movement pathway. Participants were also instructed to keep the stylus upright to minimize small wrist deviations. This was done to encourage full upper limb movements with the shoulder and elbow, rather than small corrections with the wrist.

Each trial began with a “Ready” screen that allowed participants to prepare for the proceeding trial. The subsequent screen displayed a black background with a yellow square (1cm x 1cm) starting position and a yellow outlined square target position (1cm x 1cm) vertically aligned and separated by an amplitude of 40 cm. Participants began each trial on the starting home position and had to remain within the bounds of the home position for 1 second before the next screen was triggered. In an obstacle-present trial, a perceptual obstacle was then presented followed by a variable foreperiod (800-1600ms), before the end target filled in yellow to cue movement onset. This variable foreperiod was used to reduce anticipation effects. In obstacle-absent trials, movement onset was cued following the same foreperiod protocol after participants remained in the home position for the necessary time.

Upon presentation of the movement cue, participants moved the stylus as fast as possible to the end position while avoiding any potential obstacles presented along the movement pathway. In an obstacle-present trial, perceptual obstacles were presented 100ms prior to movement onset as two-dimensional yellow squares (1cm x 1cm) via the computer monitor. Obstacles were vertically aligned with the starting home position and appeared proximal, middle, or distal to the participant, corresponding to 25%, 50% or 75% of the movement amplitude, respectively.

Prior to the experimental portion of the session, four practice trials were conducted to familiarize participants with the task. Afterwards, a total of 100 experimental trials were performed, consisting of 25 trials to each of the four conditions: No obstacle (NO), Proximal obstacle (PO), Middle obstacle (MO) or Distal obstacle (DO), presented in a pseudo-randomized order. Five blocks of 20 trials were performed, between which participants had the opportunity to take a break.

Two-dimensional positional data of the cursor were collected that allowed for the collection of performance measures, including MT and starting and end locations of the trajectories, as well as kinematic data, including measures of trajectory distance, and temporal and spatial measures of velocity, and acceleration. The TTPV was calculated as the interval from movement onset until PV was reached, and the TAPV was calculated as the interval from PV until movement end. Proportional TAPV (i.e. TAPV/MT) was then computed to provide a measure of this period, unaffected by individual differences in MT (Glazebrook et al., 2006).

2.1.4 Data Analyses

Movement trajectories were analyzed for each participant using custom Matlab software (Version 2016b, Mathworks, Natick, MA). Raw movement data were filtered at

6 Hz with a second order dual-pass Butterworth filter. MT was defined as the time interval between moving beyond the distal bound of the home position, and reaching the end position. Movement end was calculated to be the point at which the stylus, or hand velocity, fell below 0.5cm/s for 40ms (Liu & Todorov, 2007). Distance profiles were differentiated once to obtain velocity profiles, and a second time to obtain acceleration profiles. Two potential trajectory types were identified: leftwards (L), described trajectories that deviated around the obstacle to the left, and rightwards (R), described trajectories that deviated around the obstacle to the right.

Movement trajectories from each trial were divided into 25 temporal bins, each representing 4% of the movement, and the average location was calculated by summing the location of the cursor in each of the frames in a bin and then dividing by the number of frames within the bin (Hansen, Elliott & Khan, 2008). To understand the preferred movement pathway taken by participants, the average trajectory for both rightwards and leftwards movements and their associated variability were computed for each condition. This was done by calculating an overall average and standard deviation for each of these 25 bins.

Outliers were defined as trials in which participants i) hit an obstacle, ii) made an anticipation error, iii) had a delayed reaction, or iv) moved the cursor beyond the bounds of the screen. These outliers were computed based on the raw data obtained from each trial. A trial was categorized as an anticipation error if the first movement point was beyond 265.4 pixels in the primary movement axis. A delayed reaction was categorized as a trial in which 100 frames, or 200ms, of the movement fell below 8% of the movement amplitude.

2.1.5 Statistical Analyses

Descriptive statistics were generated, consisting of mean values for performance measures (MT and start and end points), and upper limb kinematics (including trajectory distance, velocity, and acceleration). Significance for all statistical tests was set at $p < 0.05$**.** Assumptions of normality and sphericity were tested using Shaprio-Wilk and Mauchly's tests (χ^2), respectively. A Greenhouse-Geisser correction factor (ε) was applied to the degrees of freedom and test statistic when data violated these assumptions of sphericity. Effect sizes were calculated using omega squared (ω^2), and can be interpreted using the magnitude of the effect: small ($\omega^2 = .01$), medium ($\omega^2 = .06$) and large ($\omega^2 = .14$) (Cohen, 1988).

A one-way repeated-measures analysis of variance (ANOVA) with four levels for Condition (NO, PO, MO, DO) was performed on the data to test for significant treatment effects for condition. Further analyses on all significant treatment effects, comprised of two or more means, were conducted using Tukey`s Honestly Significant Difference (HSD, $p < .05$).

2.2 RESULTS

A summary of the results for Study 1 are presented in Appendix A. Breakdowns of the preferred trajectory direction by participant (Table 2.2) and by condition (Figure 2.2) are presented. Additionally, trajectory tracings for each condition can be found in Figures 2.3-2.6, and the average trajectory for each condition can be found in Figure 2.7.

2.2.1 Performance measures

Movement Time: A main effect for condition, $F(3, 33) = 12.60$, $p < .01$, $\omega^2 = .04$, was observed, such that movements were performed faster in the NO condition compared to the PO, MO, and DO conditions. When an obstacle was present, individuals took longer to complete the movement, likely a result of the need to deviate around the obstacle.

Start position: A main effect for condition, $F(1.20, 13.18) = 7.05$, $p = .02$, $\omega^2 = .03$, on the start position in the primary movement axis was found to be significant. However, as expected, post-hoc analyses did not reveal differences between conditions. No main effect for condition, $F(1.18, 12.93) = 2.57$, $p = .13$, $\omega^2 = .04$, on the start position in the secondary movement axis was found. Together, these results indicate that participants began their trajectory similarly across conditions.

End position: No main effects for condition on the end position in the primary movement axis, $F(1.97, 21.63) = 3.00$, $p = .07$, $\omega^2 = .05$, or the secondary movement axis, $F(3, 33) = 1.27$, $p = .30$, $\omega^2 = .01$, were found to be significant. As expected, these results indicate that participants ended their movements similarly and within the bounds of the target across conditions.

2.2.2 Kinematic measures

Trajectory distance: A main effect for condition, $F(1.52, 16.70) = 17.49$, $p < .01$, $\omega^2 = .31$, was found, such that participants travelled a shorter distance in the NO condition compared to the PO, MO, and DO conditions. Trajectory distance likely corresponds to the curvature of the trajectory, such that greater distances are indicative of increased curvature.

Peak velocity: A main effect for condition, $F(3, 33) = 45.16$, $p < .01$, $\omega^2 = .05$, was found to be significant. Peak velocities in the NO and DO conditions were significantly greater than those in the other conditions, and each other. Peak velocities were highest in the NO condition, followed by the DO condition, suggesting that when no obstacle was present, or an obstacle was present further along the movement amplitude, participants took advantage of the ability to propel their limb further during the initial portion of the movement.

Time to peak velocity: A main effect for condition, $F(1.44, 15.88) = 9.05$, $p = 0.01$, $\omega^2 = .13$, was found. The NO and DO conditions were significantly less than the PO condition suggesting that participants reached PV earlier in the movement when no obstacle was present, or the obstacle was present further along the movement pathway.

Proportional time after peak velocity: A main effect for condition, $F(1.51, 16.65) = 8.41$, $p = .01$, $\omega^2 = .16$, was found. Participants spent a longer proportion of their movement in the TAPV in the DO condition than the PO condition.

Spatial location of peak velocity: A main effect for condition $F(1.63, 17.94) = 3.59$, $p = .06$, $\omega^2 = .11$, on PV in the primary movement axis approached significance. Though not significant, PV occurred further into the movement in the PO condition, compared to the

DO condition. No differences were found for the position of PA in the secondary movement axis, $F(1.34, 14.78) = 2.54, p = .13, \omega^2 = .03$.

Peak acceleration: A main effect for condition was found, $F(3, 33) = 7.53, p < 0.01, \omega^2 = .02$, such that individuals reached significantly higher accelerations in the NO condition than in the PO and MO conditions.

Time to peak acceleration: No main effect for condition was found, $F(3, 33) = 0.29, p = 0.84, \omega^2 = .00$, thus participants reached PA similarly across conditions.

Spatial location of peak acceleration: A main effect for condition, $F(3, 33) = 4.29, p = .01, \omega^2 = .04$, on PA in the primary movement axis was found to be significant. Specifically, PA occurred further along the primary movement axis in the NO condition than in the MO condition. However, no differences were found for spatial location of PA in the secondary movement axis, $F(1.18, 12.95) = 2.19, p = .16, \omega^2 = .03$.

2.3 DISCUSSION

The goal of this study was to examine movement trajectories when an expected obstacle could be incorporated into the initial movement plan. The presentation of an obstacle prior to movement onset allowed for individuals to plan and execute a movement trajectory that incorporated its spatial location to successfully deviate around the obstruction.

As expected, findings from this study replicate those from previous obstacle avoidance studies, such that curved trajectories are observed when an obstacle is present (i.e. Dean & Brüwer, 1997). Individuals altered their trajectories to deviate around the obstacle prior to successfully acquiring the end target. As predicted, clear differences in hand trajectories are observed between the condition without an obstacle, and those with an obstacle. Despite similar start and end points across all conditions, on average, individuals perform the task faster, reach higher peak velocities and accelerations, and travel a shorter distance when an obstacle is not present. When considering the nature of the task, these results are to be expected. Trajectories in the NO condition are straighter, as a direct movement pathway is able to be completed (Figure 2.3). When an obstacle is present however (Figure 2.4, Figure 2.5, Figure 2.6), this direct pathway is obstructed, thereby forcing a deviation within the trajectory to complete the task. From these results, increases in movement times and distances of the hand can be attributed to this required deviation.

These results also demonstrate that the location of an obstacle influences the movement kinematics. When an obstacle is located further along the movement amplitude, individuals reach higher peak velocities, and spend a larger proportion of the movement in the latter, corrective phase. Conversely, the opposite results are found for the condition in which the obstacle is located closer to the starting position. A lack of differences in movement time across these conditions suggests that individuals alter the structure of their movement depending on the obstacle location. Specifically, an obstacle present further along the movement pathway affords a spatial advantage such that there is a greater distance between the starting location and the point at which the trajectory must be modified to avoid a collision. In line with the multiple process model (Elliott et al., 2010), individuals are able to propel their limb faster and further during the initial portion of the movement to allow for a greater amount of time in the homing phase when an obstacle is located further along the movement amplitude. This allows for more time to ensure endpoint accuracy, while simultaneously reducing the risk of a collision with an obstacle.

The primary purpose of this study was to calculate the preferred movement pathway when avoiding a single, expected obstacle. When an obstacle was present, handedness was not specifically related to the preferred trajectory direction. That is, some participants chose to cross the midline of the body when performing the movement. Therefore, the average, optimal trajectory for each condition was computed for deviations directed in both directions. These average pathways and their associated variability are clearly demonstrated in Figure 2.7.

Table 2.1: Summary of participant characteristics.

Participant	Age	Sex	LI	Handedness	*BAPQ Results* Aloof	Pragmatic Language	Rigidity	Total score
1	23	F	100	R	3.08	2.58	3.67	3.11
2	23	F	80	R	1.67	1.83	4.50	2.67
3	27	F	100	R	1.58	1.92	2.83	2.11
4	24	F	75	R	2.58	1.42	2.50	2.17
5	31	F	90	R	2.25	2.25	2.33	2.28
6	24	M	75	R	1.83	2.58	2.08	2.17
7	21	F	-55	L	2.42	3.08	2.17	2.56
8	33	F	-40	L	2.08	1.92	2.83	2.28
9	33	M	85	R	2.33	2.50	2.67	2.50
10	39	M	85	R	4.00	2.83	2.75	3.19
11	32	M	-75	L	2.25	2.00	2.83	2.36
12	31	M	75	R	2.08	2.75	2.58	2.47

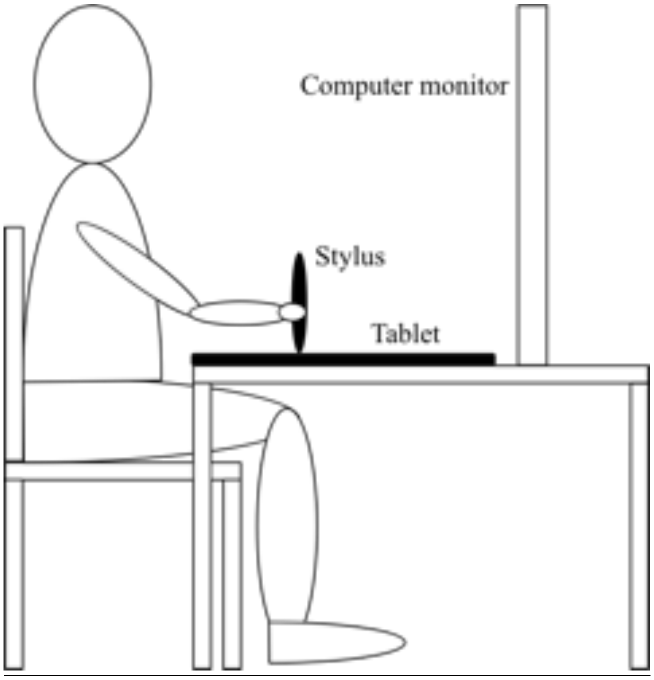
Age = 28.42 years ± 5.52; mean ± standard deviation

Table 2.2: Summary of trajectory direction, leftwards (L), and rightwards (R), performed as a function of each condition: No obstacle (NO), Proximal obstacle (PO), Middle obstacle (MO), Distal obstacle (DO).

		Participant												
		1	2	3	4	5	6	7	8	9	10	11	12	**Total**
NO		23	25	24	24	25	25	23	25	25	25	24	25	**293**
PO	L	0	0	0	11	0	7	23	0	11	0	24	22	**98**
	R	24	24	24	13	25	16	0	24	12	25	0	0	**187**
MO	L	0	0	0	13	0	17	24	0	3	0	25	1	**83**
	R	24	25	24	10	25	8	1	25	20	25	0	25	**212**
DO	L	0	0	0	10	0	11	24	0	7	0	24	1	**77**
	R	23	25	23	9	25	13	0	21	16	22	0	3	**200**
Total		**94**	**99**	**95**	**90**	**100**	**97**	**95**	**95**	**94**	**97**	**97**	**97**	**1150**

Figure 2.1: Diagram of experimental apparatus and setup (A) and layout of possible initial obstacle locations (B).

A



B

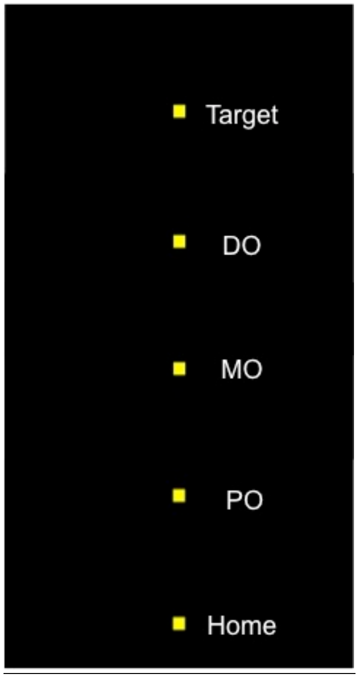


Figure 2.2: Total number of trajectories as a function of condition (Proximal obstacle (PO), Middle obstacle (MO), and Distal obstacle (DO)), and trajectory choice (leftwards (L), rightwards (R), leftwards between (LB), or rightwards between (RB)).

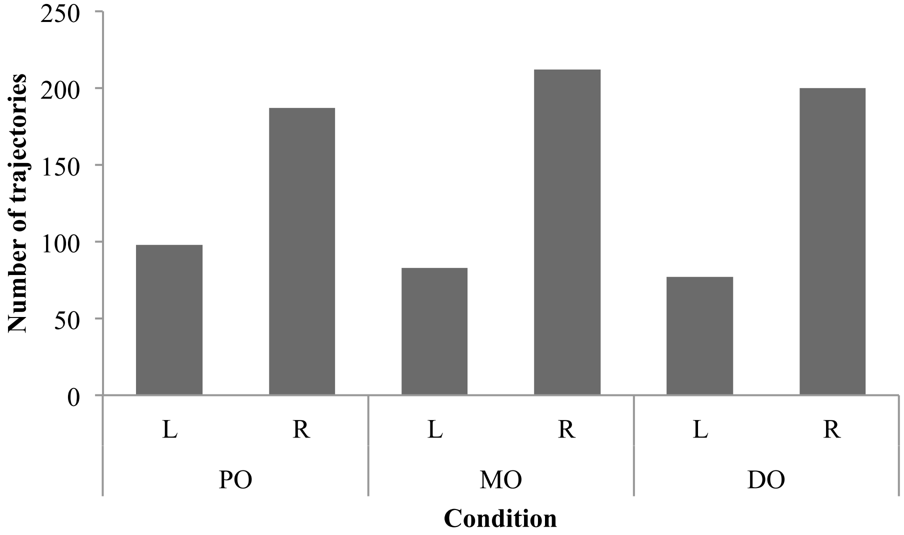


Figure 2.3: Trajectory tracings (A) and kinematic data (B) of all participants in the No Obstacle (NO) condition in Study 1. Temporal bins in Figure B correspond to the division of data points, such that Bin 5 represents 20% of the movement, and Bin 25 represents 100% of the movement.

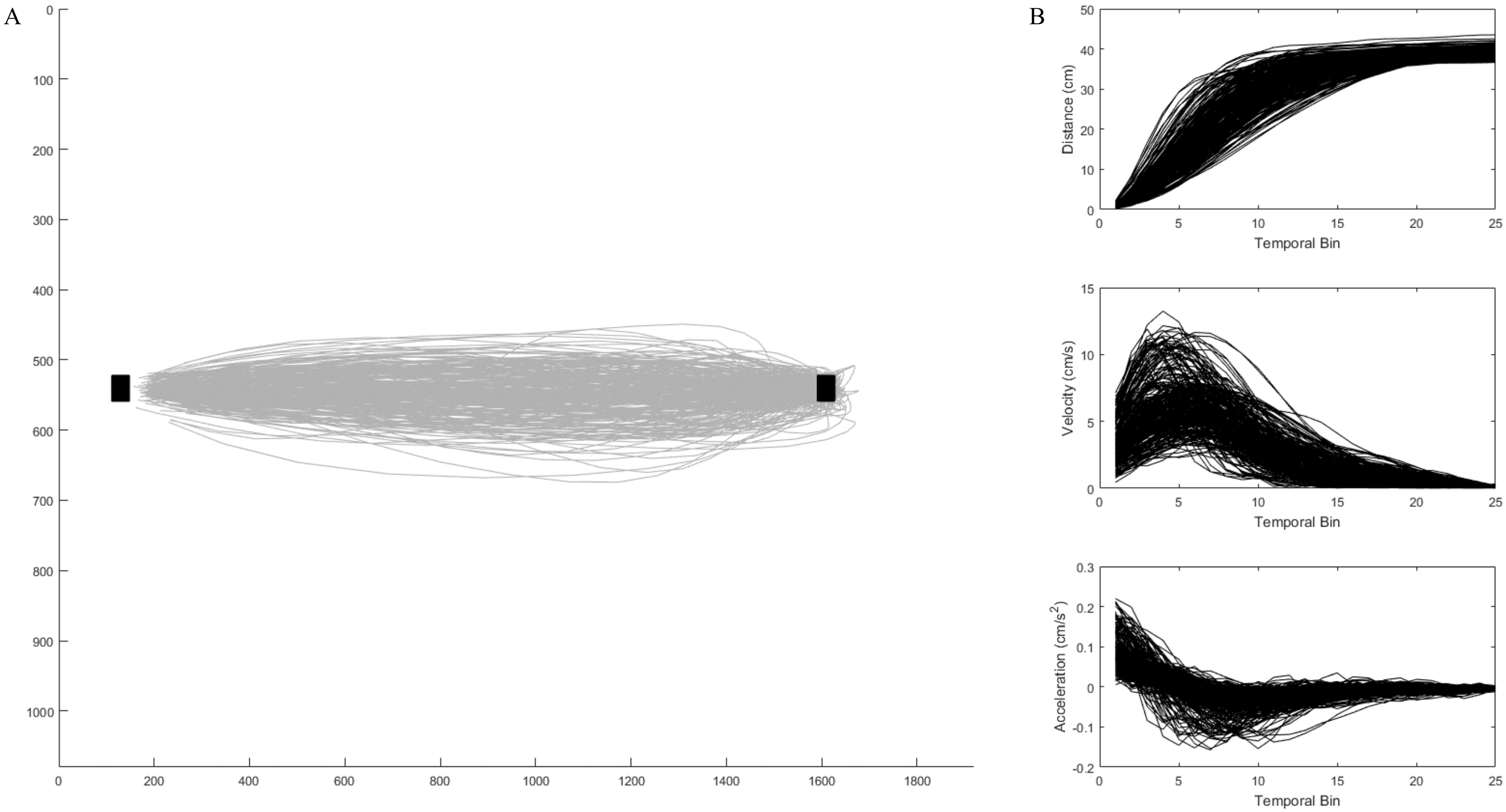


Figure 2.4: Trajectory tracings (A) and kinematic data (B) of all participants in the Proximal Obstacle (PO) condition in Study 1. Temporal bins in Figure B correspond to the division of data points, such that Bin 5 represents 20% of the movement, and Bin 25 represents 100% of the movement.

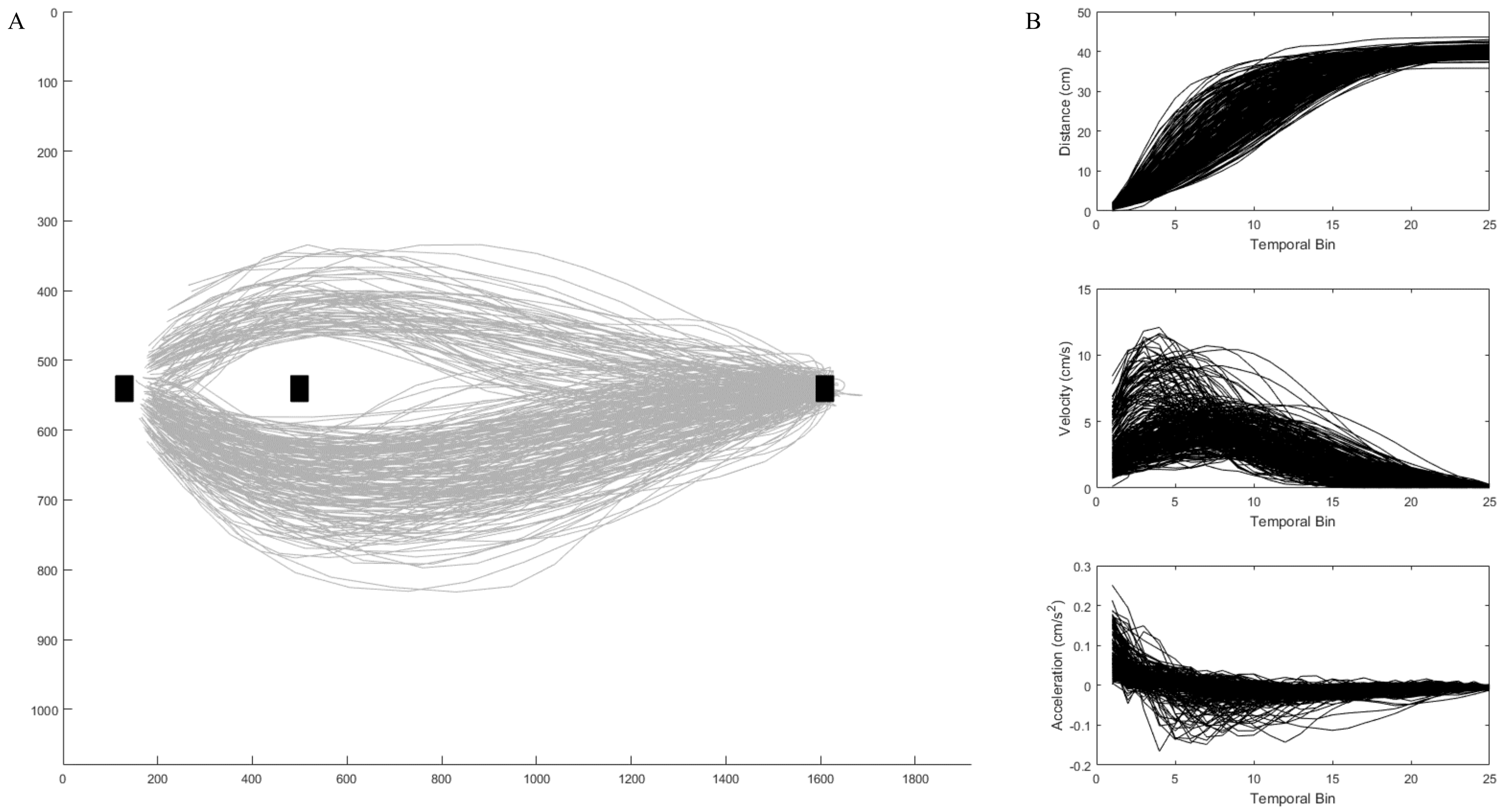


Figure 2.5: Trajectory tracings (A) and kinematic data (B) of all participants in the Middle Obstacle (MO) condition in Study 1. Temporal bins in Figure B correspond to the division of data points, such that Bin 5 represents 20% of the movement, and Bin 25 represents 100% of the movement.

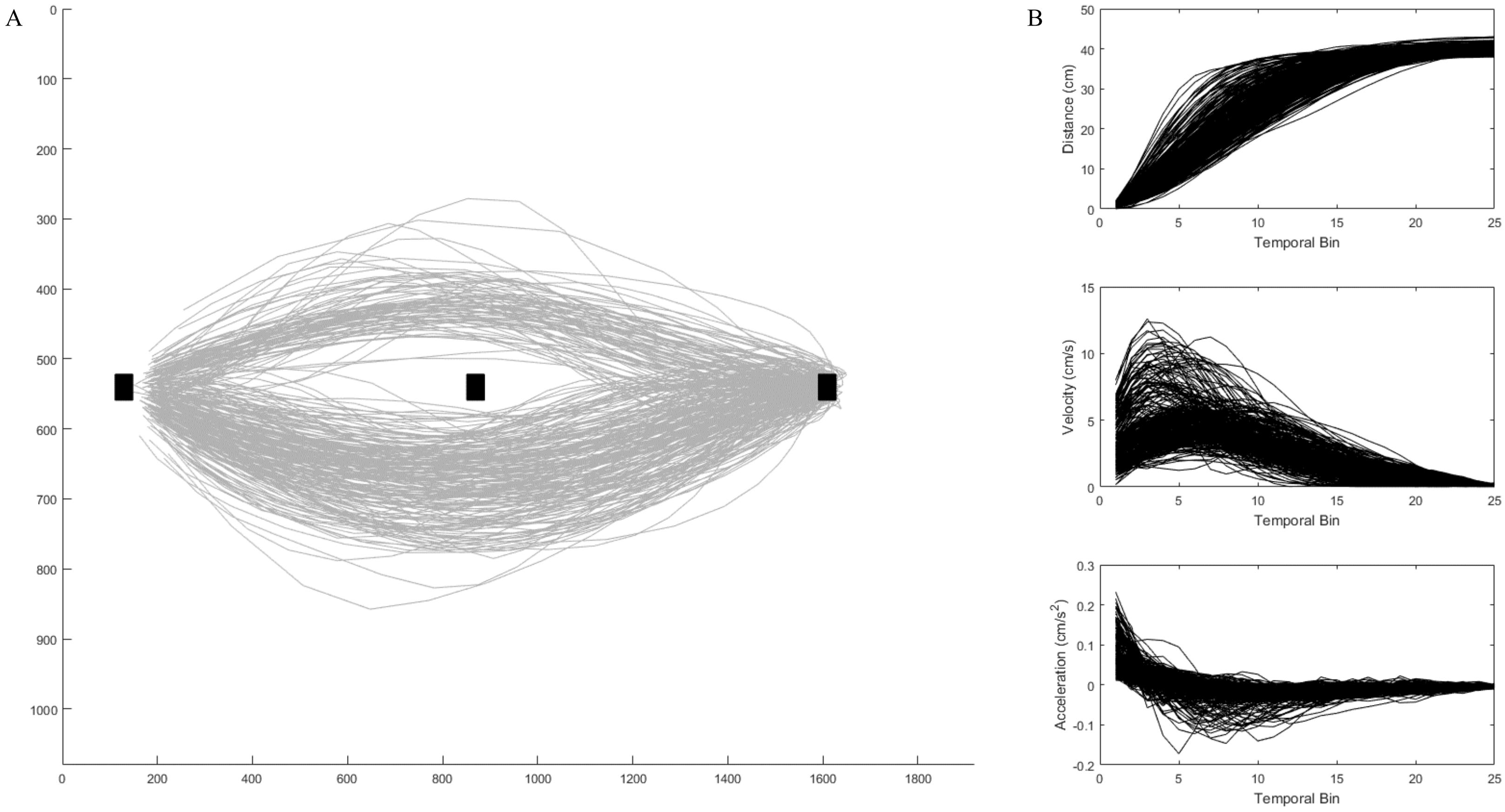


Figure 2.6: Trajectory tracings (A) and kinematic data (B) of all participants in the Distal Obstacle (DO) condition in Study 1. Temporal bins in Figure B correspond to the division of data points, such that Bin 5 represents 20% of the movement, and Bin 25 represents 100% of the movement.

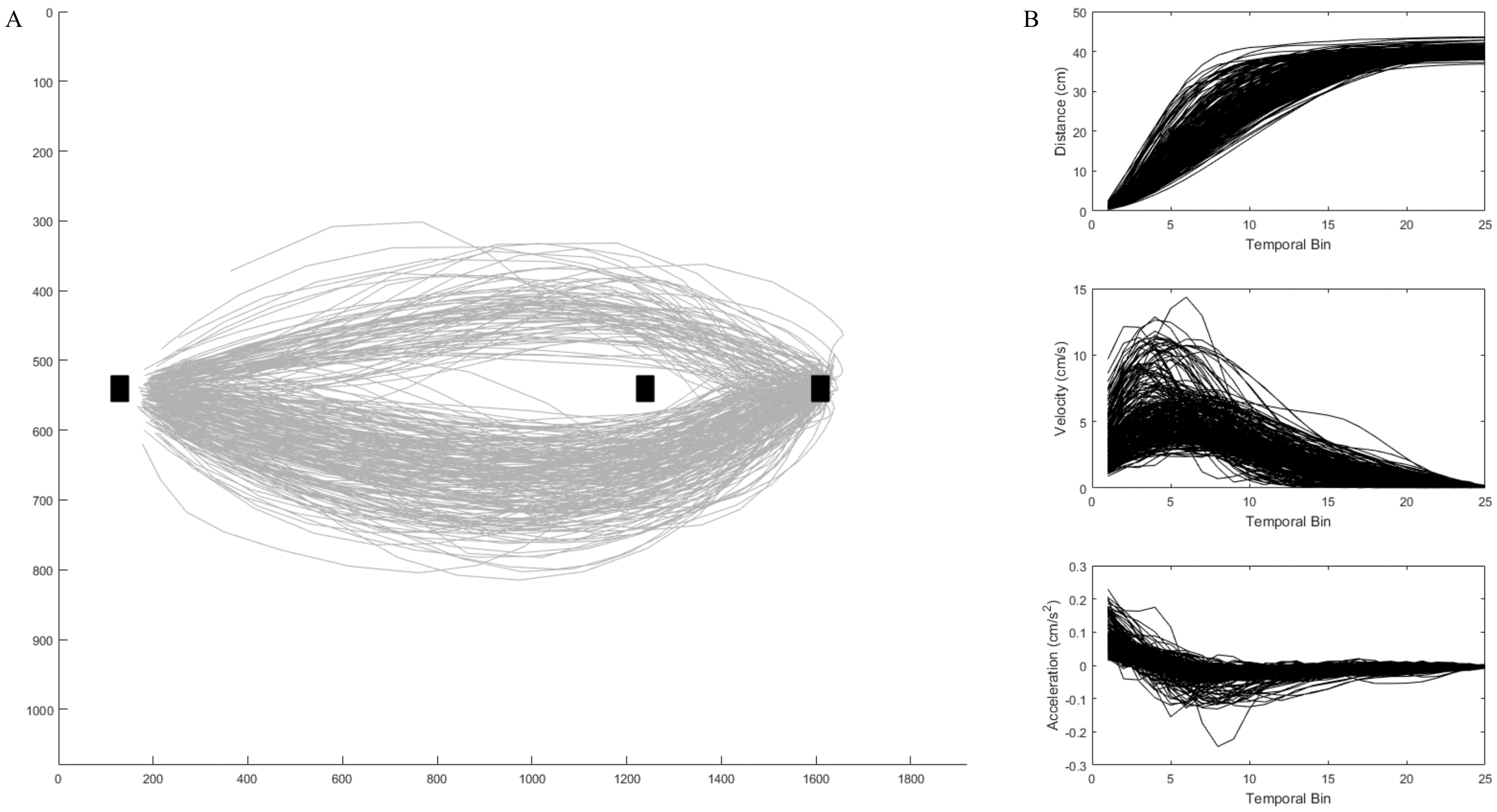


Figure 2.7: Trajectory tracings from the Proximal Obsatcle (A), Middle Obstacle (B), and Distal Obsatcle (C) in Study 1. The average trajectory (solid black line) and the standard deviation trajectory (dashed black line) are portrayed in each condition with the placement of the second set of obstacle.

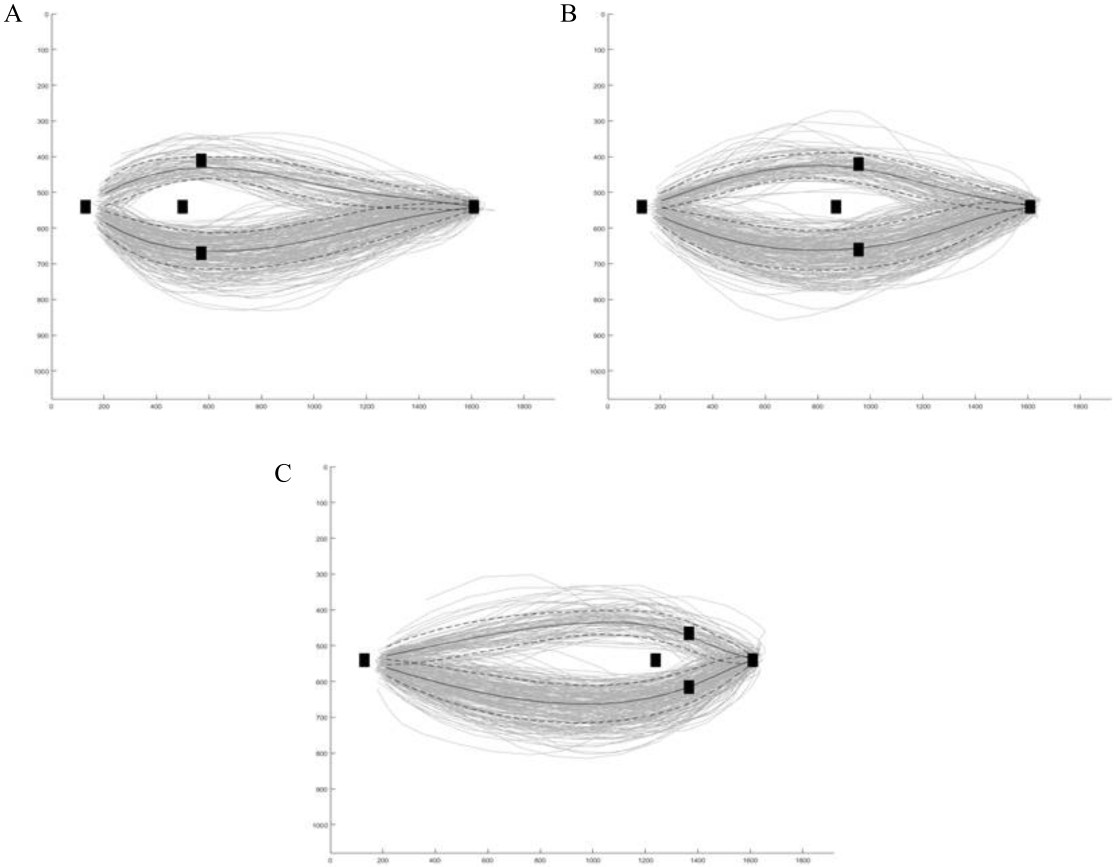


Figure 2.8: Mean time to peak velocity (ms) and standard error bars, as a function of condition for Study 1.

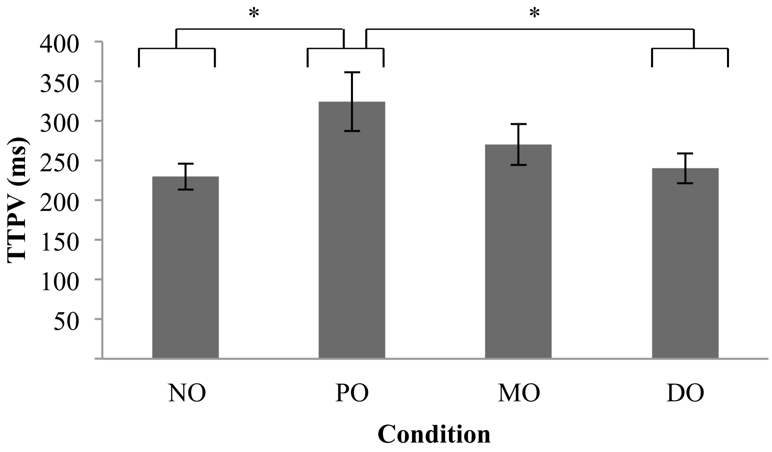
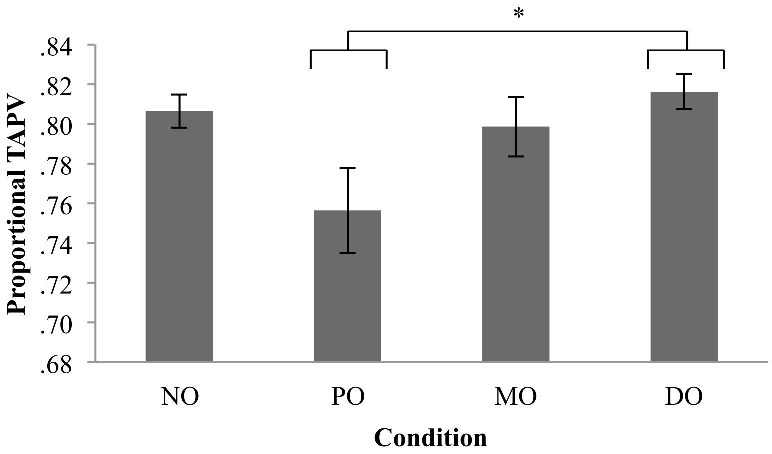


Figure 2.9: Mean proportional time after peak velocity and standard error bars, as a function of condition for Study 1.



CHAPTER 3: STUDY TWO

The purpose of Study 2 was to understand how limb trajectories changed as a result of the potential addition of a second set of unexpected obstacles. The location of these second obstacles was computed from the preferred movement pathway calculated in Study 1. These obstacles were placed along the trajectory preferentially taken in each condition in an attempt to perturb movements thus forcing participants to make an online correction to update and successfully carry out their movement. Their onset corresponded to the different phases of limb control in an attempt to disrupt the early and late feedback-driven processes identified by multiple component models of limb control (Woodworth, 1899; Elliott et al., 2001; Elliott et al., 2010).

3.1 METHODS

3.1.1 Participants

A total of twelve participants were recruited for this study, using the same inclusion criteria as Study 1. All participants were right-handed, novel to the task, and had not participated in the first study. Participant data were removed if >10% of trials did not qualify as being completed successfully. As a result, one data set was removed and eleven participants (6 males), between the ages of 20-40 years were included in the analyses. An independent samples t-test confirmed that there was no significant age difference between the average age of participants across both studies, $t(21) = .51$, $p = .62$.

Similar to Study 1, participants completed the Edinburgh Handedness Inventory, and the BAPQ. A summary of these results, including participant characteristics, can be found in Table 3.1. Participants received financial compensation for their time in the amount of $5.

3.1.2 Instrumentation and Data Acquisition

The instrumentation and data acquisition methods were identical to those in Study 1. To allow for a longer movement capture window, the collection frequency was modified to collect at 250Hz, resulting in a six second capture period. This study was also intended to be conducted in a population (i.e. ASD), that is known to take longer to produce movements, thus this increase allowed for the full capture of these potentially longer movements.

3.1.3 Experimental Procedures and Protocol

The apparatus was identical to that used in Study 1 (Figure 2.1). Similar to Study 1, each trial began with a "Ready" screen followed by the initial obstacle screen portraying the start position, the end target vertically aligned and separated by the same amplitude of 40 cm. In this study however, any initial obstacle was presented in unison with the start position and end target prior to movement onset. In Study 1, the separate appearance of the initial obstacle and the start position and end target induced a high number of false starts as individuals mistook the onset of the obstacle for the movement cue. Because a fewer number of trials were collected per condition in this study, the presentation of these stimuli simultaneously was an effort to reduce the number of error trials. After the cursor had remained within the bounds of the home position for one second, the variable foreperiod was triggered followed by the movement cue.

Similar to Study 1, upon presentation of the movement cue, participants moved the stylus as fast as possible to the end position while avoiding a potential initial obstacle presented along the movement pathway. A second set of obstacles also appeared in some trials, located distal to and on either side of the initial obstacle. Two possibilities for timing of these secondary obstacles were used: early and late. Early second obstacle onset was triggered at movement onset, whereas late second obstacle onset was triggered relative to the condition, when participants were 75% of the way between the home-position and the initial obstacle. The location of this second obstacle was calculated based on the results of Study 1, and placed along the preferred movement pathway where inter-participant trajectory variability was low (see Figure 2.7). As individuals preferentially chose to deviate towards the right in Study 1, the location of these obstacles was chosen relative to the preferred movement pathway of the rightwards trajectory. Both obstacles were located in the same position on either side of the initial obstacle, and the distance between the centers of each of the second obstacles relative to the initial obstacle was kept at 4 cm. This permitted for the same aperture across conditions.

Prior to the experimental portion of the session, a researcher demonstrated three trials to the participant. Following this, participants practiced each condition, for a total of 10 practice trials. Participants were given more practice trials in this study in an attempt to minimize the number of outliers resulting from incorrect performance. All participants were able to comfortably perform the task after the practice block. Afterwards, a total of 200 experimental trials were performed, consisting of 20 trials to each of the ten conditions: No Obstacle (NO), Proximal Obstacle (PO), Proximal Early (PE), Proximal

Late (PL), Middle Obstacle (MO), Middle Early (ME), Middle Late (ML), Distal Obstacle (DO), Distal Early (DE), or Distal Late (DL), presented in a pseudo-randomized order. Ten blocks of 20 trials were performed, between which participants had the opportunity to take a break.

The same performance and kinematic measures as in Study 1 were collected in this study. In addition, the point at which the onset of the second set of unexpected obstacles occurred was calculated for each trajectory. This was done to examine whether a perceptual perturbation affected trajectory path in a similar manner as a mechanical perturbation. Specifically, where trajectory direction is influenced by the position of the limb at perturbation onset (Nashed et al., 2014)

3.1.4 Data Analyses

Movement trajectories were analyzed using the same methodology as in Study 1. In trials where only one obstacle was present, the same trajectory types were identified as in Study 1: leftwards (L) and rightwards (R). The addition of the second set of obstacles also introduced two additional trajectory types: leftwards between (LB) occurred when a participant passed between the first and second obstacles from the left, and rightwards between (RB) occurred when a participant passed between these obstacles from the right. Trials were categorized as outliers using the same criteria; however a delayed reaction was not considered an outlier in this study. As the second set of unexpected obstacles occurred upon movement onset on some trials, a failure to continue a movement after leaving the home position could be categorized as part of the movement re-programming stage where participants considered a new movement strategy as a result of the change in movement context.

A custom Matlab (Version 2016b, Mathworks, Natick, MA) code was created to obtain the point in each trajectory when the second set of unexpected obstacles occurred.

3.1.5 Statistical Analyses

Similar statistical procedures were used in Study 2, as in Study 1. Significance for all tests was set at $p < .05$. A one-way repeated-measures ANOVA with four levels for Condition (NO, PO, MO, DO) was performed on the data to test for significant effects of condition for trials in which a second set of obstacles did not occur. The purpose of this analysis was to understand how the potential for a second set of unexpected obstacles influenced movement trajectories when the preferred movement pathway was not perturbed.

To understand how the presence and timing of the additional, second set of obstacles affected movements, a one-way repeated-measures ANOVA with nine levels for Condition (PO, PE, PL, MO, ME, ML, DO, DL, DE) was performed on the data. This analysis was conducted to examine differences across all obstacle-present conditions to understand how the potential presence and timing of a second set of unexpected obstacles perturbed movements.

Additionally, a 2 by 4 mixed factorial ANOVA with repeated measures on initial obstacle location (NO, PO, MO, DO) and between subjects factor of study (S1, S2) was performed on the data to compare the results of the similar conditions across both studies.

This was done to specifically understand how the potential for an unexpected perturbation influenced movement relative to when the movement context remained unchanged.

Further analyses on all significant effects, comprised of two or more means, were conducted using Tukey`s HSD ($p < .05$). In the analysis across all obstacle-present trials, relevant comparisons included comparisons across conditions with similar initial obstacle location, and across conditions with similar second obstacle onset time.

3.2 RESULTS

Results for the analyses across trials in which there was the potential for a second unexpected obstacle followed by the analyses across all obstacle-present trials are presented first.

3.2.1 Performance measures

Movement Time: A main effect for condition, $F(3, 30) = 13.82$, $p < .01$, $\omega^2 = .05$, was found to be significant. Specifically, movements in the NO condition were performed faster than the PO, MO and DO conditions, suggesting that movements made in the presence of a single, expected obstacle took longer than when no obstacle was present.

A comparison of the obstacle-present conditions found a main effect for condition, $F(8, 80) = 3.34$, $p < .01$, $\omega^2 = .01$. Of the relevant comparisons, MT was significantly longer in the DE condition than in the ME condition.

Start position: Main effects for condition on movements in the primary movement axis, $F(1.49, 14.88) = .17$, $p = .78$, $\omega^2 = .00$, and secondary movement axis, $F(1.38, 13.84) = 1.22$, $p = .31$, $\omega^2 = .00$, were not found to be significant.

A comparison of the obstacle-present conditions revealed an effect for condition for the primary movement axis, $F(2.35, 23.50) = 5.65$, $p = .01$, $\omega^2 = .14$. However, post hoc tests did not reveal any significant difference between the relevant conditions. Additionally, no effect of condition was found to be significant for the secondary movement axis, $F(1.39, 13.85) = 2.38$, $p = .14$, $\omega^2 = .01$.

Together, these results indicate that participants began their trajectories from similar start positions across all conditions.

End position: No main effect for condition on the primary movement axis, $F(3, 30) = .39$, $p = .76$, $\omega^2 = .00$, was found. However, a main effect for condition on the secondary movement axis, $F(3, 30) = 3.59$, $p = .03$, $\omega^2 = .11$, was found to be significant. Specifically, participants ended their movements slightly more laterally in the PO condition compared to the MO condition.

Main effects for condition on the primary movement axis, $F(8, 80) = 2.18$, $p = .04$, $\omega^2 = .07$, and the secondary movement axis, $F(8, 80) = 3.63$, $p < .01$, $\omega^2 = .14$, were found to be significant when comparing the obstacle-present trials. Post-hoc tests did not reveal any differences for the primary movement axis; however, participants ended their trajectory differently along the secondary movement axis in the DE condition compared to the PE condition. It is important to note however, that all movements were terminated within the end target boundaries, indicating successful target acquisition.

3.2.2 Kinematic measures

Trajectory distance: A main effect for condition, $F(1.47, 14.65) = 19.04$, $p < .01$, $\omega^2 = .16$ was found to be significant. Specifically, the trajectory distance in the NO condition was less than the distances in the PO, MO and DO conditions, suggesting that the average path of the trajectories was much more direct when no obstacle was present than when one was.

No significant results were found for differences in distance across obstacle-present conditions, $F(2.45, 24.51) = 1.19$, $p = .33$, $\omega^2 = .00$. Thus, hand paths travelled similar distances when an obstacle was present, regardless of the presence and timing of the second set of obstacles along the movement pathway.

Peak velocity: Analyses did not reveal a main effect for condition, $F(1.35, 13.49) = 2.03$, $p = .18$, $\omega^2 = .01$, on measures of PV when comparing the NO, PO, MO and DO conditions.

A main effect for condition on peak velocity measures, $F(2.03, 20.26) = 4.38$, $p = .03$, $\omega^2 = .03$, was observed for the obstacle-present conditions. However, no differences were found after post-hoc analyses.

Together these results suggest that individuals reached similar velocities whether or not an obstacle was present, regardless of the presence and timing of a second obstacle along the movement pathway.

Time to peak velocity: A main effect for condition, $F(1.42, 14.15) = 8.05$, $p = .01$, $\omega^2 = .21$, was found to be significant. Specifically, participants reached PV faster in the DO condition than in the PO condition, with no differences across the other conditions.

A main effect for condition, $F(1.59, 15.87) = 6.45$, $p = .01$, $\omega^2 = .19$, was found to be significant for the obstacle-present trials. However, post-hoc analyses did not reveal any relevant significant differences.

Proportional time after peak velocity: A main effect for condition, $F(3, 30) = 7.22$, $p < .01$, $\omega^2 = .19$, was found to be significant. Participants spent a shorter amount of time in the TAPV in the PO condition compared to the NO, MO, and DO conditions.

A main effect for condition, $F(1.53, 15.32) = 6.23$, $p = .02$, $\omega^2 = .18$, was found to be significant between the obstacle-present conditions as well. However, post-hoc analyses did not reveal any differences.

Spatial location of peak velocity: A main effect for condition was found, $F(3, 30) = 4.1$, $p = .02$, $\omega^2 = .09$, to be significant along the primary movement axis. Specifically, PV occurred further along the primary movement axis in the PO condition compared to the DO condition, with no other differences observed across the other conditions. No main effect along the secondary movement axis was found, $F(3, 30) = .52$, $p = .67$, $\omega^2 = .00$.

A main effect for condition, $F(2.57, 25.71) = 7.77$, $p < .01$, $\omega^2 = .25$, was found to be significant for the obstacle-present trials along the primary movement axis. Specifically, PV occurred further along the primary movement axis in the DL condition than in the DE condition only. Additionally, a main effect for condition along the secondary movement axis was found to be significant, *F*(2.44, 24.44) = 5.75, *p* = .01, ω^2 = .04. However, post-hoc analyses did not reveal any differences.

Peak acceleration: A main effect for condition, *F*(2.09, 20.94) = 5.95, *p* = .01, ω^2 = .05, was found to be significant across conditions with a single obstacle. Specifically, participants reached higher PA in the NO conditions than in the PO condition, with no other observed differences.

Additionally, a main effect for condition on all obstacle-present trials, *F*(1.41, 14.06) = 28.15, *p* < .01, ω^2 = .37, was found to be significant. Of the relevant comparisons, participants reached significantly higher PA in the PL condition compared to the PO and PE conditions.

Time to peak acceleration: Main effects for condition were found when comparing the NO, PO, MO, and DO conditions, *F*(1.24, 12.39) = 8.74, *p* = .01, ω^2 = .28, , and across all obstacle-present trials, *F*(2.08, 20.81) = 6.21, *p* = .01, ω^2 = .23. However, post-hoc analyses did not reveal significant differences in either analysis, suggesting that the presence of an initial obstacle, and the presence and timing of a second obstacle did not affect the time taken to reach peak accelerations.

Spatial location of peak acceleration: A main effect for condition, *F*(3, 30) = 8.41, *p* < .01, ω^2 = .28, was found to be significant. Specifically, PA occurred further along the primary movement axis in the PO condition compared to the NO, MO, and DO conditions. No main effect for condition was observed in the secondary movement axis, *F*(1.67, 16.70) = 1.77, *p* = .20, ω^2 = .02.

A main effect for condition, $F(2.12, 21.24) = 11.56$, $p < .01$, $\omega^2 = .42$, was found to be significant for the obstacle-present trials. Specifically, PA occurred further along the primary movement axis in the DL condition than in the DO condition. No main effect for condition was observed in the secondary movement axis, $F(1.77, 17.67) = 2.99$, $p = .08$, $\omega^2 = .05$.

Together, these results allow for the examination of movement characteristics when the potential for a second obstacle was available, but did not occur, specifically in the PO, MO, and DO conditions. These findings are similar to those in Study 1 such that despite similar starting and end points, movements were performed faster with a shorter distance travelled when no obstacle was present compared to when only one obstacle was present.

Individuals spent less time in the time leading up to peak velocities when the obstacle was more distal to the starting location which also corresponds to similar results in the time spent after reaching peak velocities. Specifically, individuals spent the most time in the decelerative portion of their movement when the obstacle was more distal to the starting location, than when it was closer. Additionally, the point at which individuals reached peak velocities showed some interesting results. Specifically, only in the proximal obstacle location condition was peak velocity achieved after clearing the obstacle.

3.3 RESULTS: A COMPARISON

The following section presents the results of the 2 (Study) by 4 (Condition) mixed factorial ANOVA.

3.3.1 Performance measures

Movement Time: A main effect for condition, $F(2.12, 44.61) = 26.44$, $p < .01$, $\omega^2 = .05$ was found to be significant. Specifically, movements were faster in the NO condition compared to the PO. MO, and DO conditions. No main effect for study, $F(1, 21) = .05$, $p = .82$, $\omega^2 = .00$, or study by condition interaction, $F(2.12, 44.61) = 1.12$, $p = .34$, $\omega^2 = .00$, were found.

Start position: Main effects for condition, $F(1.21, 25.39) = 6.37$, $p = .01$, $\omega^2 = .00$, and study, $F(1, 21) = 47.51$, $p < .01$, $\omega^2 = .40$, were found for the primary movement axis. Overall, participants began their movements further along the primary movement axis in Study 1 than in Study 2; however post-hoc analyses did not reveal any differences across conditions. A condition by study interaction was also observed, $F(1.21, 25.39) = 6.08$, $p = .02$, $\omega^2 = .00$ such that the start location for trajectories in Study 1 were further along the primary movement axis than their matched conditions in Study 2.

No main effects for condition, $F(1.31, 27.51) = 3.51$, $p = .06$, $\omega^2 = .03$, or study, $F(1, 21) = .02$, $p = .89$, $\omega^2 = .00$, were found for the secondary movement axis. Additionally, a condition by study interaction was not found to be significant, $F(1.31, 27.51) = .59$, $p = .49$, $\omega^2 = .00$.

The difference in start location for the primary movement axis across studies is likely a result of individuals moving faster in Study 1. Data was triggered to start recording when the cursor passed the distal home position boundary in the primary movement axis. Thus, despite this difference across studies, all movements had to begin with the cursor within the bounds of the home position.

End position: Main effects for condition, $F(3, 63) = 2.62$, $p = .06$, $\omega^2 = .03$, and study, $F(1, 21) = .98$, $p = .33$, $\omega^2 = .00$, and the condition by study interaction, $F(3, 63) = .91$, $p = .44$, $\omega^2 = .00$, were not significant for end positions along the primary movement axis. Additionally, main effects for condition, $F(3, 63) = 1.74$, $p = .17$, $\omega^2 = .02$, and study, $F(1, 21) = .13$, $p = .72$, $\omega^2 = .00$, and the condition by study interaction, $F(3, 63) = 2.14$, $p = .11$, $\omega^2 = .03$, were not significant for end positions along the secondary movement axis. Thus movements ended similarly across conditions and within the bounds of the target.

3.4.2 Kinematic measures

Trajectory distance: The main effects for condition, $F(1.56, 32.66) = 34.15$, $p < .01$, $\omega^2 =.06$, and study, $F(1, 21) = 25.11$, $p < .01$, $\omega^2 = .31$, were found to be significant. Overall, the trajectory distances in Study 2 were significantly greater than those in Study 1. The main effect for condition revealed that participants travelled a shorter distance in the NO condition compared to the PO, MO and DO conditions.

A condition by study interaction, $F(1.56, 32.66) = 5.70$, $p = .01$, $\omega^2 = .01$, revealed that hand paths travelled a greater distance in each of their matched conditions in Study 2, compared to those in Study 1 (see Figure 3.12).

Peak Velocity: Main effects for condition, $F(1.39, 29.24) = 6.09$, $p = .01$, $\omega^2 = .01$, and study, $F(1, 21) = 22.63$, $p < .01$, $\omega^2 = .33$, were found to be significant. Overall, participants reached higher PVs in Study 2 than in Study 1. Post-hoc tests condition revealed that participants reached higher PVs in the NO condition than in the MO condition. A condition by study interaction was not found to be significant, $F(1.39, 29.24) = .51, p = .54, \omega^2 = .00$.

Time to peak velocity: A main effect for condition, $F(1.43, 30.04) = 14.47, p < .01, \omega^2 = .17$, was found to be significant. Individuals spend a greater amount of time in TTPV in the PO condition compared to the NO, MO, and DO conditions. A main effect for study, $F(1, 21) = .73, p = .40, \omega^2 = .01$, and a condition by study interaction, $F(1.43, 30.04) = 3.00, p = .08, \omega^2 = .03$, were not found to be significant.

Proportional time after peak velocity: A main effect for condition, $F(1.69, 35.58) = 13.55, p < .001, \omega^2 = .17$, was found to be significant. Specifically, individuals spent a smaller proportion of their movement in the TAPV in the PO condition than any of the other conditions. A main effect for study, $F(1, 21) = 2.37, p = .139, \omega^2 = .04$, and a condition by study interaction, $F(1.69, 35.58) = 2.20, p = .132, \omega^2 = .02$, were not found to be significant.

Spatial position of peak velocity: Main effects for condition, $F(3, 63) = 7.16, p <.01, \omega^2 = .07$, and study, $F(1, 21) = 11.23, p < .01, \omega^2 = .17$, were found to be significant along the primary movement axis. Overall, PV occurred further along the primary movement axis in Study 1 compared to Study 2, and in the PO condition compared to the MO and DO conditions only. No condition by study interaction was observed, $F(3, 63) = 1.35, p = .27, \omega^2 = .00$.

Main effects for condition, $F(1.52, 31.99) = 1.88, p = .142, \omega^2 = .01$, and study, $F(1, 21) = .11, p = .745, \omega^2 = .00$, as well as a condition by study interaction, $F(1.52,$

31.99) = 1.56, $p = .226$, $\omega^2 = .00$, were not observed for the position of PV in the secondary movement axis.

Peak acceleration: Main effects for condition, $F(2.12, 44.44) = 9.41$, $p < .01$, $\omega^2 = .01$, and study, $F(1, 21) = 22.00$, $p < .01$, $\omega^2 = .32$, were found to be significant. Overall, participants reached higher PAs in Study 2 compared to Study 1. Post-hoc analyses on the effect for condition revealed that individuals reached significantly higher PAs in the NO condition than in the PO and MO conditions. However peak accelerations in the DO condition did not differ. A condition by study interaction, $F(2.12, 44.44) = 3.66$, $p = .03$, $\omega^2 = .00$, was also found to be significant. Individuals reached higher peak accelerations in each of their matched conditions in Study 2, compared to those in Study 1 (see Figure 3.13).

Time to peak acceleration: Main effects for condition, $F(1.25, 26.22) = 9.72$, $p < .01$, $\omega^2 = .12$ and study, $F(1, 21) = 10.24$, $p < .01$, $\omega^2 = .10$, were significant. Overall, participants reached PAs earlier in the movement in Study 1 compared to Study 2. Post-hoc analyses on the effect of condition revealed that participants specifically reached PA earlier in the DO condition than in the PO condition. A condition by study interaction, $F(1.25, 26.22) = 9.29$, $p < .01$, $\omega^2 = .11$, was also found to be significant. Specifically, participants reached PA later in Study 2 than in Study 1 for the PO condition.

Spatial position of peak acceleration: Main effects for condition, $F(1.79, 37.51) = 8.52$, $p < .01$, $\omega^2 = .12$, and study, $F(1, 21) = 6.69$, $p = .02$, $\omega^2 = .14$, were observed for the location of PA in the primary movement axis. Overall, PA occurred further along the primary movement axis in Study 2, compared to Study 1, and in the PO condition compared to the DO and NO conditions. A condition by study interaction, $F(1.79, 37.51) = 9.80$, $p < .01$, $\omega^2 = .14$, revealed that the PO conditions were significantly different across both studies.

A main effect for condition, $F(1.60, 33.56) = 2.82$, $p = .09$, $\omega^2 = .02$, and study, $F(1, 21) = .03$, $p = .87$, $\omega^2 = .00$, as well as a condition by study interaction $F(1.60, 33.56) = 1.08$, $p = .34$, $\omega^2 = .00$, were not significant for the location of PA in the secondary movement axis.

3.3 DISCUSSION

It is evident that participants adapted their movement strategy according to the presence of an obstacle. Clear differences were observed when no obstacle was present, compared to when one had to be incorporated into the initial movement plan. The lack of spatial differences in the start and end points of movements indicate that any differences in trajectory distance are related to the distance travelled by the hand. As expected, when no obstacle was present, the hand path distance was significantly less than when an obstacle had to be avoided, indicative of straighter movements being performed. These results are supported by the trajectory tracings in Figures 3.2- 3.11.

Higher velocities are seen when no obstacle was present or it was present further along the movement amplitude, relative to when one was closer, which also lead to greater amount of time in the TTPV. Conversely, when an obstacle was present closer along the movement pathway, individuals spent less time in the TTPV, but greater time in the TAPV. In addition, participants achieved higher accelerations when no obstacle was present, compared to when an obstacle was present closer along the movement pathway.

It is evident that when an obstacle is not present, individuals perform straighter, direct movements to the target. Coupled with the increases in speed and time spent in the initial, more rapid phase of the movement, and the reduction in time spent in the homing phase of the movement, it is clear that less feedback is needed to accomplish the task in this condition. These movements are biomechanically more efficient and are performed at significantly faster allow individuals to complete the task more quickly.

A lack of differences in the early and late obstacle onset conditions suggests that visual information is incorporated into the movement in a continuous fashion and adaptations to the movement are possible throughout the duration of the movement, a finding that strongly supports the tenets of the multiple-process model of movement control (Elliott et al., 2010).

The purpose of this study was to understand how individuals altered their movements when an unexpected obstacle was present. The presence of an obstacle prior to movement onset allowed individuals to incorporate it into their initial movement plan. However, upon movement onset, the perturbation induced by the appearance of a second set of obstacles was intended to obstruct this preferential trajectory. The possibility of this second perturbation led to very different trajectories.

Table 3.1: Summary of participant characteristics in Study 2.

Participant	Age	Sex	LI	Handedness	*BAP-Q Results*			
					Aloof	Pragmatic Language	Rigidity	Total score
1	23	F	80	R	2.00	1.92	2.17	2.03
2	21	F	70	R	2.42	2.33	2.00	2.25
3	23	F	70	R	2.17	3.08	2.50	2.58
4	28	M	95	R	2.17	2.58	2.75	2.50
5	26	M	75	R	2.58	2.33	3.25	2.72
6	36	M	100	R	2.58	1.75	2.92	2.42
7	37	F	100	R	2.17	1.92	2.83	2.31
8	30	M	100	R	3.42	2.67	4.25	3.44
9	27	M	70	R	2.25	3.00	2.75	2.67
10	23	F	90	R	1.42	2.42	2.75	2.19
11	26	F	95	R	2.17	2.75	4.25	3.06

Age = 27.27 ± 5.26 years; mean ± standard deviation (SD)

Table 3.2: Summary of trajectory direction, leftwards (L), rightwards (R), left between (LB), and right between (RB), as a function of condition: No obstacle (NO), Proximal obstacle (PO), Proximal early (PE), Proximal late (PL), Middle obstacle (MO), Middle early (ME), Middle late (ML), Distal obstacle (DO), Distal early (DE), Distal late (DL) in Study 2.

			Participant											
			1	2	3	4	5	6	7	8	9	10	11	**Total**
	NO		20	19	20	20	20	20	20	20	19	20	20	**218**
Proximal	PO	L	0	8	20	5	0	12	0	0	0	0	0	**45**
		R	20	12	0	15	20	7	20	20	20	20	20	**174**
	PE	L	0	8	18	0	0	3	0	0	0	0	0	**29**
		R	19	11	0	0	20	2	20	20	17	4	16	**129**
		LB	0	0	0	0	0	8	0	0	0	16	0	**24**
		RB	0	0	0	20	0	7	0	0	3	0	4	**34**
	PL	L	0	6	19	0	0	4	0	0	0	0	0	**29**
		R	19	12	0	0	19	2	20	20	16	3	14	**125**
		LB	0	0	0	3	0	9	0	0	0	0	0	**12**
		RB	0	1	0	17	0	3	0	0	2	14	3	**40**
Medal	MO	L	0	8	20	5	0	11	0	0	0	0	0	**44**
		R	20	12	0	15	20	7	20	20	20	20	20	**174**
	ME	L	0	6	20	0	0	5	0	0	0	0	0	**31**
		R	20	12	0	0	20	4	20	20	16	6	18	**136**
		LB	0	0	0	3	0	4	0	0	0	0	0	**7**
		RB	0	2	0	17	0	6	0	0	4	13	2	**44**
	ML	L	0	6	19	0	0	4	0	0	0	0	0	**29**
		R	19	12	0	0	20	2	18	20	17	2	11	**121**
		LB	0	0	0	5	0	8	0	0	0	0	0	**13**
		RB	0	1	0	15	0	4	0	0	2	17	8	**47**
Distal	DO	L	1	10	20	11	0	10	0	0	0	1	0	**53**
		R	19	10	0	9	20	8	20	20	20	19	20	**165**
	DE	L	0	12	20	0	0	1	0	0	0	0	0	**33**
		R	18	8	0	0	17	2	19	19	18	13	15	**129**
		LB	0	0	0	8	0	4	0	0	0	0	0	**12**
		RB	2	0	0	11	0	10	1	0	1	6	5	**36**
	DL	L	0	9	17	0	0	3	0	0	0	0	0	**29**
		R	13	9	0	0	16	2	14	20	17	6	7	**104**
		LB	0	0	0	6	0	11	0	0	0	0	0	**17**
		RB	7	1	0	14	0	0	0	0	1	9	13	**44**
	Total		**197**	**194**	**193**	**199**	**192**	**183**	**192**	**199**	**193**	**189**	**196**	**2127**

Figure 3.1: Total number of trajectories as a function of obstacle distance, obstacle onset, and trajectory choice (leftwards (L), rightwards (R), leftwards between (LB), or rightwards between (RB).

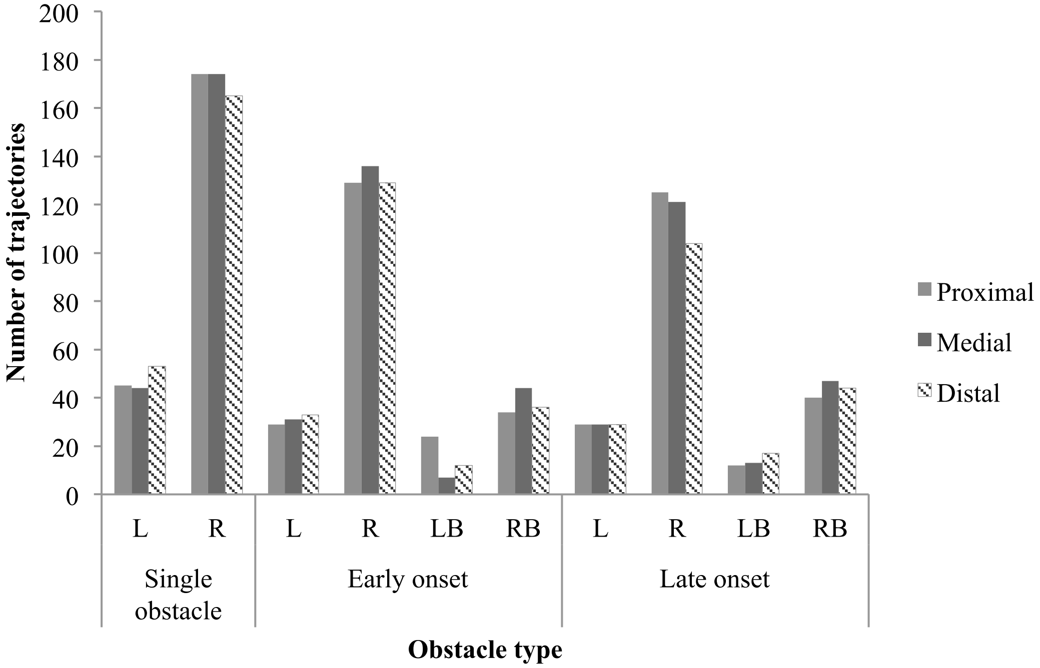


Figure 3.2: Trajectory tracings (A) and kinematic data (B) of all participants in the No Obstacle (NO) condition in Study 2. Temporal bins in Figure B correspond to the division of data points, such that Bin 5 represents 20% of the movement, and Bin 25 represents 100% of the movement.

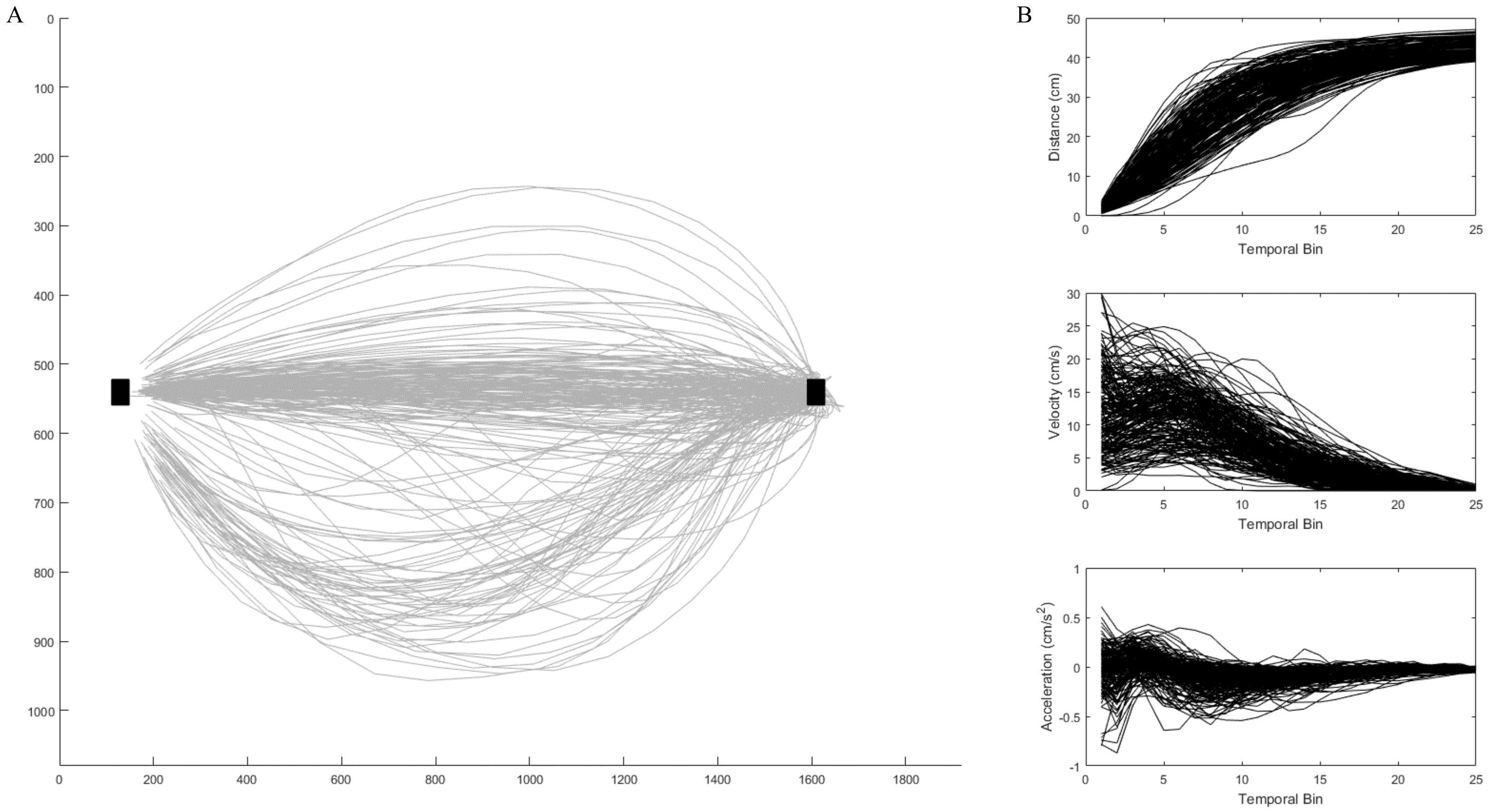


Figure 3.3: Trajectory tracings (A) and kinematic data (B) of all participants in the Proximal Obstacle (PO) condition in Study 2. Temporal bins in Figure B correspond to the division of data points, such that Bin 5 represents 20% of the movement, and Bin 25 represents 100% of the movement.

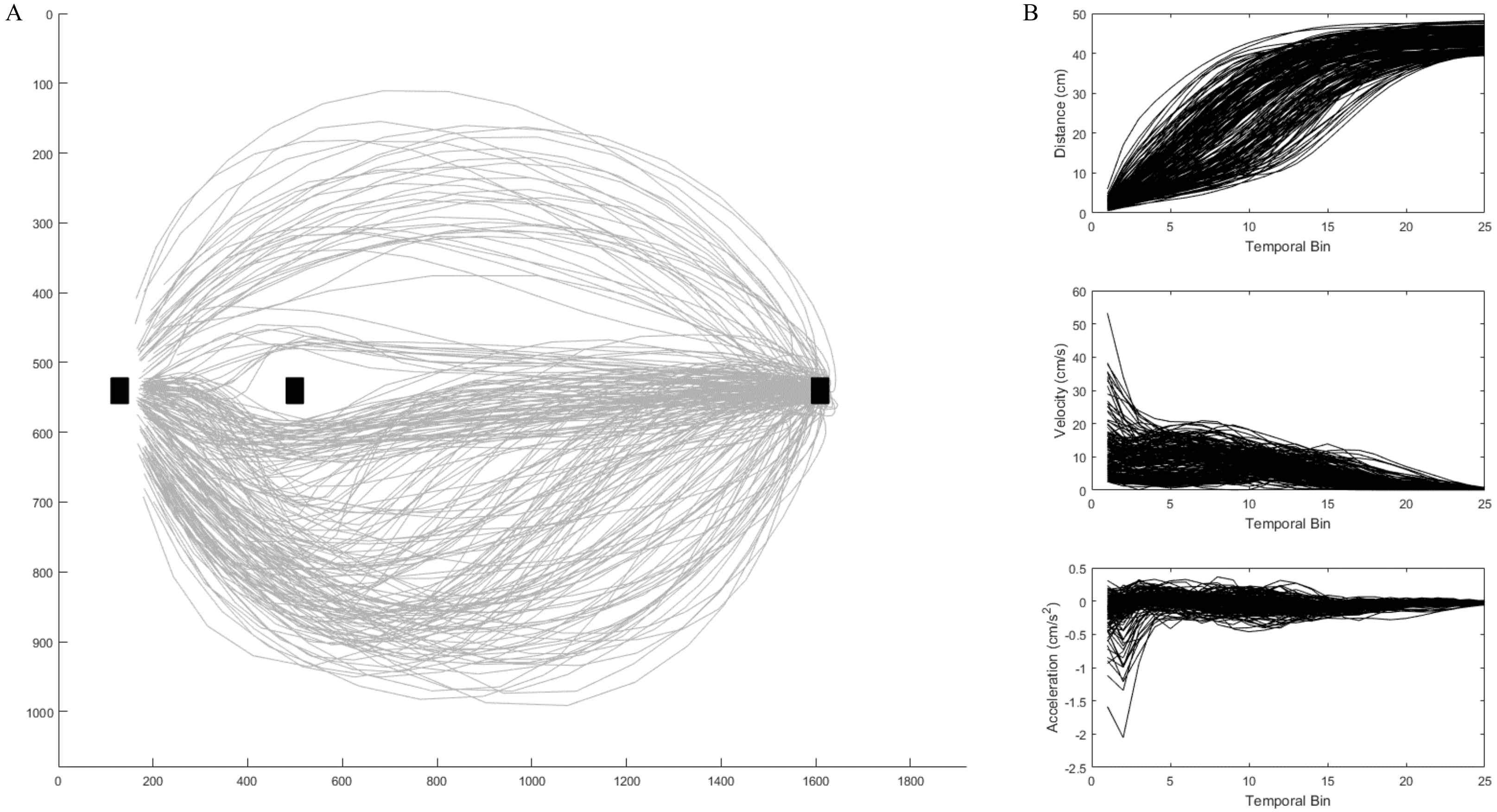


Figure 3.4: Trajectory tracings (A) and kinematic data (B) of all participants in the Proximal Early (PE) condition in Study 2. Temporal bins in Figure B correspond to the division of data points, such that Bin 5 represents 20% of the movement, and Bin 25 represents 100% of the movement.

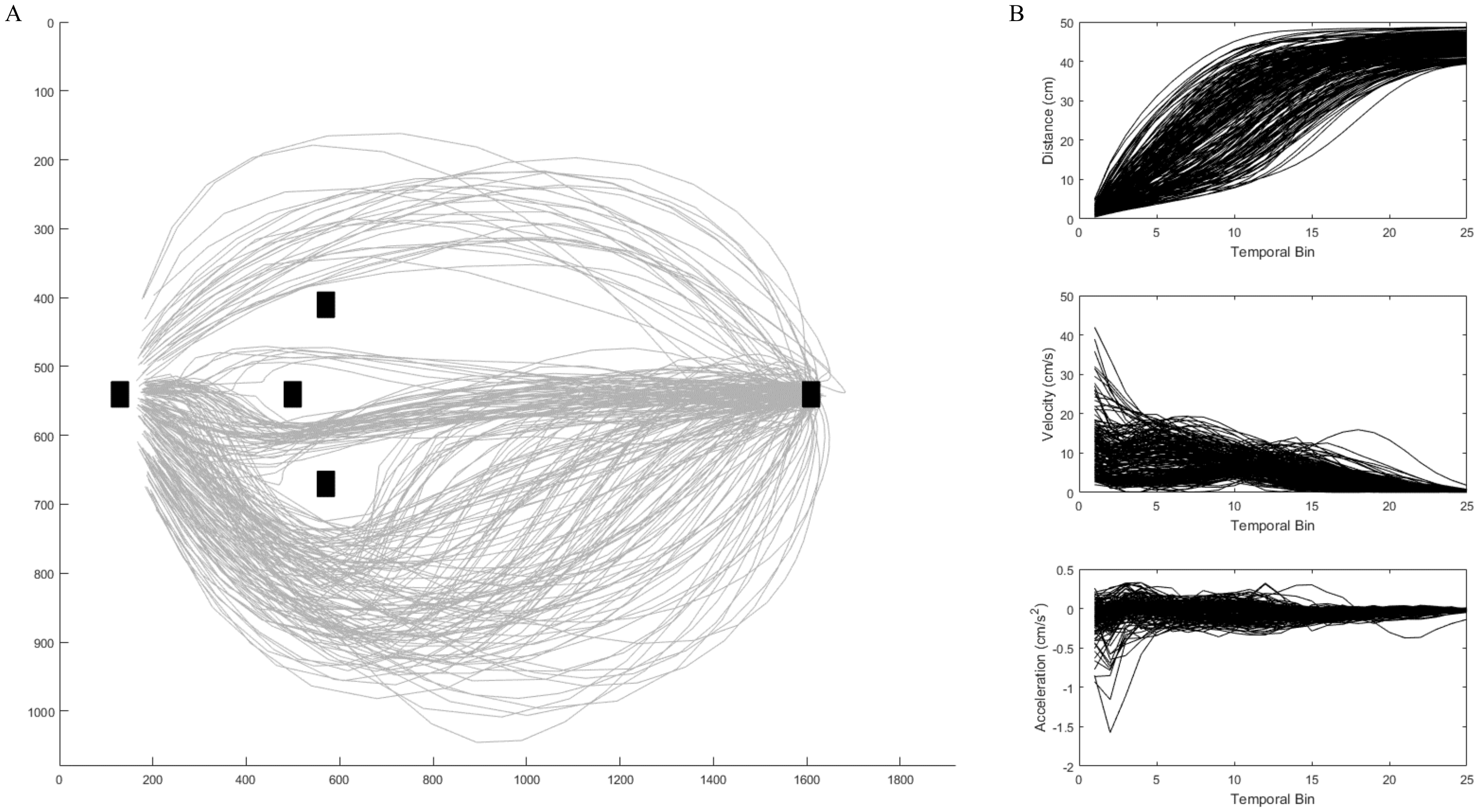


Figure 3.5: Trajectory tracings (A) and kinematic data (B) of all participants in the Proximal Late (PL) condition in Study 2. Temporal bins in Figure B correspond to the division of data points, such that Bin 5 represents 20% of the movement, and Bin 25 represents 100% of the movement.

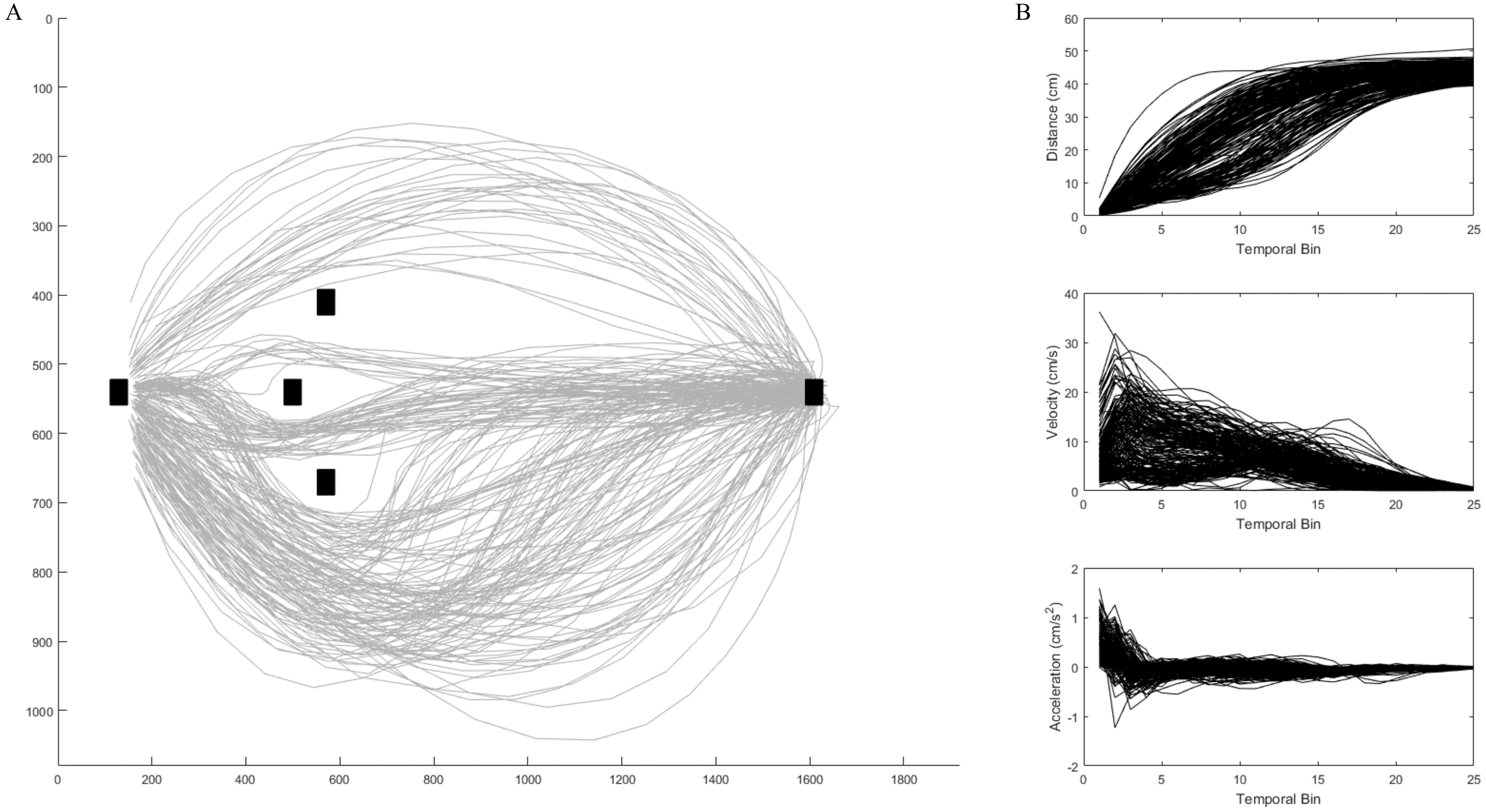


Figure 3.6: Trajectory tracings (A) and kinematic data (B) of all participants in the Middle Obstacle (MO) condition in Study 2. Temporal bins in Figure B correspond to the division of data points, such that Bin 5 represents 20% of the movement, and Bin 25 represents 100% of the movement.

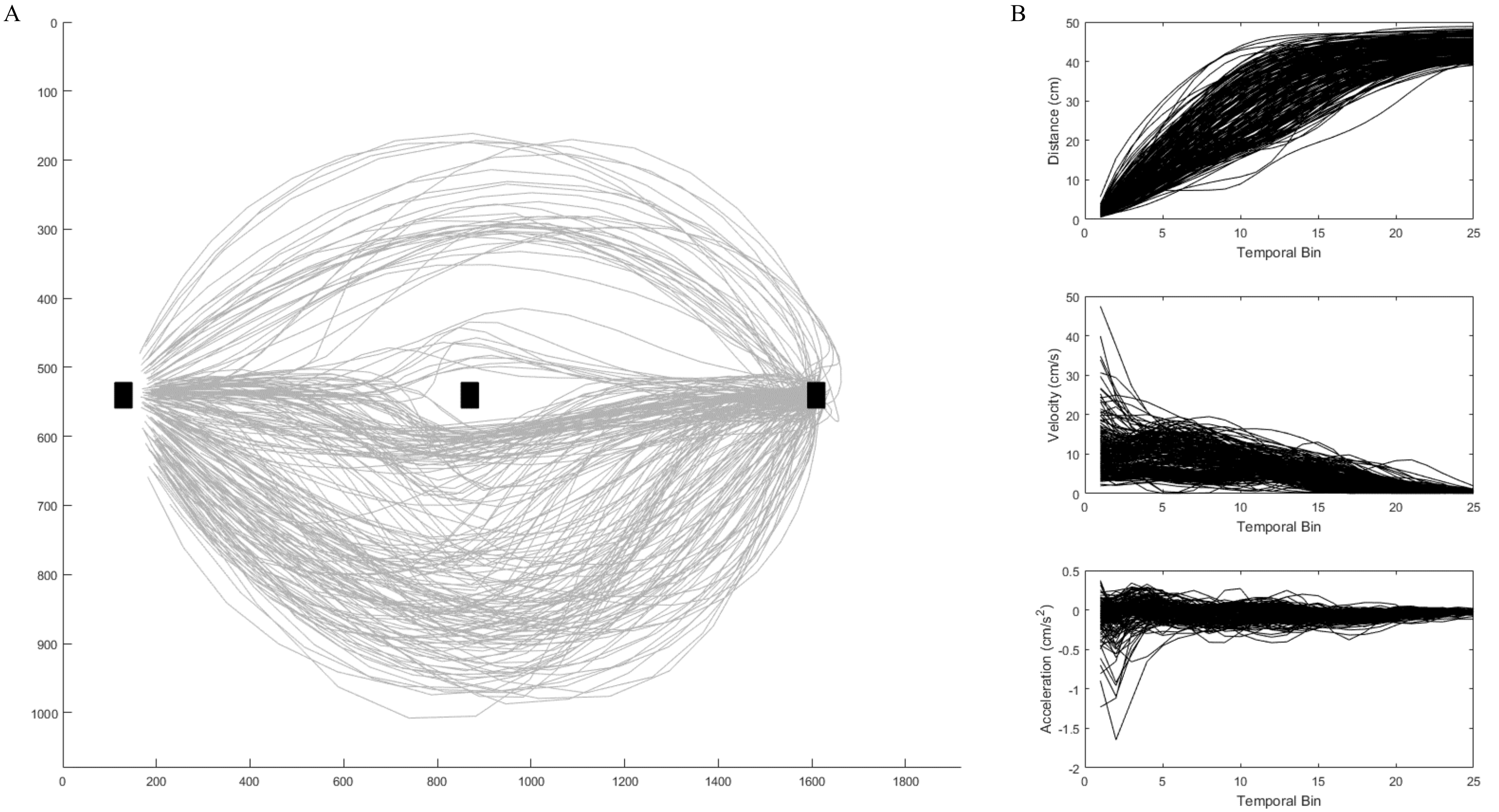


Figure 3.7: Trajectory tracings (A) and kinematic data (B) of all participants in the Middle Early (ME) condition in Study 2. Temporal bins in Figure B correspond to the division of data points, such that Bin 5 represents 20% of the movement, and Bin 25 represents 100% of the movement.

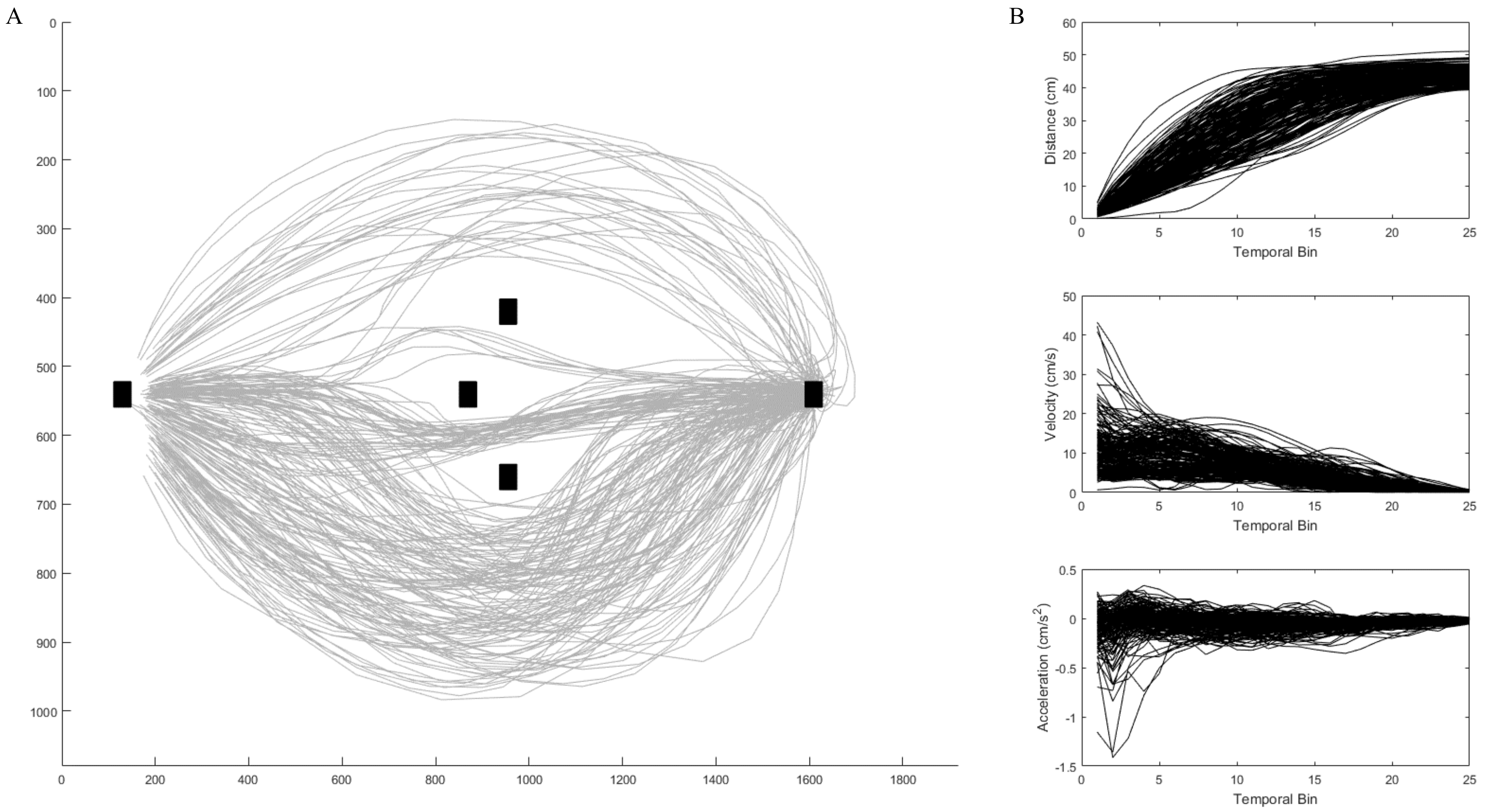


Figure 3.8: Trajectory tracings (A) and kinematic data (B) of all participants in the Middle Late (ML) condition in Study 2. Temporal bins in Figure B correspond to the division of data points, such that Bin 5 represents 20% of the movement, and Bin 25 represents 100% of the movement.

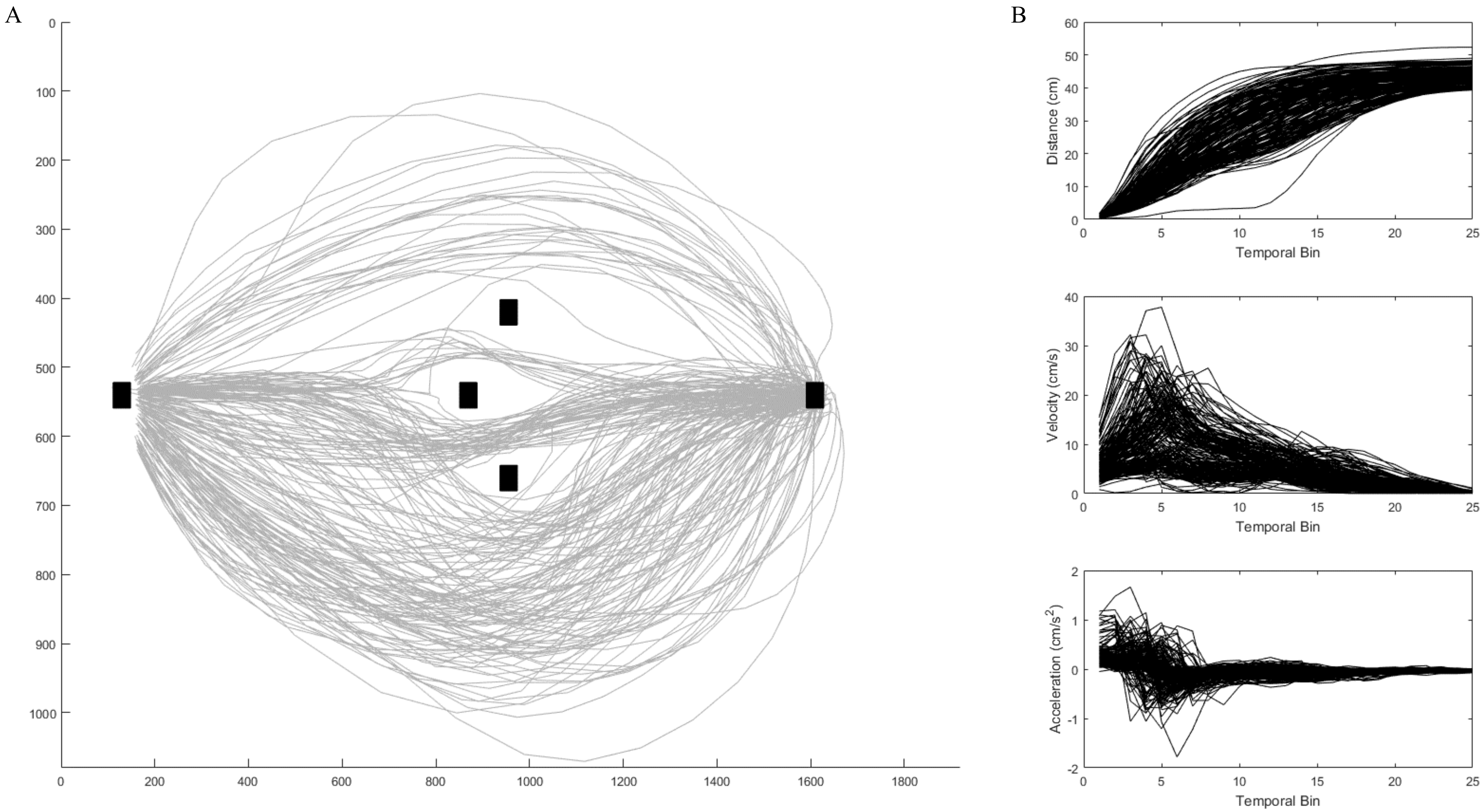


Figure 3.9: Trajectory tracings (A) and kinematic data (B) of all participants in the Distal Obstacle (DO) condition in Study 2. Temporal bins in Figure B correspond to the division of data points, such that Bin 5 represents 20% of the movement, and Bin 25 represents 100% of the movement.

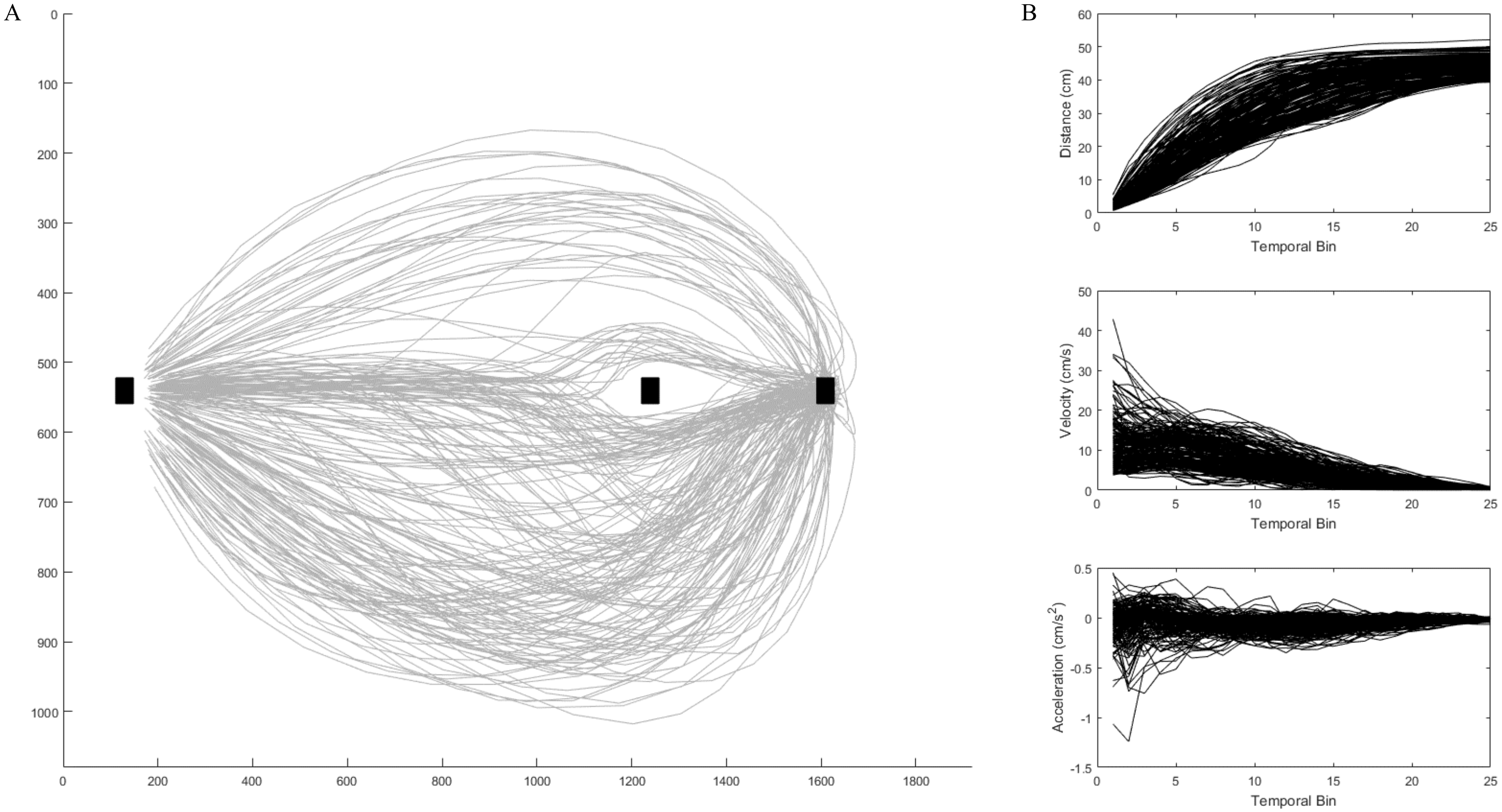
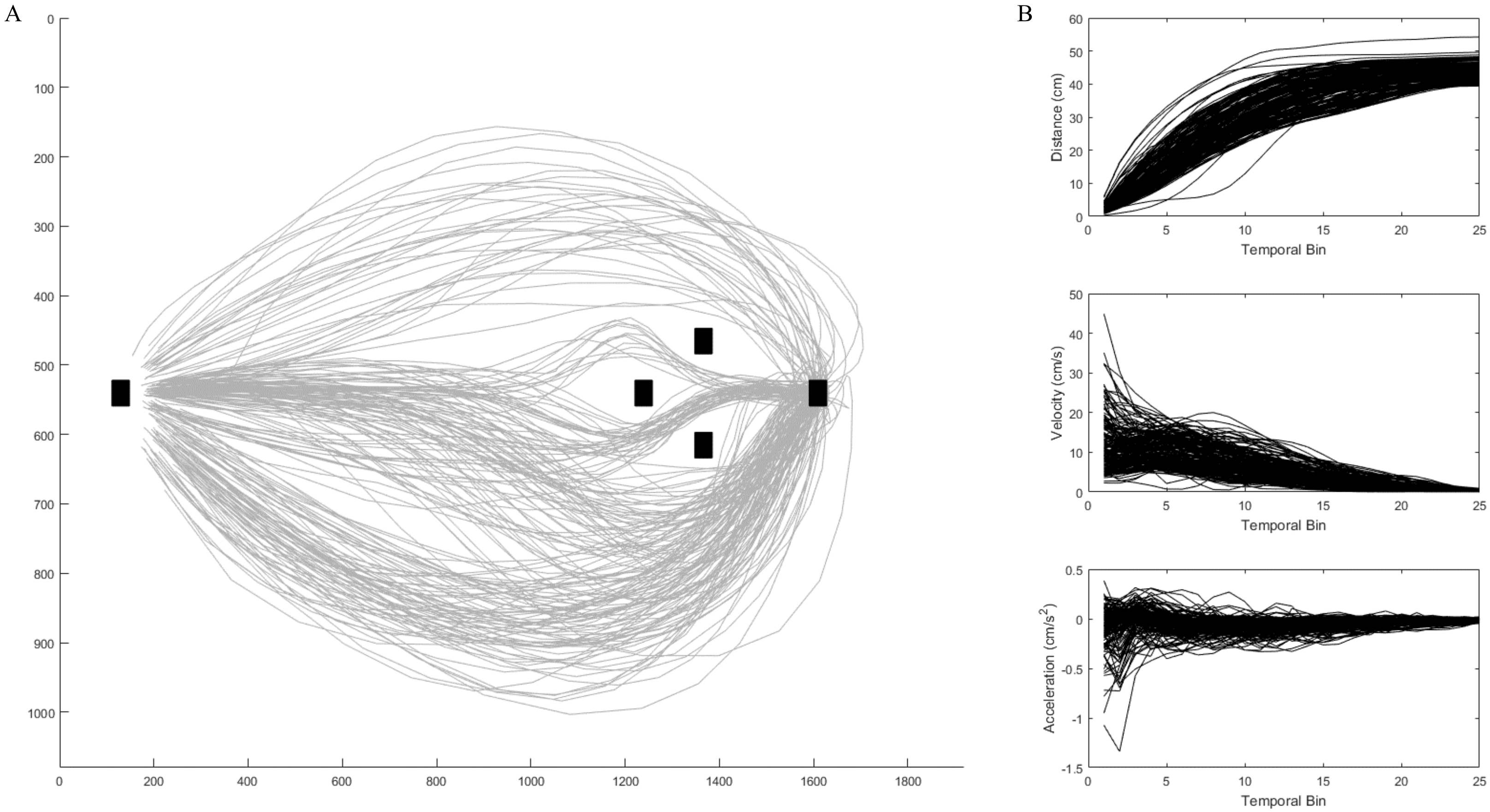


Figure 3.10: Trajectory tracings (A) and kinematic data (B) of all participants in the Distal Early (DE) condition in Study 2. Temporal bins in Figure B correspond to the division of data points, such that Bin 5 represents 20% of the movement, and Bin 25 represents 100% of the movement.



<u>Figure 3.11:</u> Trajectory tracings (A) and kinematic data (B) of all participants in the Distal Late (DL) condition in Study 2. Temporal bins in Figure B correspond to the division of data points, such that Bin 5 represents 20% of the movement, and Bin 25 represents 100% of the movement.

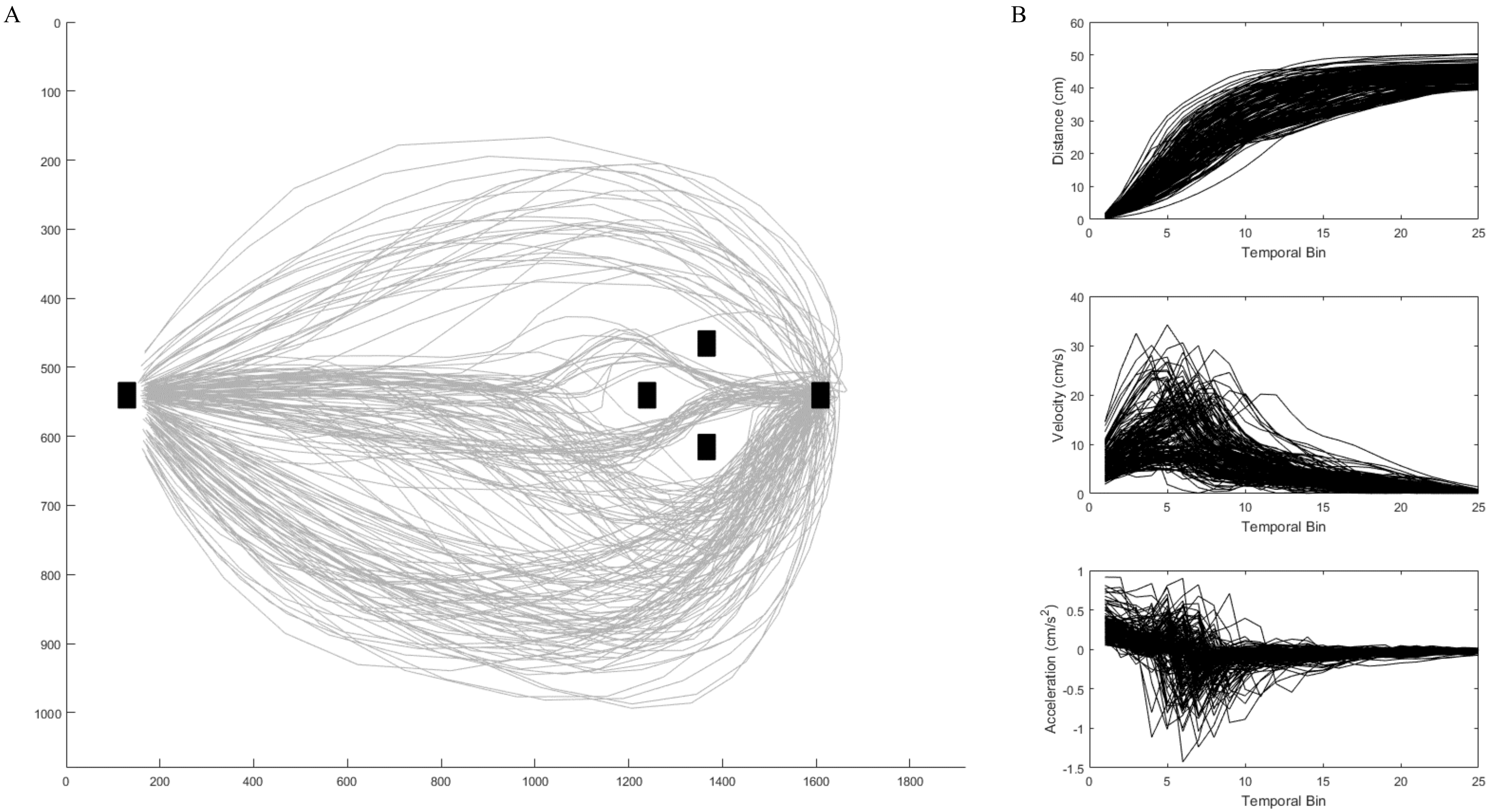


Figure 3.12: Mean trajectory distance (cm) and standard error bars as a function of study and condition.

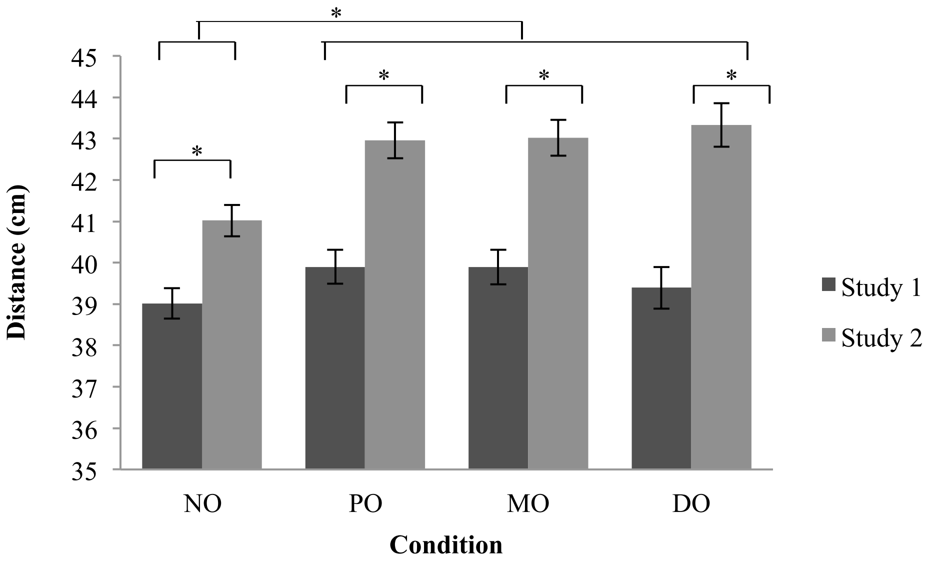


Figure 3.13: Mean peak acceleration (cm/s^2) and standard error bars as a function of study and condition.

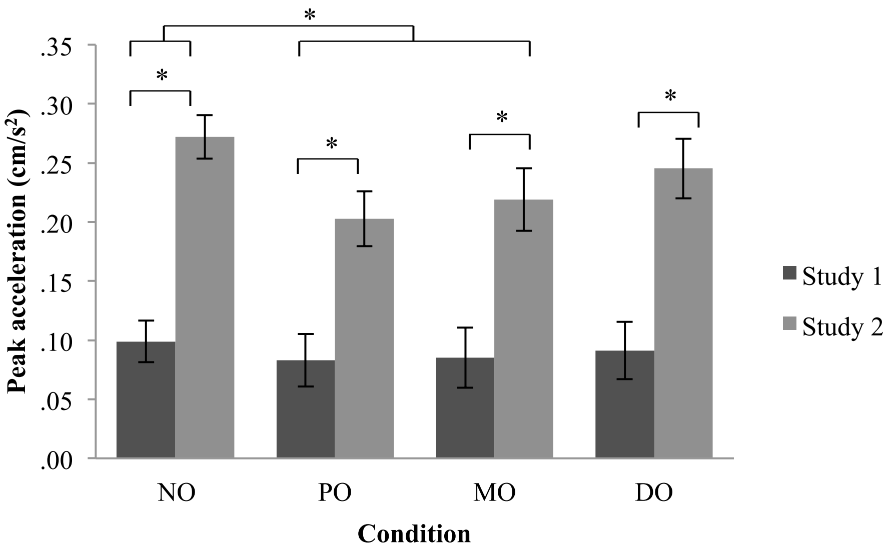


Figure 3.14: Distribution of trajectory points in the Proximal Early (PE) condition (Figure A) and Proximal Late (PL) condition (Figure B). Distribution points demonstrate leftward (L) trajectories in red, left between trajectories (LB) in green, right between trajectories (RB) in orange, and rightward trajectories (R) in blue at the point of secondary obstacle onset.

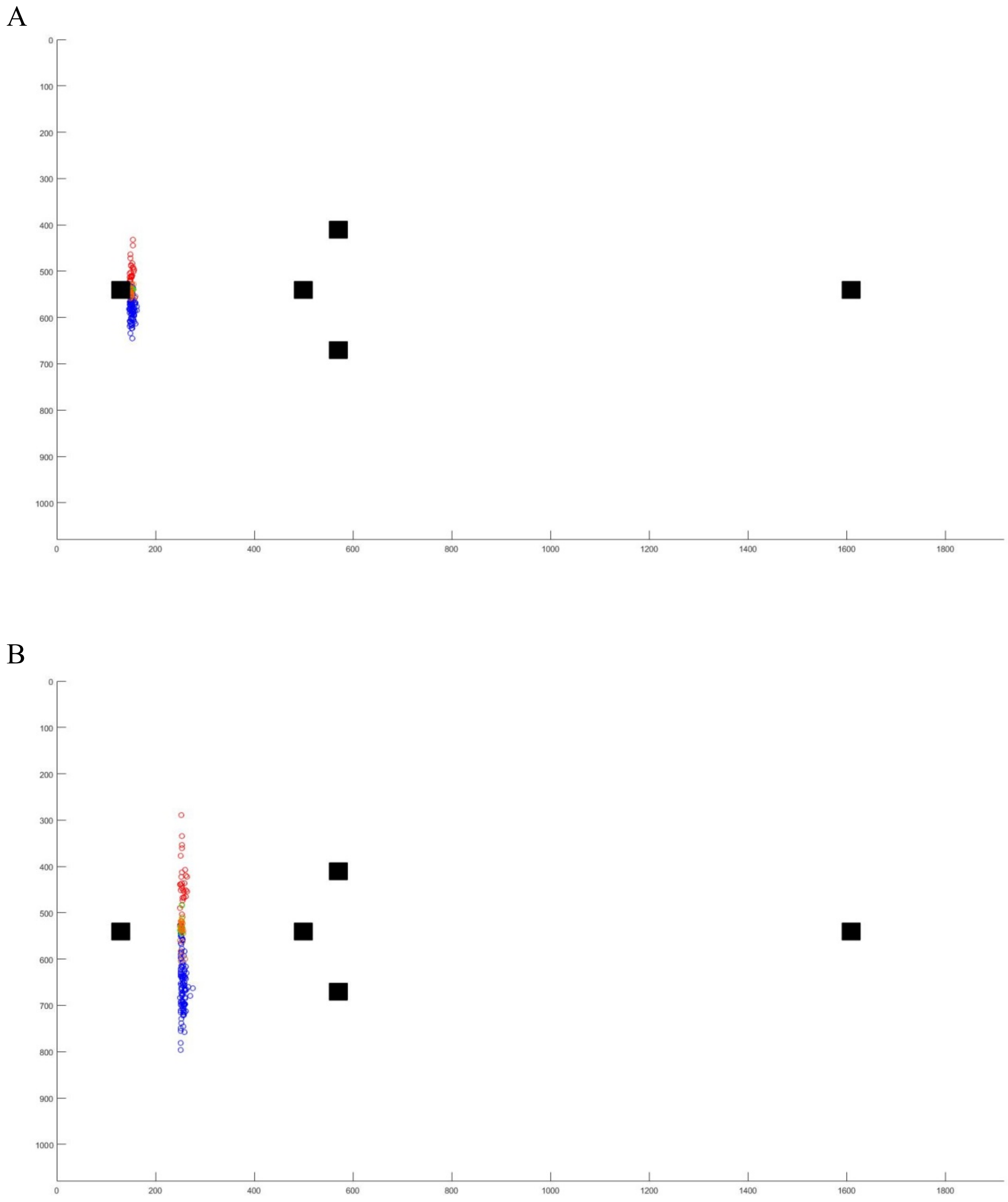
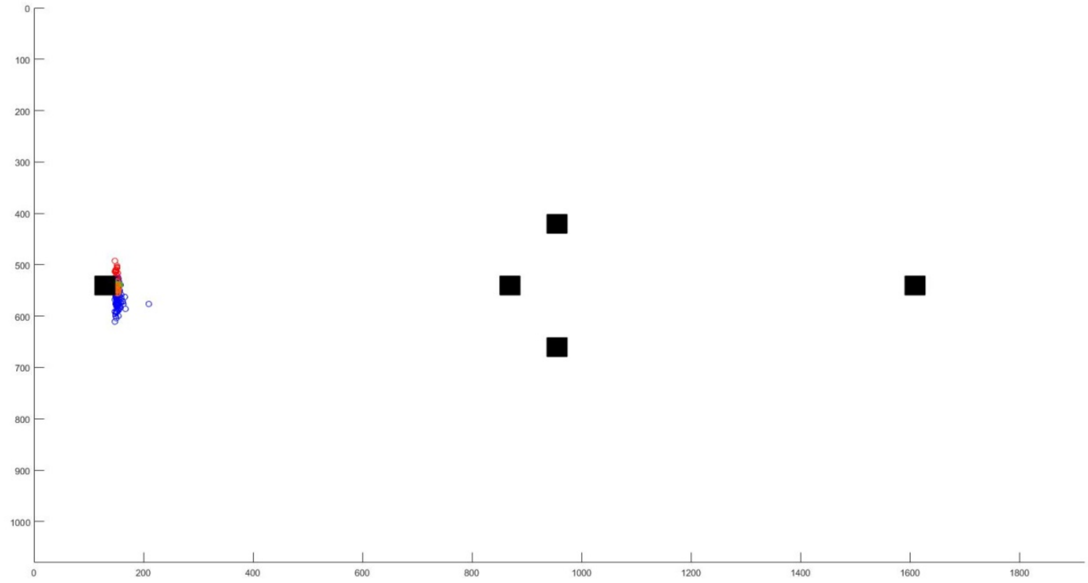


Figure 3.15: Distribution of trajectory points in the Middle Early (ME) condition (Figure A) and Middle Late (ML) condition (Figure B). Distribution points demonstrate leftward (L) trajectories in red, left between trajectories (LB) in green, right between trajectories (RB) in orange, and rightward trajectories (R) in blue at the point of secondary obstacle onset.

A



B

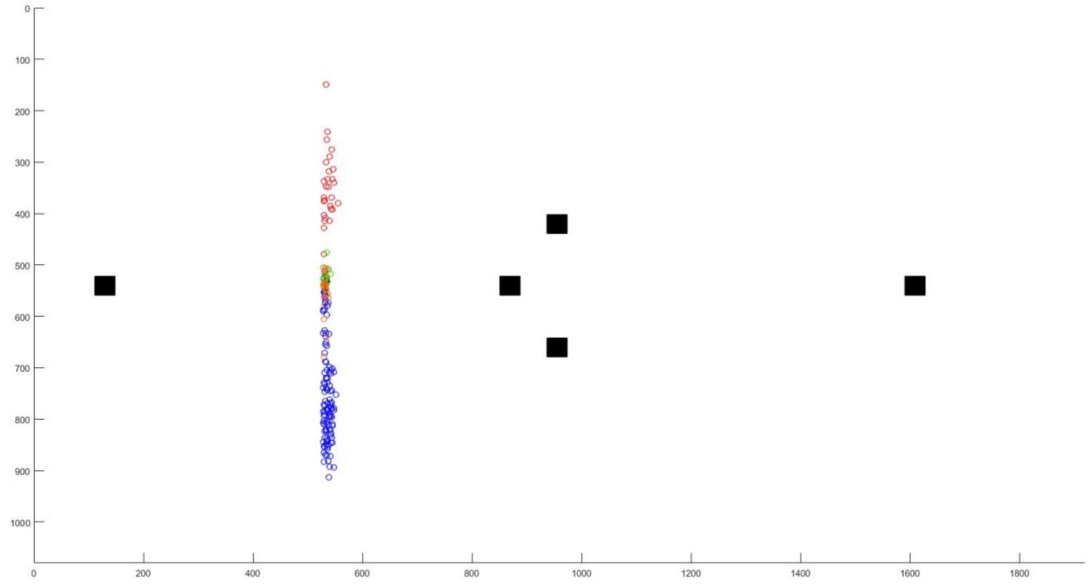
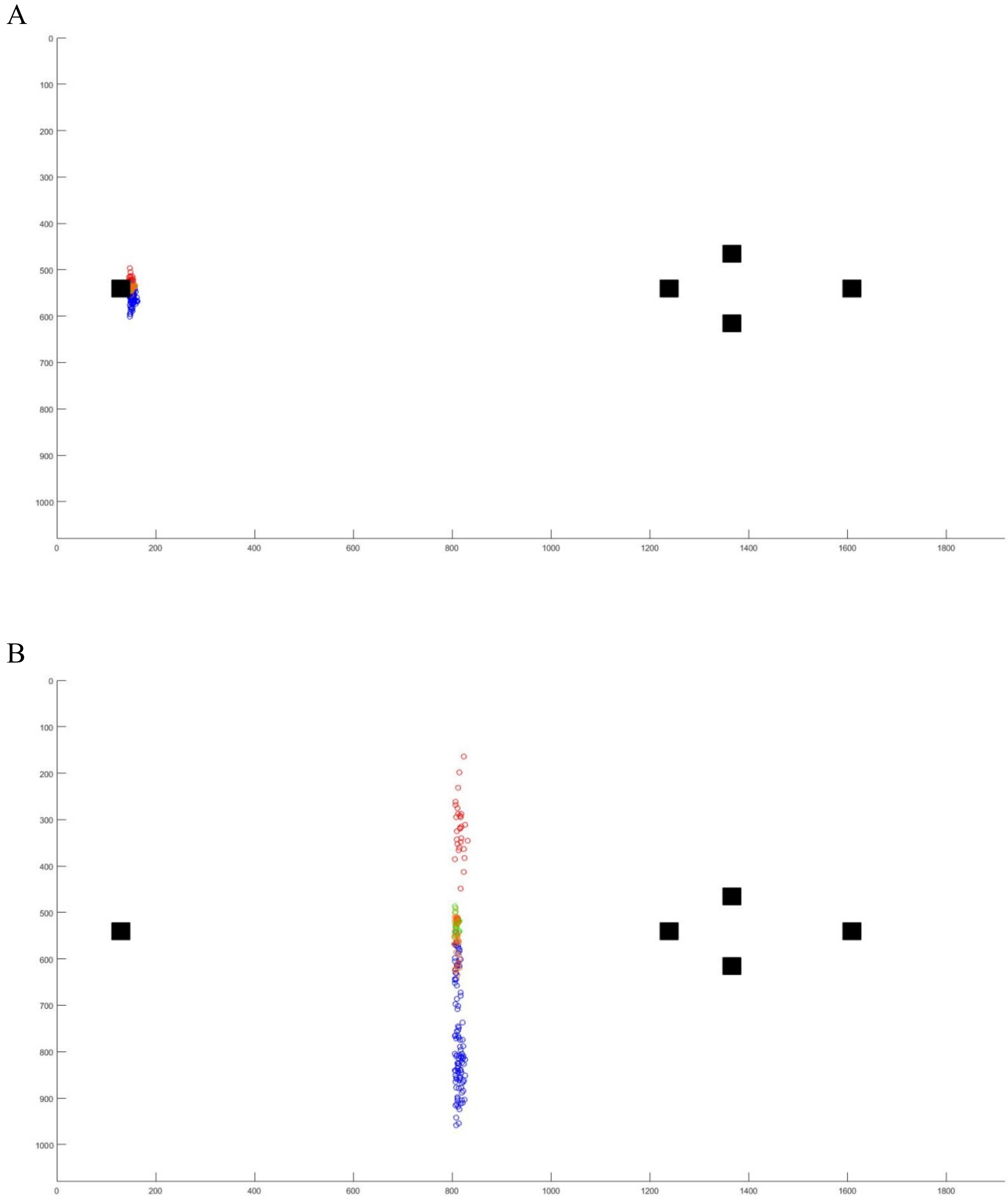


Figure 3.16: Distribution of trajectory points in the Distal Early (DE) condition (Figure A) and Distal Late (DL) condition (Figure B). Distribution points demonstrate leftward (L) trajectories in red, left between trajectories (LB) in green, right between trajectories (RB) in orange, and rightward trajectories (R) in blue at the point of secondary obstacle onset.



CHAPTER 4: AUTISM SPECTRUM DISORDER

4.1 LITERATURE REVIEW

4.1.1 Phenotypic characteristics of ASD

Autism spectrum disorder (ASD) is a neurodevelopmental disorder consisting of diagnoses into three categories: High functioning autism (HFA), Asperger's syndrome (AS), and pervasive development disorder not otherwise specified (PDD-NOS). A diagnosis of ASD is typically characterized by behavioural deficits, communication abnormalities, and stereotyped or repetitive behaviours (American Psychiatric Association, 2013). Additionally, hypersensitivity to external stimuli (e.g., Elwin, Schroder, & Kjellin, 2012) may act to regulate the larger boundaries of personal space often observed within this population (Gessaroli, Santelli, di Pellegrino, & Frassinetti, 2013). Prevalence rates estimate that approximately 1% of children at eight years of age in the United States have received a diagnosis along the spectrum, with disorder heritability estimated to be as high as 50% within families that have received a diagnosis (Sandin et al., 2014; Christensen et al., 2016). This genetic component has been linked to the identification of the broader autism phenotype, encompassing higher rates of social and communication deficits, as well as more rigid, stereotyped behaviours in family members of an individual with a diagnosis (Piven, Palmer, Jacobi, Childress, & Arndt, 1997).

Research within this population primarily focuses on atypical behavioural and social attributes associated with the disorder, however researchers are arguing for the inclusion of underlying motor dysfunction into the diagnosis (see Fournier, Hass, Naik, Lodha, & Cauraugh, 2010; Bhat, Landa, & Galloway, 2011). A meta-analysis by Fournier et al. (2010) found large effects for motor impairments across the age-span including deficits in motor coordination and arm movements. Additionally, the different subgroups comprising the overarching diagnosis of ASD demonstrated significantly lower motor capabilities compared to control groups, with some support for differences in motor function across the subclassifications (Rinehart, Bradshaw, Brereton, & Tonge, 2001a).

Motor performance has also been related to cognitive impairments, as assessed by levels of IQ (Ghaziuddin & Butler, 1998; Mari, Castiello, Marks Marraffa & Prior, 2003). Individuals with lower IQ scores have been shown to demonstrate differential movement velocities. Interestingly the decelerative portion, typically indicative of on-line control, has been found to be longer in those with an ASD compared to age-matched controls (Mari et al., 2003). Despite this, even when IQ parameters are controlled using strict cut-off criteria, those with ASD continue to show reduced performance in certain motor tasks, including balance, gait, and temporally constrained repetitive movements (Jansiewicz et al. 2006).

4.1.2 Movement planning deficits in ASD

Individuals with ASD have consistently demonstrated slower RTs compared to TD controls (Glazebrook et al., 2006; Glazebrook, Elliott, & Szatmari, 2008; Nazarali, Glazebrook, & Elliott, 2009), regardless of task complexity (Rinehart et al., 2006). On occasion these RTs are more variable (Dowd, McGinley, Taffe, & Rinehart, 2012). However, planning behaviours are believed to be task-dependent, altered by the form of visual feedback provided. When provided with direct visual information, those with ASD demonstrate similar patterns of performance to controls. However, when visual information is presented in an indirect manner, differences in performance are observed (Glazebrook et al., 2008; Rinehart, Bradshaw, Moss, Brereton, & Tonge, 2001b; Nazarali et al., 2009). Glazebrook et al. (2008) examined performance measures and start locations on a dual-aiming task with varying sized targets. Participants were given the opportunity to choose their starting location along a linear continuum to optimize performance. The TD group demonstrated an anticipatory effect, such that start locations were typically chosen in opposition to the preceding trial target side. In contrast, those with ASD consistently chose a central starting position that was not further from either of the two targets. The authors attributed this difference in advance planning to potential deficits in executive functioning as higher order planning was required for the task. Alternatively, observed differences may be due to the more local processing present in those with ASD, such that they viewed each trial discretely, unaffected by context of the previous trial.

Understanding how those with ASD are able to reprogram a movement also provides valuable information into the organization and planning strategies of the movement. Compared to TD controls, those with an ASD demonstrate greater difficulty reprogramming a movement (Nazarali et al., 2009; Rinehart et al., 2001a). By manipulating a movement sequence through the incorporation of a single out of sequence target, referred to as an ‘oddball’, Rinehart et al. (2001a) demonstrated differences in movement preparation between TD and ASD groups. Programmed movements occurred prior to the oddball, as the movements followed a sequence. However, the introduction of the oddball required a reprogrammed movement, as it did not align with the anticipated target. After the introduction of the oddball, preparation responses should be faster, because the proceeding target would reliably follow the sequence. As expected, the TD group was able to prepare for the reprogrammed movement faster, and overall, programmed movements were faster after the introduction of the oddball, relative to those made prior to it. In opposition to this, those with an ASD planned for all movements similarly, demonstrating atypical anticipatory and reprogramming patterns of behaviour. To further explore the effect of reprogrammed movements on movement preparation, Nazarali et al. (2009) had participants perform movements cued by valid or invalid visual information. Trials in which the precue was identical to the target were considered valid trials, whereas invalid trials were ones in which the target was different than the precue. Results show that when the initial movement plan was unsuccessful, as in the invalid trials, RTs for TD and ASD groups were longer, though those with an ASD slowed their RT to a greater extent.

4.1.3 Movement execution differences in ASD

Coupled with greater planning requirements for motor tasks, those with ASD demonstrate differences in movement execution. Compared to TD controls, longer MTs have been reported (Glazebrook et al., 2006; Glazebrook et al., 2008; Nazarali et al., 2009). Pertaining specifically to movement kinematics, greater trial-to-trial variability and lower absolute values are observed in measures of PV and PA (Glazebrook et al., 2006; Glazebrook et al., 2008; Glazebrook, Gonzalez, Hansen, & Elliott, 2009). Additionally, results show that this population also spends a greater amount of time in the TTPV, that portion of the movement that falls primarily under feed-forward control. However, a lack of temporal and spatial differences across groups in the TAPV and endpoint errors are noted (Glazebrook et al., 2006; Campione, Piazza, Villa, & Molteni, 2016). This finding is in accordance with a planning deficit as the initial accelerative portion of the movement is related to carrying out the initial movement plan.

A more critical look into movement execution within this population might actually suggest that execution processes are spared. Absolute MT is typically reported as being higher, however a lack of differences in the phase of the movement related to online control suggests that those with an ASD may simply be exhibiting more conservative movement strategies (Mari et al., 2003; Glazebrook et al., 2006; Campione et al., 2016). In an effort to compensate for movement variability throughout the task, individuals spend a longer amount of time in the initial phase of the movement that is more reliant on feed-forward control. Those with ASD might be more reliant on visual feedback, thus variability is reduced during the latter portion of the movement to accurately acquire the end target in a similar way as TD controls.

4.1.4 The use of visual information in ASD

Motor performance differences observed in this population may be better explained by how those with an ASD utilize visual information. Under the notion that movement execution is intact in this population, MT differences may actually be related to deficits in the integration of visual information (Rinehart et al., 2001a; Glazebrook et al., 2009). When visual feedback is available, both endpoint accuracy and MT differences were improved. Though these measures were still poorer than those of the TD population, the pattern of behaviour was consistent. Thus, it is suggested that differences arise as a result of a deficit in visual perceptual integration with ongoing movements, relative to a TD population (Glazebrook et al., 2009; Dowd et al., 2012).

In addition to difficulties integrating such information, it has also been shown that those with an ASD take significantly longer to actually disengage attention and initiate rapid eye movements to another location in space, often times failing to actually initiate a shift in attention (Landry & Bryson, 2004; Hill, 2004; Bryson et al., 2007). Thus, the nature of a visual cue influences how those with an ASD utilize visual information. Individuals in this population are better able to use direct visual information to plan movements compared to when it is presented more abstractly (Nazarali et al., 2009). Based on the lower movement velocities and increased movement execution times found by Glazebrook et al. (2009), the authors proposed that perhaps those with ASD slow the entire duration of their movement to allow more time for visual processing to occur. Additionally, the slower movements are proposed to actually be a mechanism of active planning, such that movements are slowed down to allow for successful reprogramming of a movement as individuals with an ASD have difficulty responding to rapid visual cues (Nazarali et al., 2009; Mosconi et al., 2015). However, impairments in oculomotor control can affect visual perception and coordinated movements between the hand and the eye (see Brenner, Turner, & Müller, 2007).

4.1.5 Central coherence theory as an explanation for motor behaviour

Central coherence theory (Frith, 1989) explains the phenomenon for TD individuals to process incoming sensory information for meaning. In other words typically individuals take on a more global perspective. In contrast, individuals with an

ASD possess weak central coherence, such that attention is biased towards particular details, or the more local aspects of a stimulus. As a result, processing in this population tends to be more detail-focused, characterized by faster responses to local stimuli and a reduced ability to shift attention from local to global processing (Rinehart et al., 2001b; Wang, Mottron, Peng, Berthiaume, & Dawson, 2007) except when explicitly instructed to do so (see Happé & Frith, 2006).

This bias towards local processing has been used to characterize resultant behaviours of motor tasks in those with an ASD. These behaviours include reduced trial-to-trial variability in advance planning tasks (Glazebrook et al., 2006; Rinehart et al., 2001a; Rinehart et al., 2006) and in motor sequencing tasks (Fabbri-Destro, Cattaneo, Boria, & Rizzolatti, 2009). It is suggested those with an ASD treat each trial as a discrete component, unaffected by the conditions of the preceding trial. Additionally, when individuals are required to chain movements into a coherent whole, those with an ASD program movement components independently from one another, where actions in one sequence are unaffected by components in another sequence (Cattaneo et al., 2007; Fabbri-Destro et al., 2009).

4.1.6 Summary of the literature on ASD

It is clear that a diagnosis of ASD is characterized by deficits in motor processes, specifically a deficiency in motor planning (e.g. Glazebook et al., 2006). This population is more reliant on visual information to guide movements, and it is this visuo-motor integration that may underlie the observed atypical behaviours (Rinehart et al., 2001b).

Deficits in dorsal stream processing may also be indicative of deficits in this pathway (Spencer et al., 2000).

Low trial-to-trial variability in strategy-related tasks may be demonstrative of the repetitive and stereotyped behaviours characterizing such a diagnosis, but may also be attributed to a weak central coherence, such that a bias towards the processing of local stimuli is observed, with difficulties disengaging attention from specific aspects of the task.

The behavioural consequences of being unable to successfully update movements to avoid obstacles in space are particularly high for individuals along the spectrum. Hypersensitivity to external stimuli has been reported to cause strong physical and emotional reactions (Elwin et al., 2012), and simply having a planned walking path intercepted by an unexpected passerby can have negative consequences. Thus, it is imperative to explore the processes involved in making online corrections to unexpected obstacles and how they differ from a neurotypical population.

The presentation of the following case study seeks to provide a basis for the understanding of how individuals with known challenges in incorporating visual information into the online control of goal-directed movement, specifically ASD, adapt to unexpected obstacles along the movement pathway. Following the same protocol as participants underwent in Study 2, relative behavioural differences between an individual with an ASD and that of an age and gender-matched TD control are compared. It is hypothesized that the individual will execute two distinct movements, such that when presented with a second unexpected obstacle, they will need to stop, reassess the new environment, and execute a second movement plan.

4.2 METHODS

4.2.1 Participants

This study is intended to act as a single case study to present findings of potential differences within this population. Clearly, any evidence of such differences cannot be generalized to an entire population on the basis of this single person comparison; however it is our intention here to provide a starting point for future research in this area. The participant was a 29 year old, right-hand dominant male, with normal vision, previously diagnosed with an ASD. This participant completed the Peabody Picture Vocabulary Test-Revised as a measure of receptive language, and Raven's Progressive Matrices (RPM), as a measure of non-verbal ability. These tests were used to infer IQ characteristics of the participant. The verbal mental age, of the participant was 17, and the IQ equivalent of the RPM score was 86.

The data of this participant are presented alongside those of an age, gender and handedness-matched control that presented with a BAPQ score that fell below the cut-off.

4.2.2 Data acquisition

The experimental apparatus and protocol were the same as that used in Study 2.

4.2.3 Data analyses

The positional data retrieved underwent the same analyses as those in Study 2.

4.2.4 Statistical analyses

As data from only one participant was collected, no formal statistical analyses were conducted. Instead, results are presented as a descriptive analysis of trajectories in comparison to those of the matched control.

4.3 RESULTS

Tracings of the trajectories for each condition can be found in Figures 4.1-4.10, and the points in the trajectory at which the second set of unexpected obstacles appeared are contrasted for each condition in Figures 4.11-4.16.

4.4 DISCUSSION

Though strict conclusions cannot be drawn regarding obstacle avoidance in this population, a comparison of the trajectories of the participant with an ASD and a matched control demonstrate clear differences in behaviour. Consistent with previous work (i.e., Glazebrook et al., 2009) it appears that the kinematic data of the participant with an ASD is much more variable across trials within the same condition. Despite this variability, successful task completion measures did not greatly differ compared to the matched control participant.

While the trajectories of the matched control deviated in between the obstacles, it is apparent that the participant with an ASD began to move laterally upon movement onset resulting in wide deviations to both sides. This movement reprogramming is a particular aspect of performance that individuals with an ASD have difficulty with (Nazarali et al., 2009; Rinehart et al., 2001a). Therefore, rather than potentially having to reprogram their movement in response to the new visual information induced by the perceptual perturbation, it appears that this individual adopted a strategy that allowed them to successfully complete the task without putting them at a disadvantage. That is, they adopted a strategy that responded to the worst-case scenario. The use of this strategy is particularly evident in the condition where an obstacle did not appear as they failed to recognize that an online correction would not be required. Thus, these results might be indicative of this population adapting responses to unexpected situations by optimizing task success by not putting themselves in a situation where a change to the movement plan is required.

Despite being within the internal bounds of the obstacles at second obstacle onset, the participant with an ASD initiated a trajectory deviation that went completely around the obstacles. These findings are in contrast to those produced by theories of optimal control suggesting that limb placement at the time of perturbation onset corresponds to the optimal trajectory taken (i.e. Nashed et al., 2014). This hypothesized trajectory selection however, is examined in individuals with intact perceptual motor systems. Thus, we suggest that given the specific difficulties individuals with an ASD experience in movement reprogramming and visual perceptual integration (e.g. Dowd et al., 2012), adopting a strategic movement strategy that allows for successful task performance may be their optimal pathway.

Figure 4.1: Trajectory tracings and kinematics for the No Obstacle (NO) condition for the participant with an ASD (A), and the matched control (B).

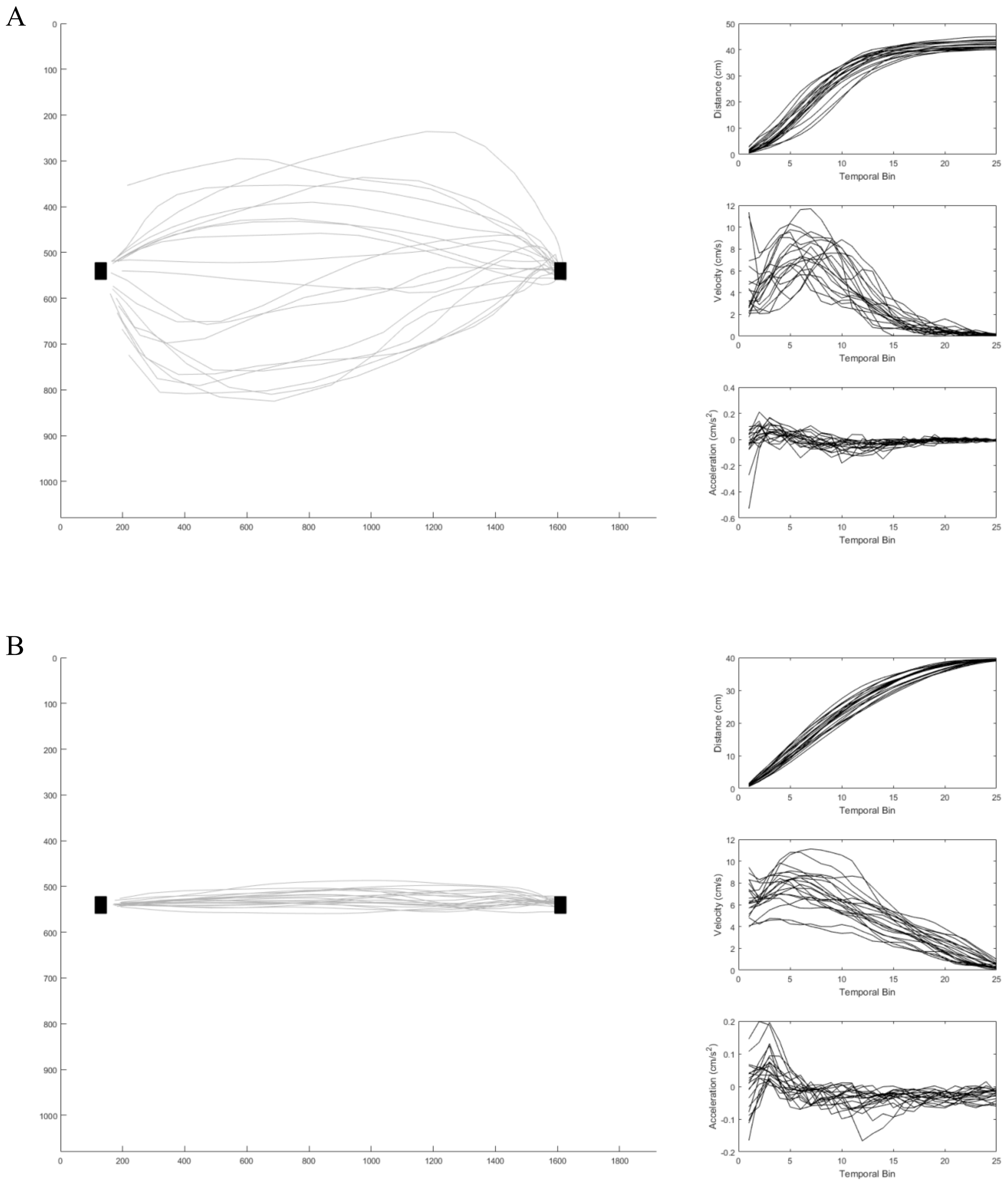


Figure 4.2: Trajectory tracings and kinematics for the Proximal Obstacle (PO) condition for the participant with an ASD (A), and the matched control (B).

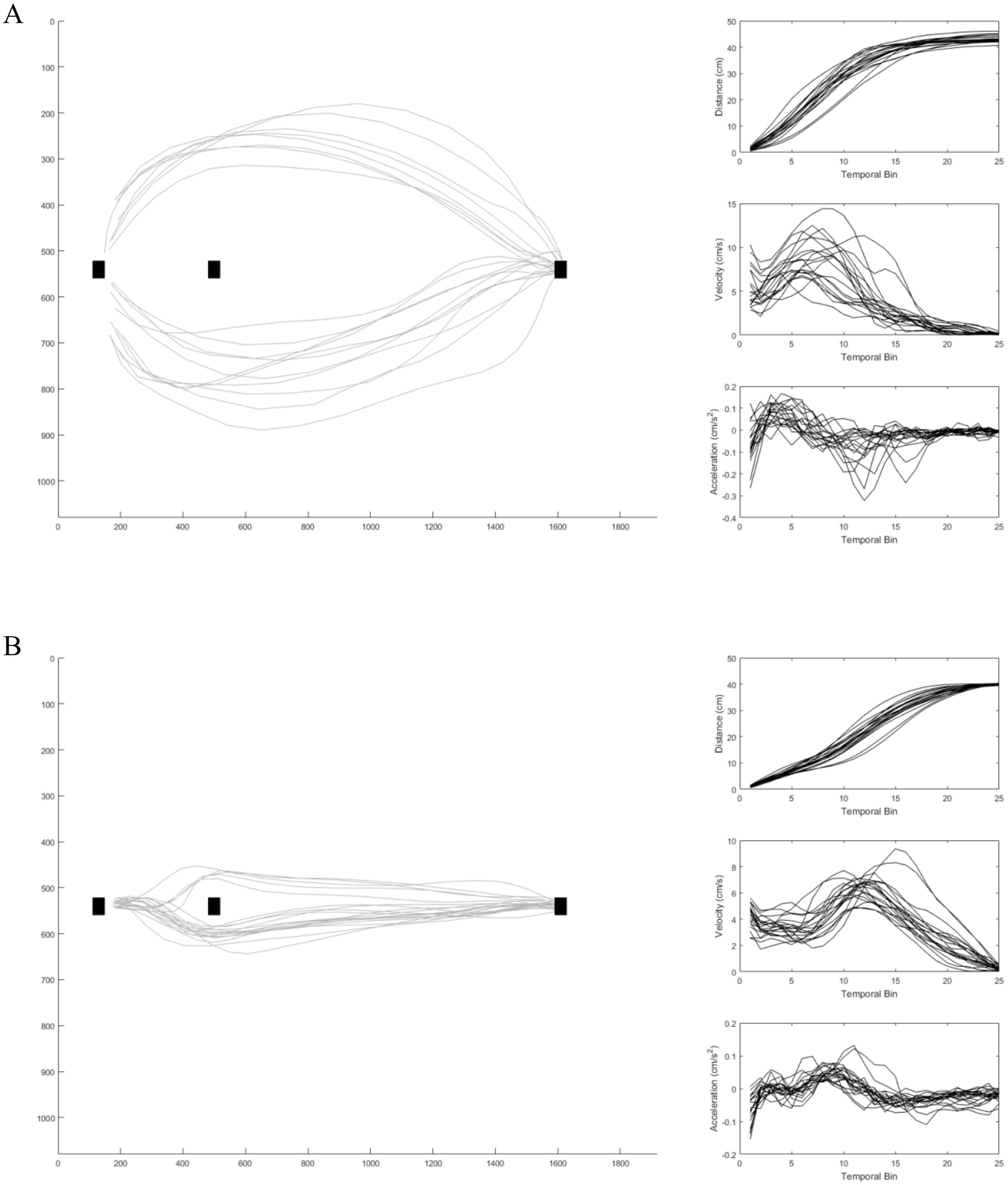


Figure 4.3: Trajectory tracings and kinematics for the Proximal Early (PE) condition for the participant with an ASD (A), and the matched control (B).

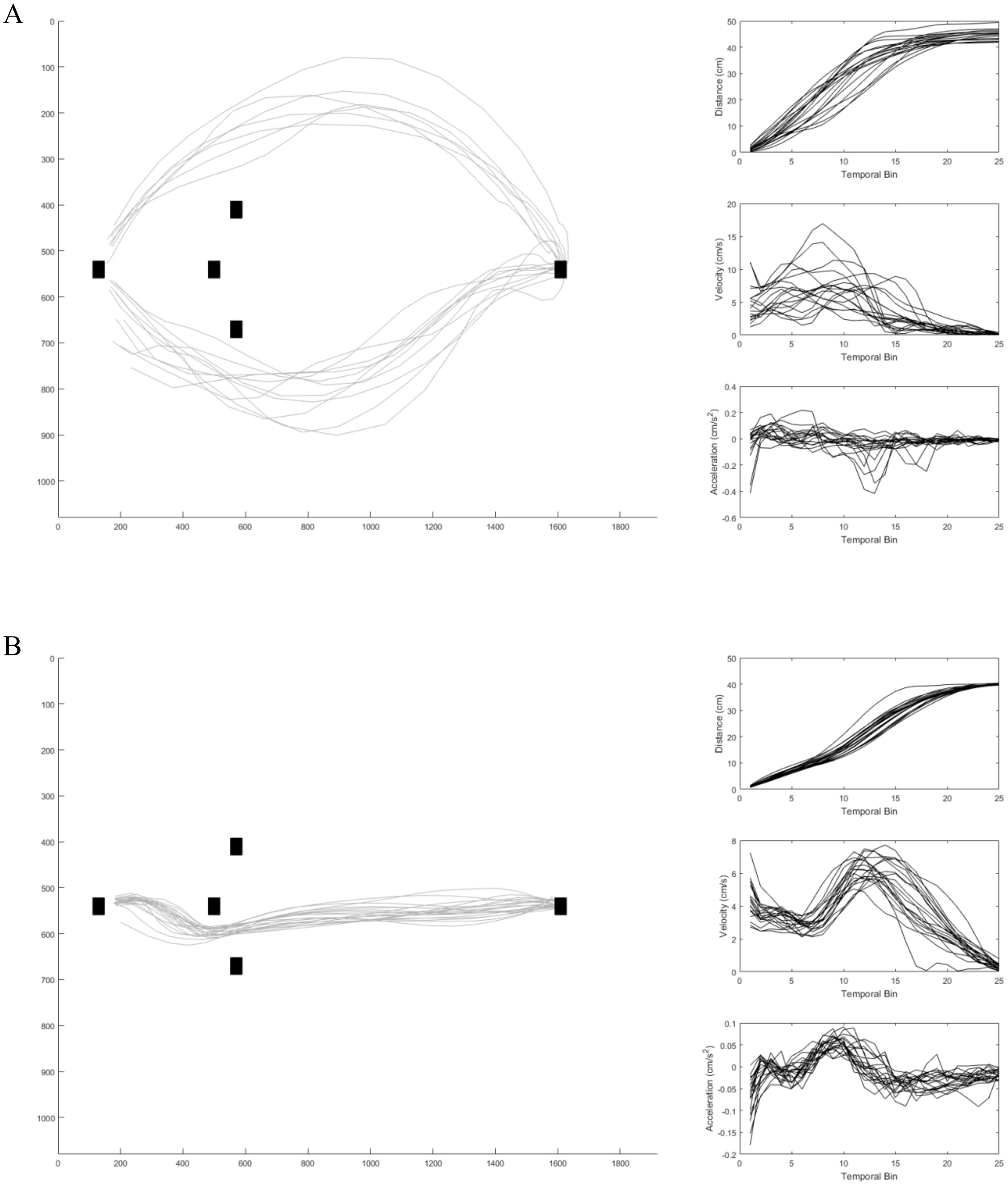


Figure 4.4: Trajectory tracings and kinematics for the Proximal Late (PL) condition for the participant with an ASD (A), and the matched control (B).

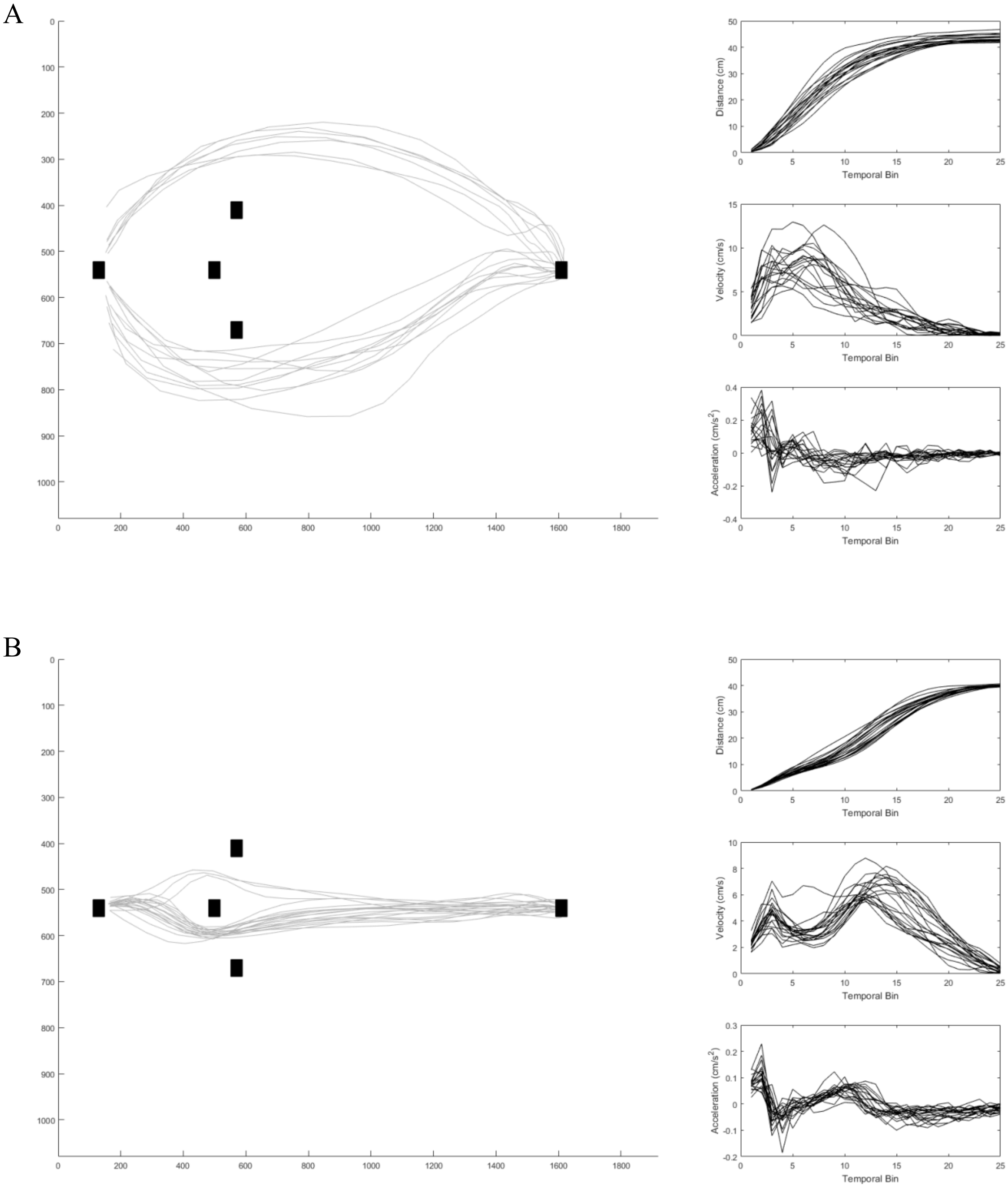


Figure 4.5: Trajectory tracings and kinematics for the Middle Obstacle (MO) condition for the participant with an ASD (A), and the matched control (B).

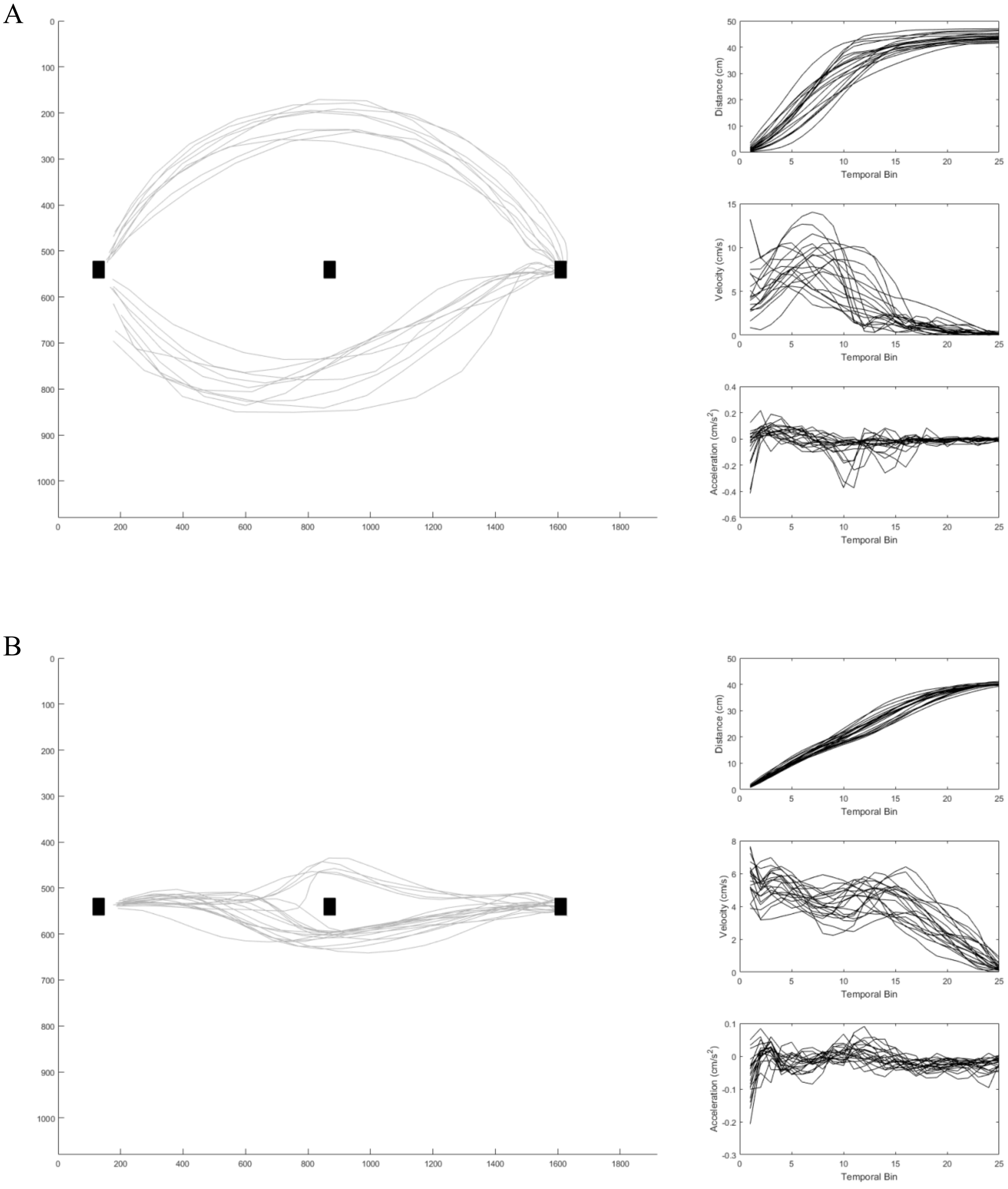


Figure 4.6: Trajectory tracings and kinematics for the Middle Early (ME) condition for the participant with an ASD (A), and the matched control (B).

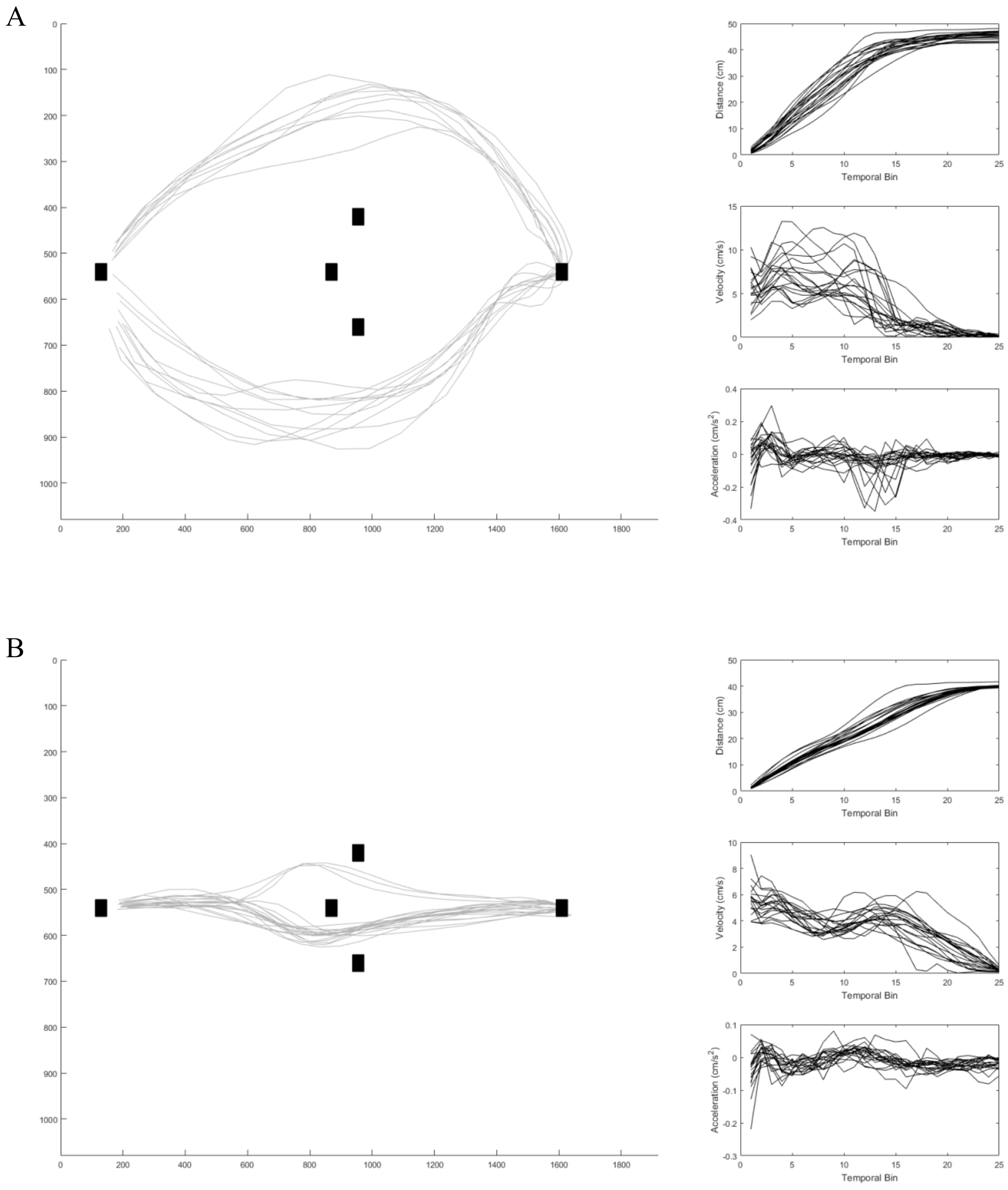


Figure 4.7: Trajectory tracings and kinematics for the Middle Late (ML) condition for the participant with an ASD (A), and the matched control (B).

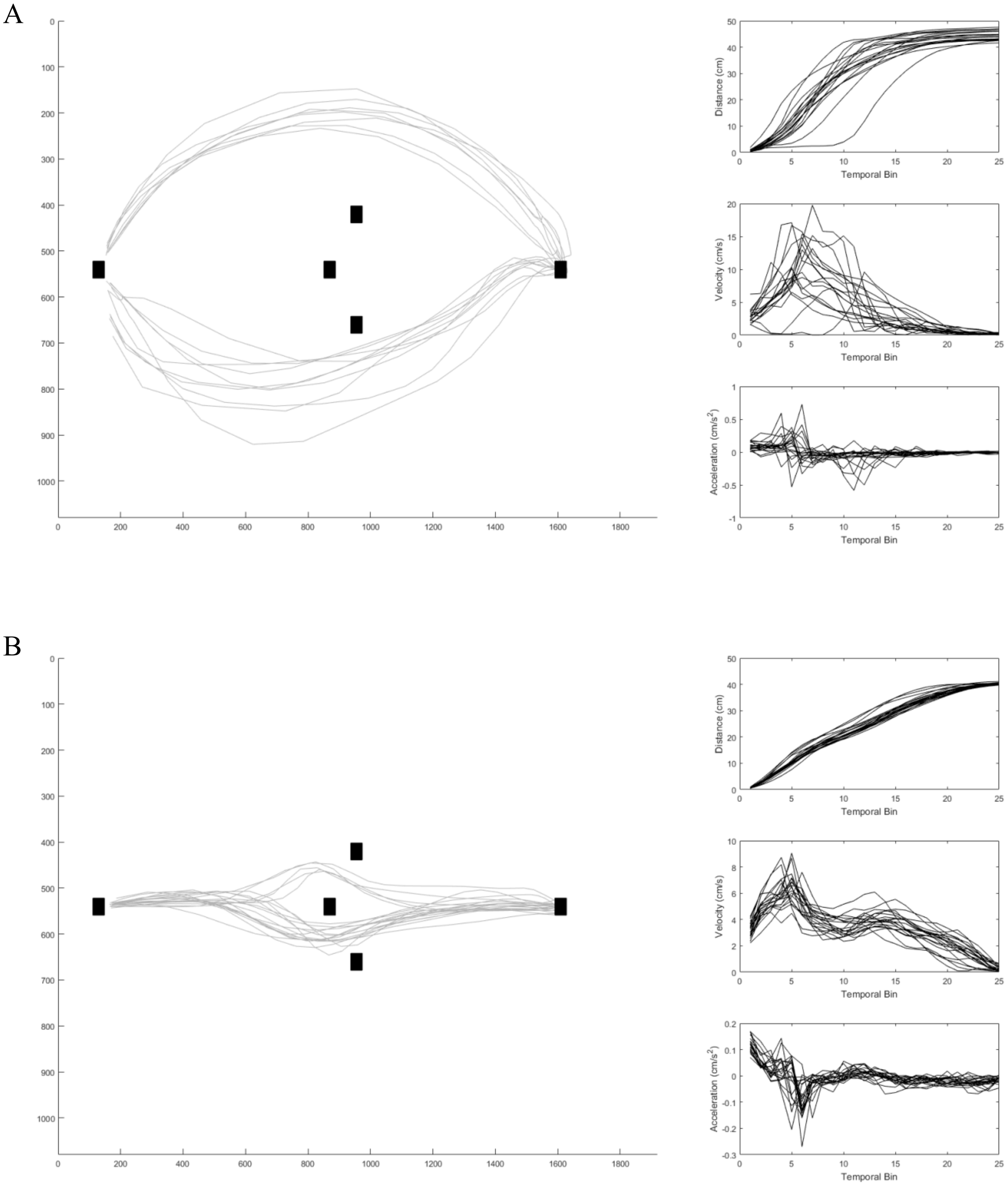


Figure 4.8: Trajectory tracings and kinematics for the Distal Obstacle (DO) condition for the participant with an ASD (A), and the matched control (B).

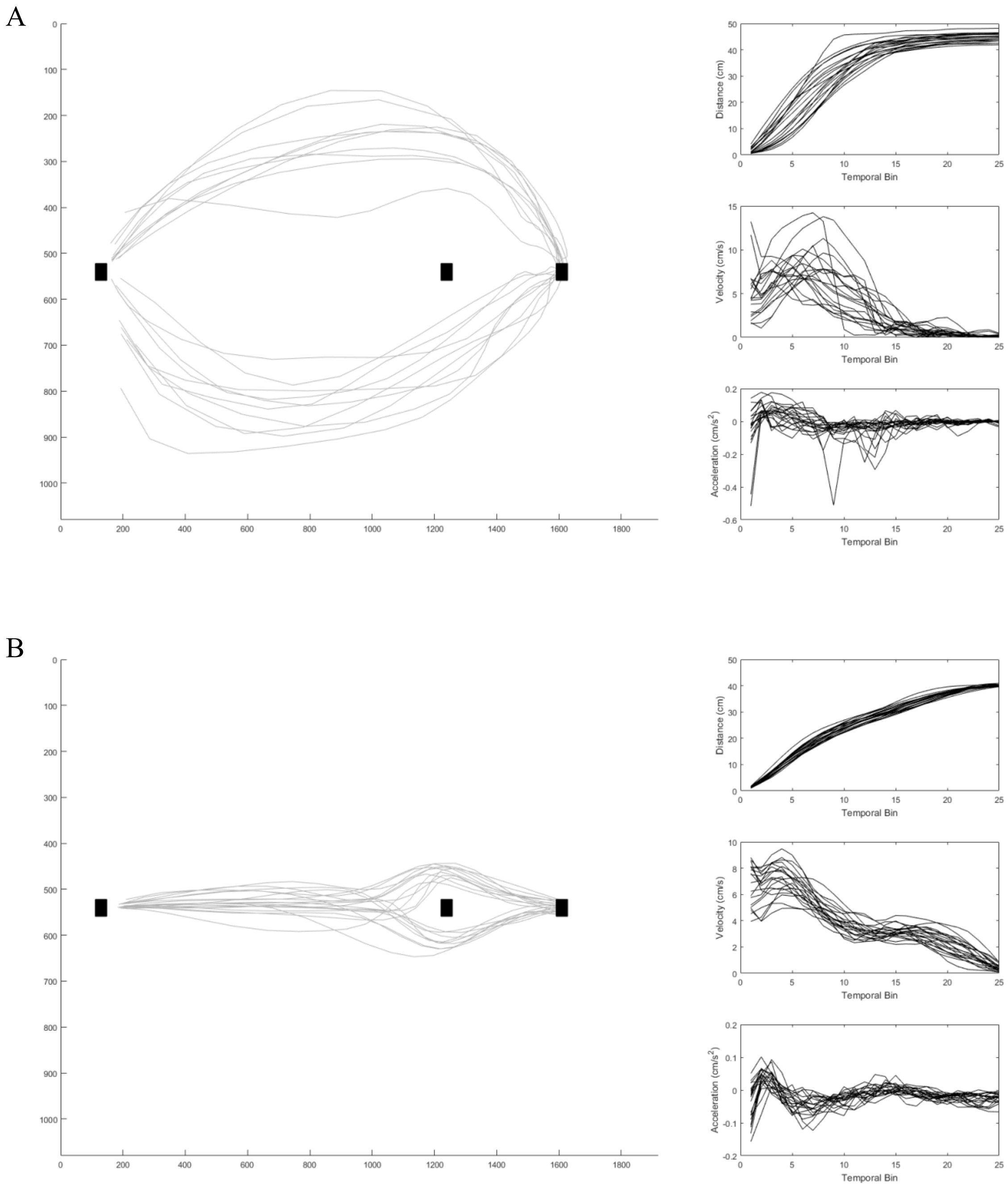


Figure 4.9: Trajectory tracings and kinematics for the Distal Early (DE) condition for the participant with an ASD (A), and the matched control (B

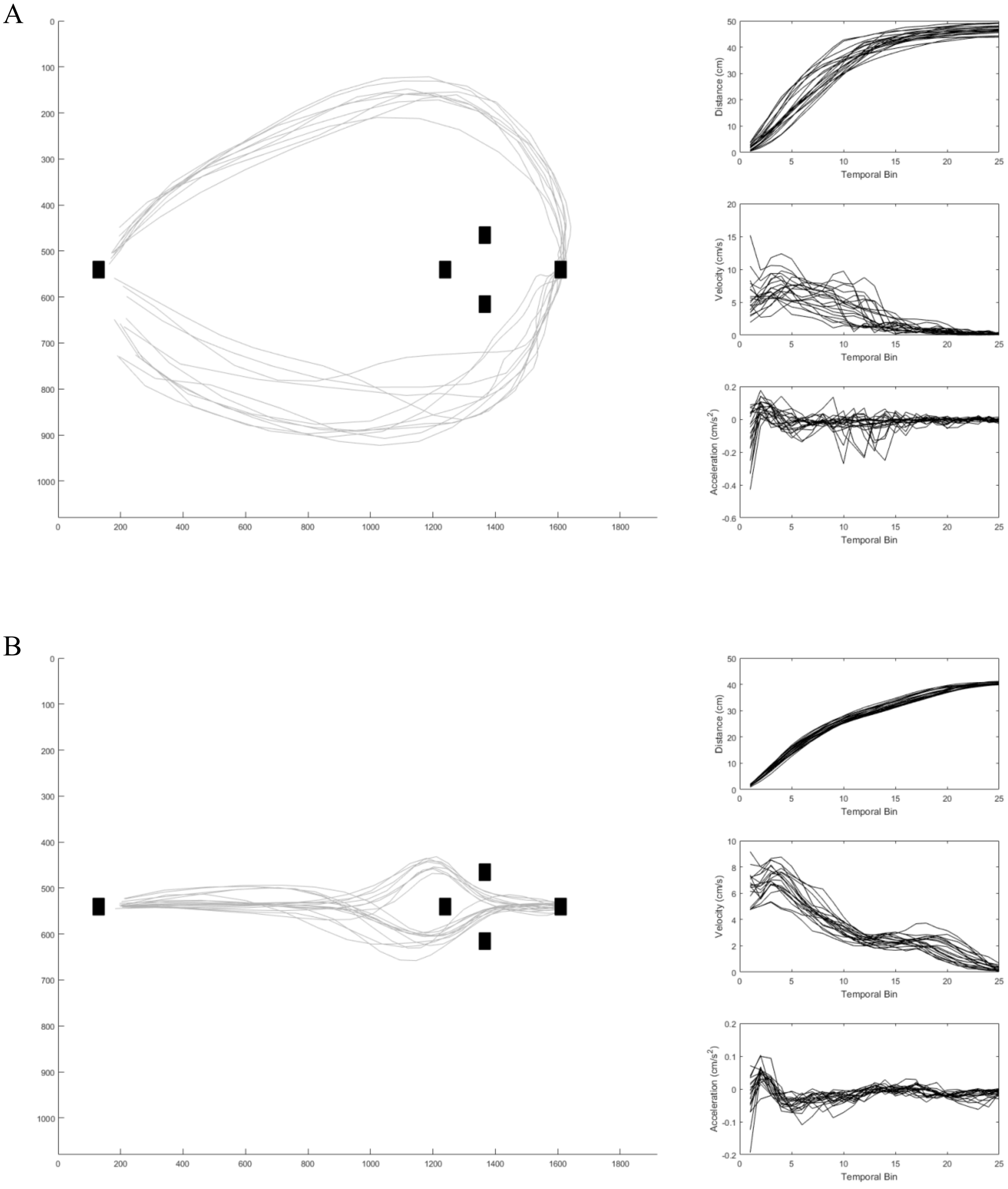


Figure 4.10: Trajectory tracings and kinematics for the Distal Late (DL) condition for the participant with an ASD (A), and the matched control (B).

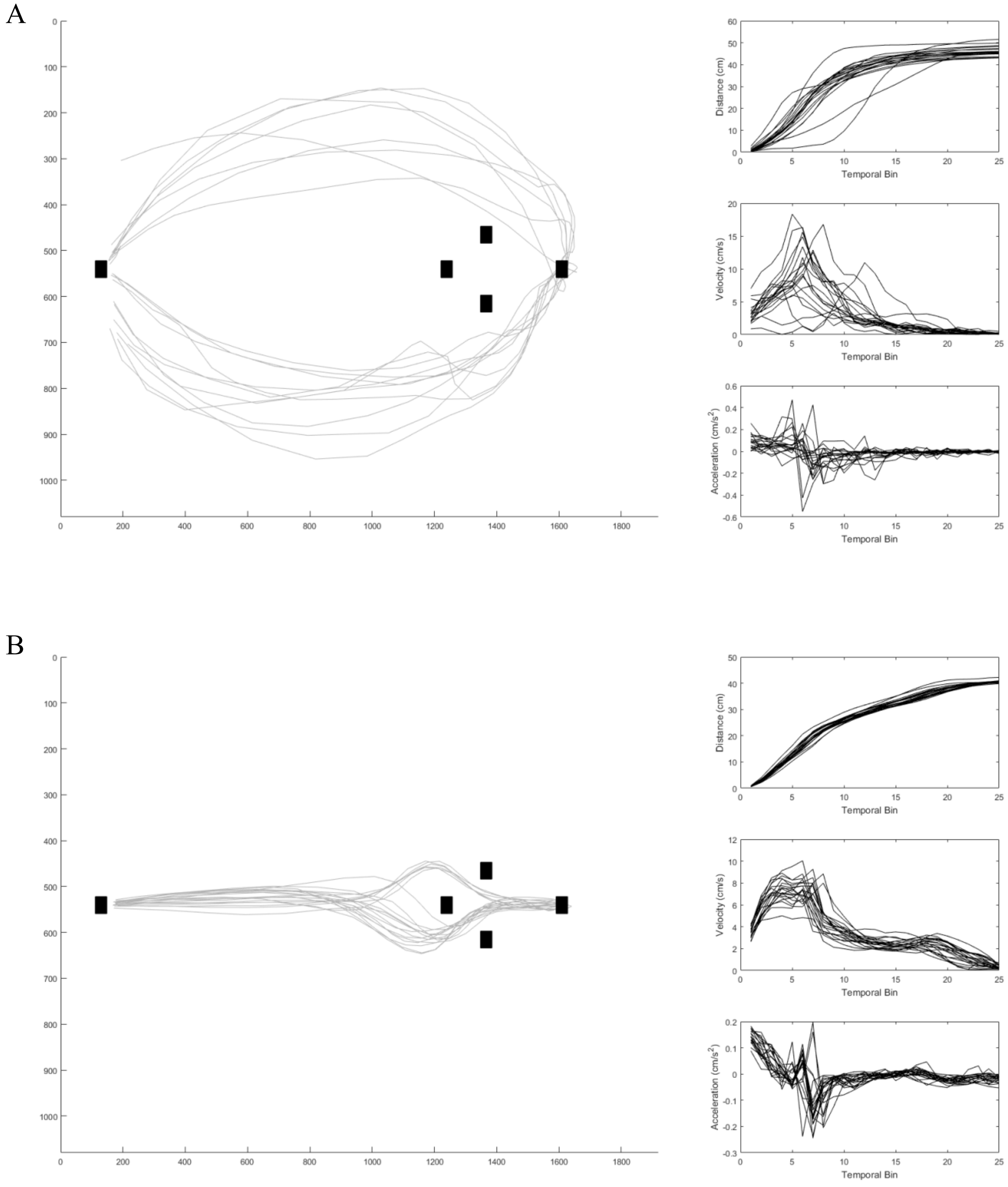


Figure 4.11: Distribution of trajectory points in the Proximal Early (PE) condition for the participant with an ASD (A) and the matched control (B). Distribution points demonstrate leftward (L) trajectories in red, left between trajectories (LB) in green, right between trajectories (RB) in orange, and rightward trajectories (R) in blue at the point of secondary, early obstacle onset.

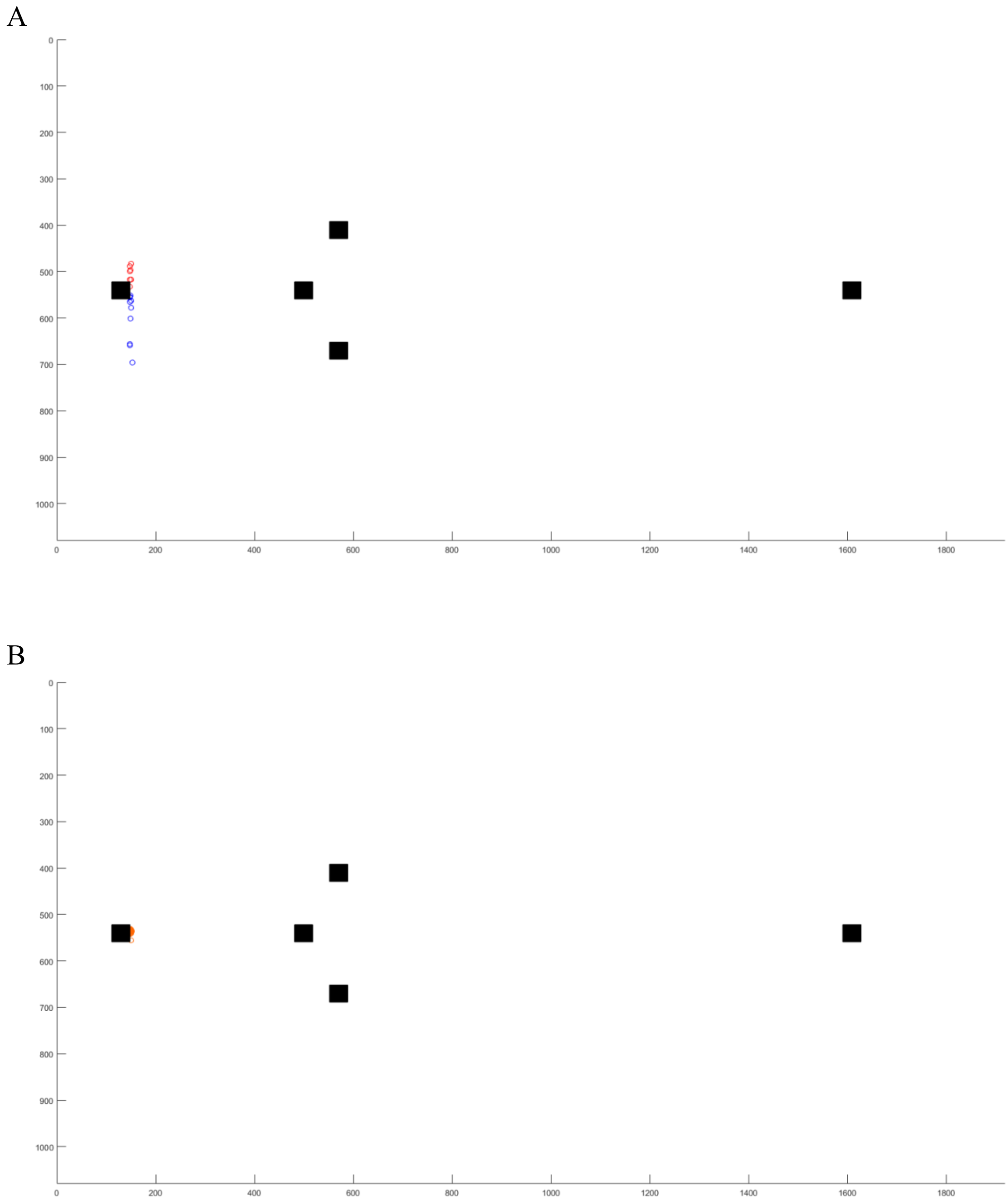


Figure 4.12: Distribution of trajectory points in the Proximal Late (PL) condition for the participant with an ASD (A) and the matched control (B). Distribution points demonstrate leftward (L) trajectories in red, left between trajectories (LB) in green, right between trajectories (RB) in orange, and rightward trajectories (R) in blue at the point of secondary, late obstacle onset.

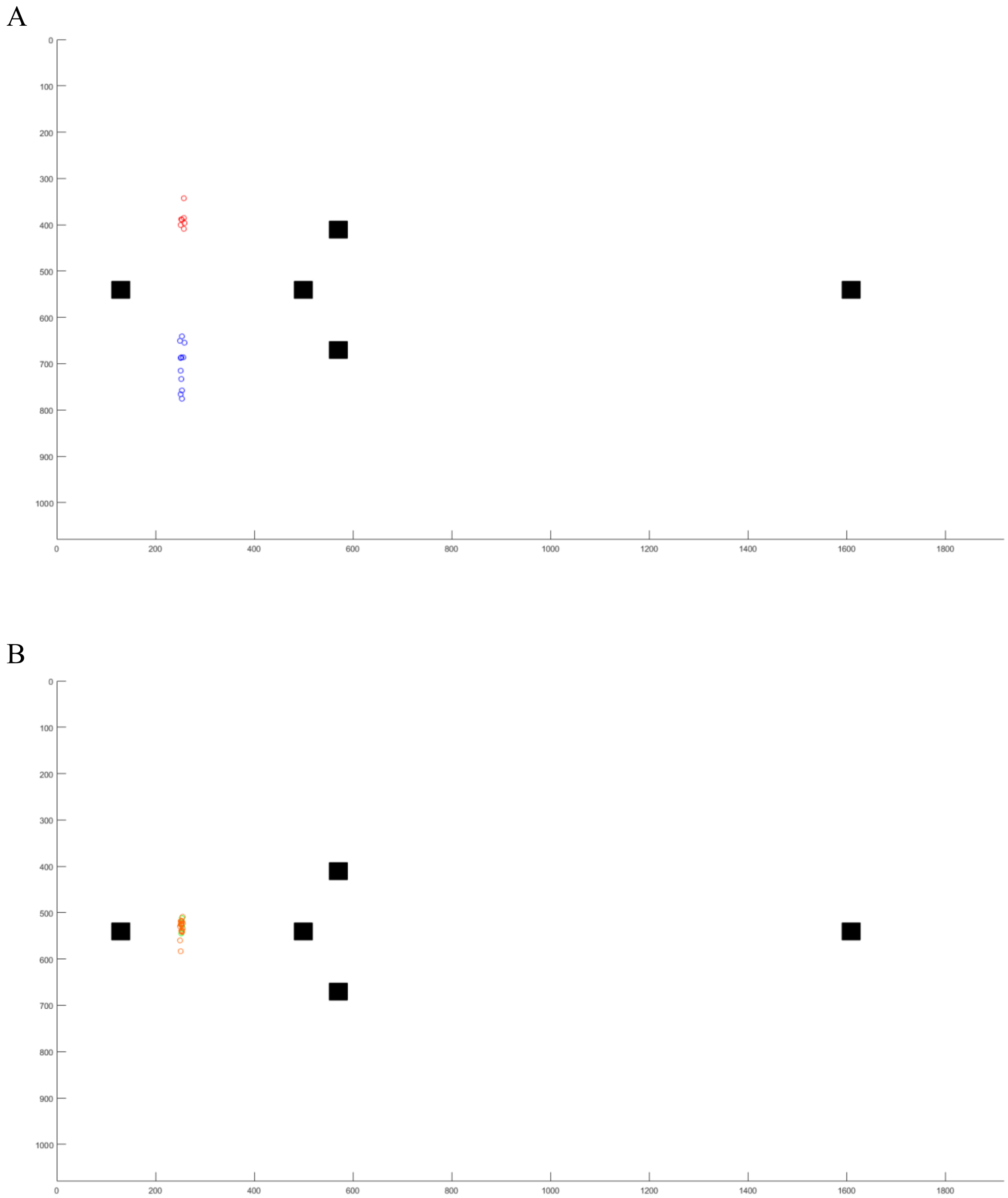
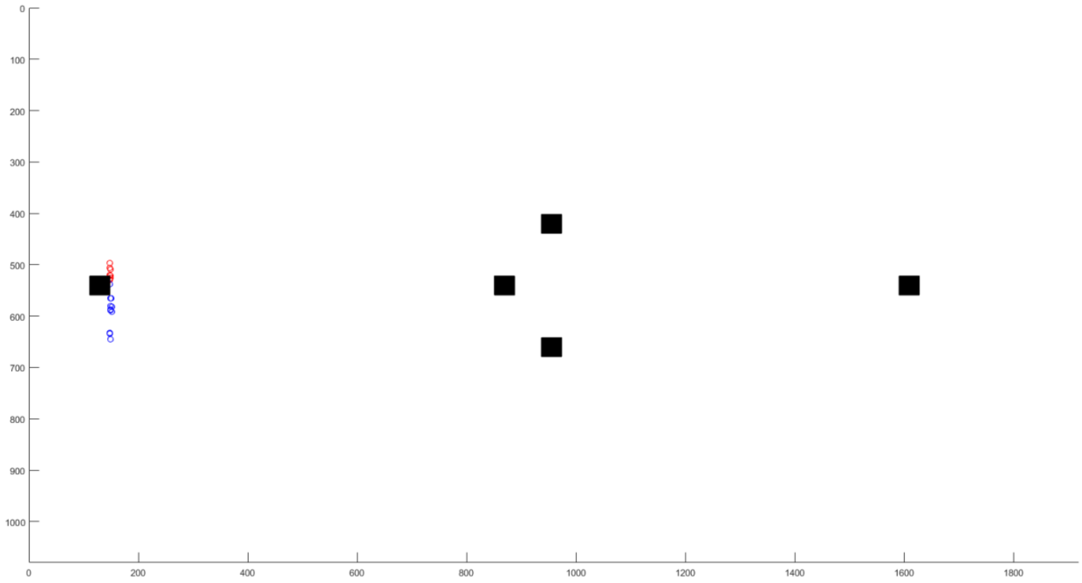


Figure 4.13: Distribution of trajectory points in the Middle Early (ME) condition for the participant with an ASD (A) and the matched control (B). Distribution points demonstrate leftward (L) trajectories in red, left between trajectories (LB) in green, right between trajectories (RB) in orange, and rightward trajectories (R) in blue at the point of secondary, early obstacle onset.

A



B

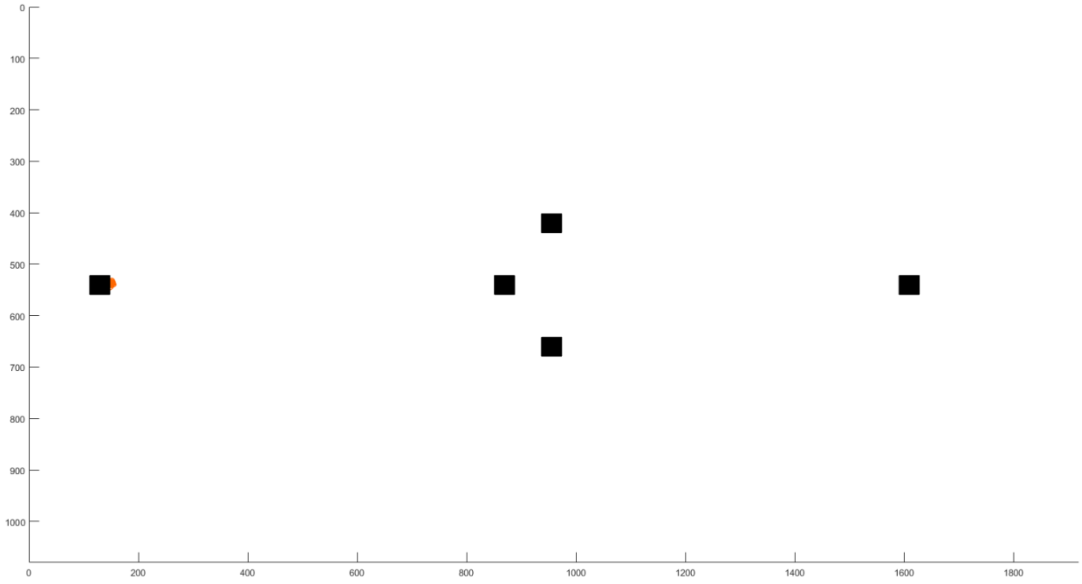
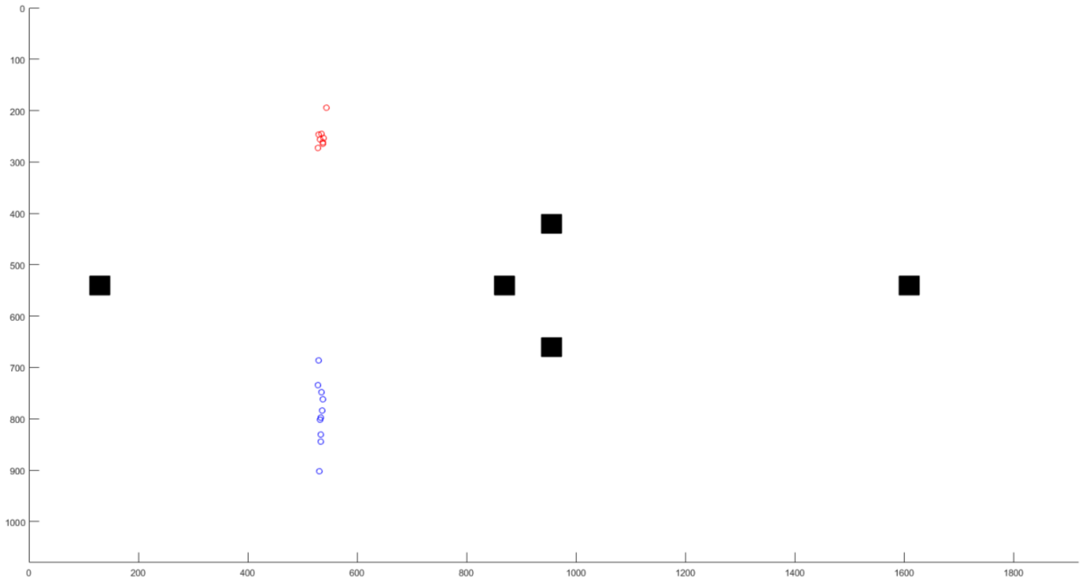


Figure 4.14: Distribution of trajectory points in the Middle Late (ML) condition for the participant with an ASD (A) and the matched control (B). Distribution points demonstrate leftward (L) trajectories in red, left between trajectories (LB) in green, right between trajectories (RB) in orange, and rightward trajectories (R) in blue at the point of secondary, late obstacle onset.

A



B

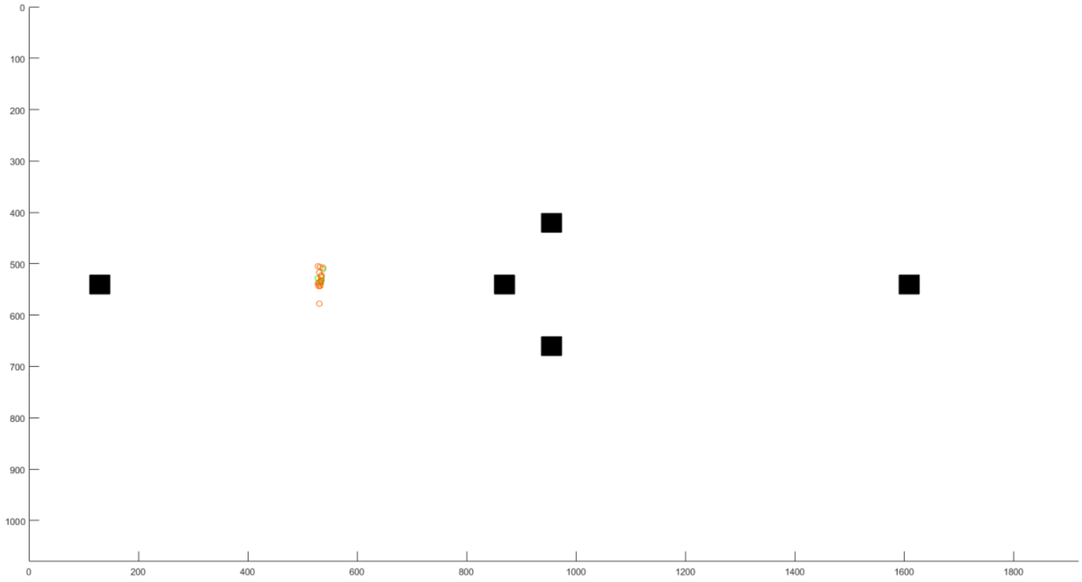
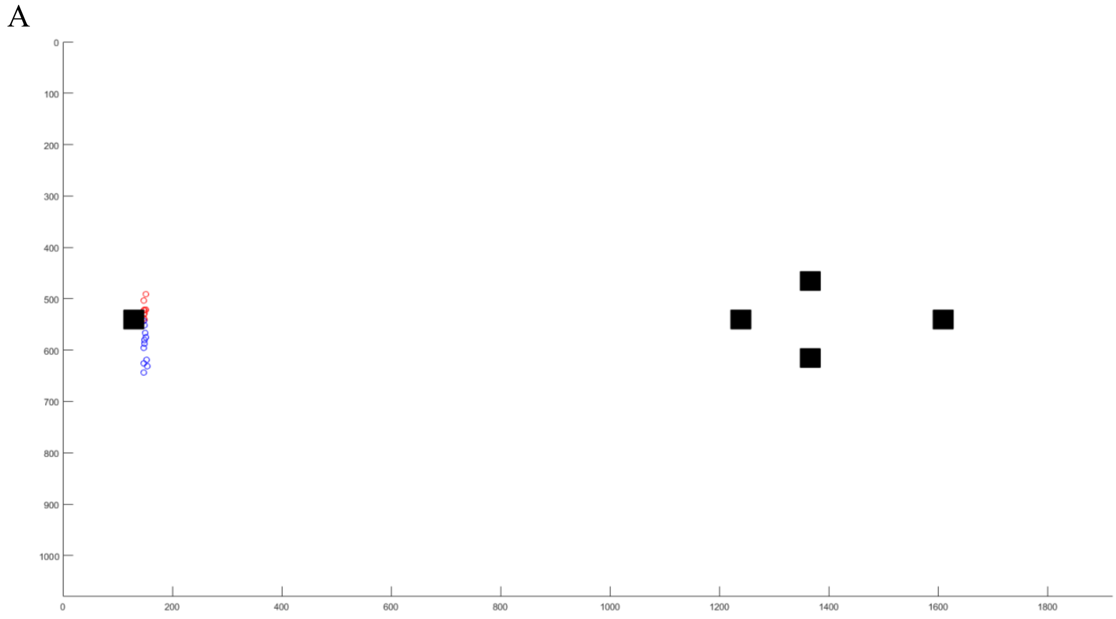


Figure 4.15: Distribution of trajectory points in the Distal Early (DE) condition for the participant with an ASD (A) and the matched control (B). Distribution points demonstrate leftward (L) trajectories in red, left between trajectories (LB) in green, right between trajectories (RB) in orange, and rightward trajectories (R) in blue at the point of secondary, early obstacle onset.



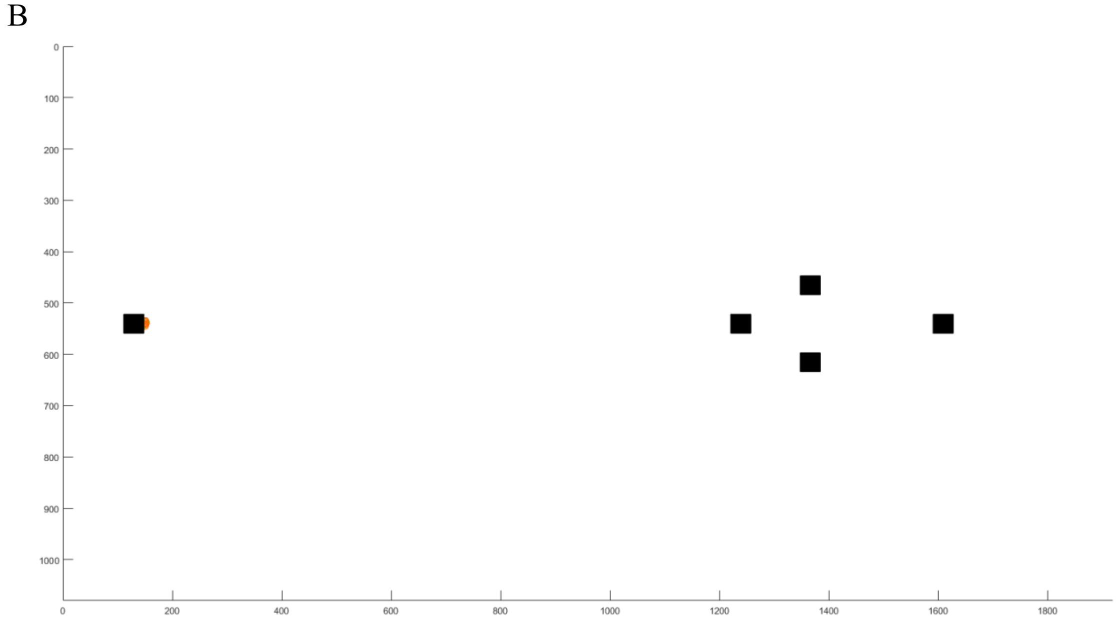
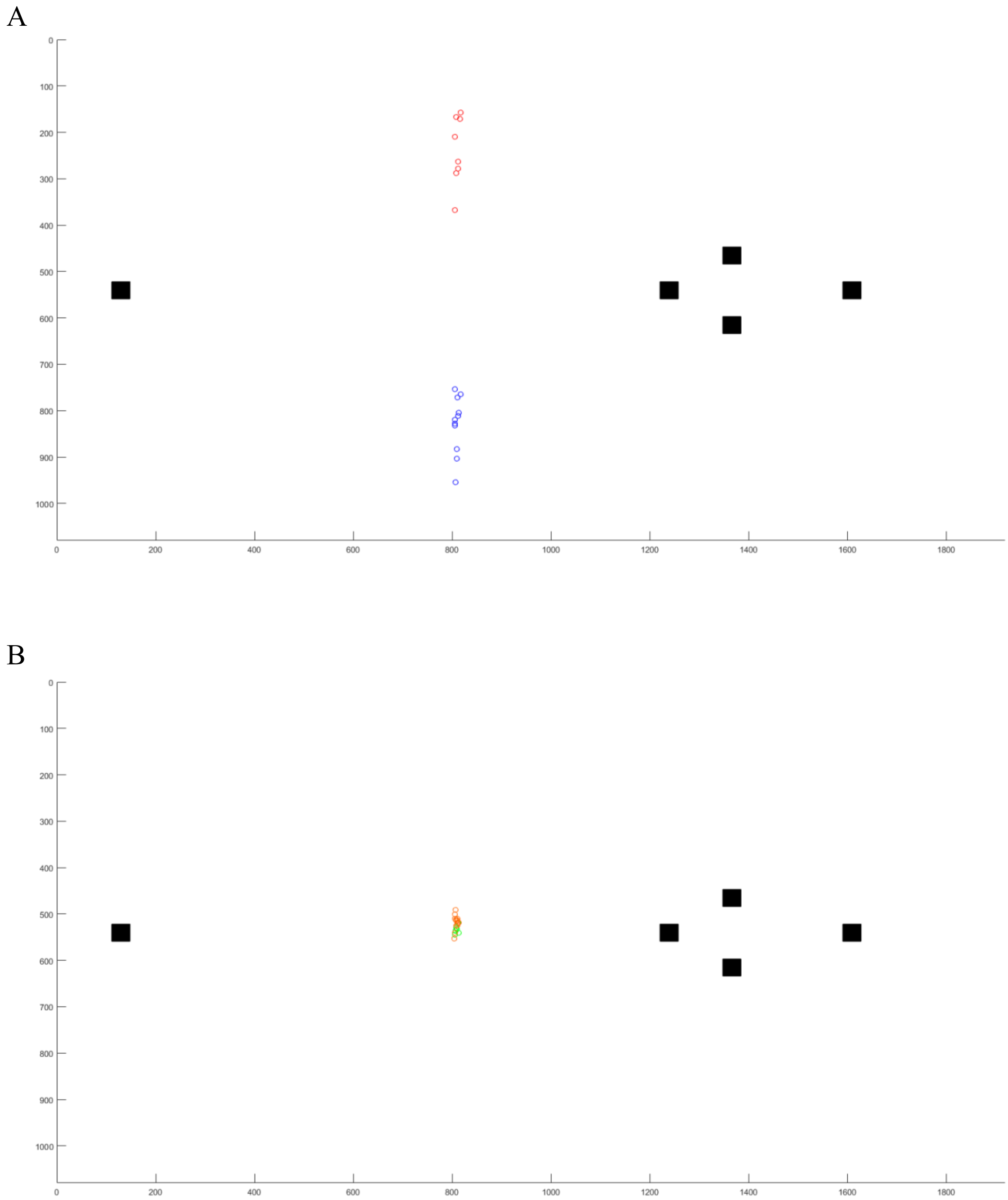


Figure 4.16: Distribution of trajectory points in the Distal Late (DL) condition for the participant with an ASD (A) and the matched control (B). Distribution points demonstrate leftward (L) trajectories in red, left between trajectories (LB) in green, right between trajectories (RB) in orange, and rightward trajectories (R) in blue at the point of secondary, late obstacle onset.



CHAPTER 5: GENERAL DISCUSSION

In its entirety, this work provides several novel insights into the behavioural responses that arise when an unexpected visual obstacle perturbs the movement during a manual obstacle avoidance task. Unlike mechanical perturbations that displace the limb as a result of an external force, this type of perceptual obstacle changes the visual environment and requires a self-initiated adjustment to the movement. Contrary to theories of optimal control (see Todorov, 2004) that stipulate that changes in proprioceptive information result in emergent, proprioceptively driven behaviours to produce an optimal solution, the multiple process model suggests that top-down processing allows for the integration of visual information with downstream information to produce accurate movements, despite changing visual environments (Elliott et al., 2010). The results from this study support the prediction that the motor system quickly adapts to visual perceptual perturbations (as early as movement onset) to execute trajectory modifications that result in ultimately successful and accurate movements. Thus, while in no way discounting optimal control explanations for our observations, the data certainly support and extend multiple-process models of movement control from which these predictions arise.

5.1 The influence of obstacle onset timing

Study 2 manipulated the onset timing of obstacles to trigger perceptual perturbations that corresponded with the phases highlighted in the multiple component models (Elliott et al., 2010; Woodworth et al., 1899). The second set of unexpected obstacles appeared early or late into the movement. Early appearance of these second obstacles corresponded with movement onset in an attempt to perturb the initial impulse.

Late second obstacle onset occurred when participants had travelled two thirds of the way to the first obstacle in an attempt to perturb the homing phase of the movement.

One explanation for the lack of differences across these conditions is that individuals were able to rapidly utilize visual information and adapt to changes in the movement context, as would be predicted by Elliott and colleagues (Elliott et al., 2010). We suggest that the different onset times may have elevated the unpredictability of the task. That is, the computational demands on the perceptual motor system in executing successful responses increased as a result of the unpredictability of the task condition and the onset of the second set of obstacles when they occurred. Measures of acceleration were different in the proximal obstacle condition, such that acceleration was higher when the obstacle occurred later in the movement than when it occurred earlier. We suggest that this difference arises from the performance of more cautious movements, which will be discussed in the following section.

5.2 The potential for a perceptual perturbation

Of particular interest to the aim of this study is how movements are affected by the mere possibility of an unexpected perceptual perturbation. A comparison across similar conditions in both studies indicates that simply the potential presence of a second set of obstacles significantly influences movement behaviours. That is, both Study 1 and Study 2 had identical conditions in which an initial obstacle appeared prior to movement onset. In Study 2 however, these conditions had the potential for a second set of unexpected obstacles to appear during movement execution. Though movement times were not different between studies, trajectory distances *were* affected. That is, the distance travelled was significantly influenced by the potential for encountering an unexpected perceptual perturbation. This can be explained by studies examining the use of continuous control in updating movements (e.g. Elliott et al., 2010; Hansen et al., 2006), and studies examining manual obstacle avoidance behaviours (Jax & Rosenbaum, 2007). In Study 2, participants were unaware whether an update to the original movement plan would be needed, as would be the case when the preferred trajectory was perturbed by the onset of an unexpected obstacle. This very likely resulted in an increase in the computational demands of the task, as each condition required a slight, but significant, change to the movement plan to perform the most biomechanically efficient trajectory. Previous work has found that individuals develop a compromise between these biomechanical and computational demands, such that avoidance movements are executed even when an expected obstacle is not present (i.e. Jax & Rosenbaum, 2007). We suggest therefore, that simply the added potential for a second, unexpected obstacle increased the demands on the perceptual-motor system. In turn, rather than developing a new movement plan for each trial, individuals immediately adopted a more cautious movement plan that was quickly adaptable to avoid obstacles even if they were not present but could be.

Overall, results from this study demonstrate that individuals are able to successfully adapt to perceptual perturbations in their environment. Though these adaptations were not necessarily made by the initiation of a second movement plan, it is evident that the potential for the perturbation resulted in an adaptation to the movement that resulted in similar success. That is, movement time and endpoint errors were not influenced by the second obstacle as individuals planned for the worst-case scenario and executed more cautious movements.

5.3 Optimal path trajectories

Theories of optimal control suggest that the optimal trajectory is that with the lowest accumulated cost, dictated by a specific control law, for example the minimization of movement time (e.g. Todorov, 2004). In tasks with unexpected physical perturbations, models of optimal control suggest that limb position at perturbation onset corresponds to the optimal trajectory (Nashed et al., 2014). The first study of this thesis characterized the optimal trajectory under predictable task conditions, such that individuals successfully incorporated the initial obstacle to execute smooth movements around its location. We then disrupted this optimal trajectory by placing an unexpected obstacle within its pathway that still provided a wide enough aperture to pass through. Under these conditions, optimal control models would likely suggest that if the limb was within the lateral bounds of the obstacles at perturbation onset, the most optimal movement would have been to pass between the obstacles. However, our data demonstrate that this was not the most favoured trajectory. Instead, individuals primarily made wide rightward movements to completely avoid any obstacles, suggesting that the unpredictability of the task conditions altered the optimal movement pathway.

5.4 Obstacle avoidance in special populations

The goal of this thesis is not intended to strictly compare obstacle avoidance behaviours in ASD against those of a typically developing population. Rather, this work aims to develop a protocol to allow for predictions to be made during these tasks. Though data were only collected on one individual with an ASD, the pattern of observed results qualitatively demonstrate clearly observable differences in behaviours. The trajectories of this individual were always directed around the obstacles, rather than between them, and divided fairly evenly to either direction. What is interesting is that despite these observed differences, this individual was able to successfully complete the task to the same degree as the matched control. Though more work is needed in this area, this finding supports the conclusions of previous work suggesting that movement execution processes in ASD are spared (Mari et al., 2003; Glazebrook et al., 2006). Perhaps, given that this population has difficulties in reprogramming movements (e.g., Rinehart et al., 2001a), the most optimal solution for these individuals is to adopt an absolute “worst-case scenario” strategy and move laterally as soon as possible to avoid the need to update their movement. Whether this pattern exists across this population remains to be seen, however our data suggest that it is reasonable to speculate that what is in fact an “optimal” movement strategy for one, might be decidedly sub-optimal for another.

5.5 Conclusion

Overall, results from these studies demonstrate that individuals are able to successfully adapt to perceptual perturbations in their environment. It is however, the nature of this adaptation that is particularly relevant and lends support to the multiple-process model of limb control (Elliott et al., 2010).

We propose that the idea of optimal control can be quantified on an individual basis, such that what is optimal for one individual may not be optimal for another. This may be the case both in a typically developing population and a population with known difficulties in updating movements (e.g., autism spectrum disorder). When faced with environmental uncertainty, the most optimal trajectory may not be the one that is the most biomechanically efficient. Instead, it appears that individuals preferentially choose the added biomechanical cost for a reduction in task uncertainty. It is evident that in response to a visual perceptual perturbation, the most optimal trajectory is the safest trajectory. Early control in goal-directed movements arises from the comparison of the expected and the perceived sensory information. The addition of task uncertainty in this study induces a measure of unpredictability to the movement. This lack of advance information regarding the conditions of the task reduces the ability of the perceptual-motor system to prepare a successful movement plan. Similar to movements in which the availability of vision is uncertain, individuals in this task performed movements likened to a worst-case scenario. That is, on average, individuals executed wider trajectories across all conditions when the possibility for an unexpected perturbation existed.

5.6 Limitations

A limitation to this study was the inability to collect measures of reaction time. Due to the nature of the task and the available equipment, the computer was only able to collect a certain amount of positional data per trial. Because the relative behavioural data regarding the avoidance of the obstacle was of particular interest in this study, successful data capture throughout the movement was important. Thus, in an effort to not temporally restrain avoidance movement by having the collection program cut out during a trial, the decision was made to only trigger data collection once participants had reacted to the movement cue and begun their movement.

Another limitation is that a 40cm movement amplitude was used. It has been shown that at extreme joint positions, degrees of freedom become more limited. Optimal paths may have been affected as a result. Specifically, when individuals reached the end target, they may have been at the maximum joint angle for the elbow, thereby limiting small corrections, or the ability to alter their trajectory during the movement.

Additionally, the experimental setup in this study did not specifically control for visual angle. This may have influenced the manner in which individuals perceived each of the obstacles and the point at which the end target hit the retina.

5.7 Future directions

Future work should examine emerging avoidance behaviours to a perceptual obstacle when multiple target goals are presented. Work by Nashed et al. (2012) found that sensorimotor strategies are flexible and mechanical perturbations to movements can lead to alternate targets becoming a more favourable termination point. It would be interesting to examine whether similar strategies are noted when individuals encounter a perceptual obstacle and have to self-initiate the trajectory deviation.

This study provides evidence for potential differences in avoidance behaviours in a population with an ASD. To the best of our knowledge, obstacle avoidance behaviours are yet to be characterized in this population. Thus, by extending this setup and understanding how individuals with an ASD respond to unpredictable stimuli in a changing environment, we can perhaps facilitate their success in adapting to changes in planned movements.

APPENDICES

Appendix A: Summary of results from a 4 x 1 repeated measures ANOVA for Study 1.

DV	Outcome	χ^2	ε	F	ω^2	Mean ± SD
MT	Condition	.42	-	12.60**	.04	NO: 1185.57ms ± 185.64 PO: 1315.14ms ± 265.05 MO: 1287.25ms ± 259.90 DO: 1282.47ms ± 254.24
Primary axis start position	Condition	.04**	.40	7.05*	.03	NO: 187.15pix ± 12.93 PO: 179.93pix ± 17.97 MO: 180.68pix ± 15.93 DO: 185.32pix ± 16.25
Secondary axis start position	Condition	.02**	.39	2.57	.04	NO: 541.67pix ± 6.53 PO: 556.27pix ± 31.10 MO: 548.73pix ± 22.41 DO: 546.97pix ± 17.16
Primary axis end position	Condition	.31*	.66	2.99	.05	NO: 1608.50pix ± 1.86 PO: 1608.95pix ± 2.90 MO: 1609.80pix ± 3.11 DO: 1610.34pix ± 2.34
Secondary axis end position	Condition	.59	-	1.27	.01	NO: 540.14pix ± 2.10 PO: 539.63pix ± 1.79 MO: 539.08pix ± 2.22 DO: 540.43pix ± 1.66
Trajectory distance	Condition	.09**	.51	17.49**	.31	NO: 39.02cm ± 0.55 PO: 39.90cm ± 0.67 MO: 39.89cm ± 0.48 DO: 39.93cm ± 0.51
PV	Condition	.67	-	45.16**	.05	NO: 6.94cm/s ± 1.96 PO: 5.72cm/s ± 1.95 MO: 5.80cm/s ± 2.17 DO: 6.14 cm/s ± 2.26
TTPV	Condition	.08**	.48	9.05*	.13	NO: 229.75ms ± 56.44 PO: 324.27ms ± 128.01 MO: 270.25ms ± 89.41 DO: 240.28ms ± 65.23

DV	Outcome	χ^2	ε	F	ω^2	Mean ± SD
Proportional TAPV	Condition	.11[*]	.50	8.41[*]	.16	NO: .81 ± .03 PO: .76 ± .07 MO: .80 ± .05 DO: .82 ± .03
Primary axis PV position	Condition	.25[*]	.54	3.59	.11	NO: 721.69pix ± 56.11 PO: 750.01pix ± 109.98 MO: 681.24pix ± 65.60 DO: 672.83pix ± 53.48
Secondary axis PV position	Condition	.05[**]	.45	2.54	.03	NO: 545.49pix ± 22.01 PO: 599.33pix ± 91.67 MO: 581.37pix ± 100.68 DO: 577.45pix ± 85.88
PA	Condition	.66	-	7.53[*]	.02	NO: .10cm/s^2 ± .04 PO: .08cm/s^2 ± .05 MO: .09cm/s^2 ± .05 DO: .09cm/s^2 ± .05
TTPA	Condition	.56	-	.29	.00	NO: 15.45ms ± 13.23 PO: 16.94ms ± 16.24 MO: 13.87ms ± 13.86 DO: 14.60ms ± 11.25
Primary axis PA position	Condition	.56	-	4.29[*]	.04	NO: 201.19pix ± 16.54 PO: 193.33pix ± 20.46 MO: 190.89pix ± 15.98 DO: 198.87pix ± 18.25
Secondary axis PA position	Condition	.02[**]	.39	2.19	.03	NO: 541.71pix ± 6.69 PO: 556.06pix ± 33.68 MO: 548.79pix ± 24.09 DO: 547.04pix ± 19.85

[*] indicates significance at the *p* < .05 level

[**] indicates significance at the *p* < .001 level

Appendix B: Summary of results from a 4 (Condition) x 1 (Study) repeated measures ANOVA for Study 2. Conditions include No obstacle (NO), Proximal obstacle (PO), Middle obstacle (MO), and Distal obstacle (DO).

DV	Outcome	χ^2	ε	F	ω^2	Mean ± SD
MT	Condition	.49	-	13.82**	.05	NO: 1169.72ms ± 283.15 PO: 1354.34ms ± 358.87 MO: 1318.50ms ± 331.23 DO: 1331.73ms ± 287.92
Primary axis start position	Condition	.20*	.50	.17	.00	NO: 151.15pix ± 1.26 PO: 150.99pix ± 1.76 MO: 151.25pix ± 1.75 DO: 151.22pix ± 1.53
Secondary axis start position	Condition	.04**	.46	1.22	.00	NO: 545.55pix ± 16.44 PO: 551.50pix ± 28.13 MO: 547.34pix ± 17.98 DO: 544.98pix ± 15.31
Primary axis end position	Condition	.53	-	.39	.00	NO: 1608.62pix ± 1.93 PO: 1608.38pix ± 1.37 MO: 1608.73pix ± 1.54 DO: 1609.05pix ± 1.45
Secondary axis end position	Condition	.76	-	3.59*	.11	NO: 540.11pix ± 1.59 PO: 539.02pix ± .71 MO: 540.63pix ± 1.60 DO: 540.19pix ± 1.71
Trajectory distance	Condition	.12*	.49	19.04**	.16	NO: 41.02cm ± 1.75 PO: 42.96cm ± 1.94 MO: 43.02cm ± 2.05 DO: 43.33cm ± 2.47
PV	Condition	.07**	.45	2.03	.01	NO: 15.04cm/s ± 4.45 PO: 13.92cm/s ± 6.26 MO: 13.16cm/s ± 5.68 DO: 13.94cm/s ± 5.60

DV	Outcome	χ^2	ε	F	ω^2	Mean ± SD
TTPV	Condition	.11*	.47	8.05*	.21	NO: 176.89ms ± 115.85 PO: 383.52ms ± 277.80 MO: 210.70ms ± 129.84 DO: 142.81ms ± 79.75
Proportional TAPV	Condition	.29	.-	7.22*	.19	NO: .85 ± .06 PO: .75 ± .15 MO: .84 ± .10 DO: .89 ± .07
Primary axis PV position	Condition.	.60	-	4.1*	.10	NO: 553.97pix ± 140.23 PO: 659.12pix ± 250.95 MO: 516.58pix ± 215.35 DO: 454.49pix ± 174.31
Secondary axis PV position	Condition	.29	-	.52	.00	NO: 563.74pix ± 72.63 PO: 565.52pix ± 121.06 MO: 573.29pix ± 123.49 DO: 553.78pix ± 98.00
PA	Condition	.21*	.70	5.95*	.05	NO: .27cm/s^2 ± .11 PO: .20cm/s^2 ± .07 MO: .22cm/s^2 ± .10 DO: .25cm/s^2 ± .12
TTPA	Condition	.04**	.41	8.74*	.28	NO: 39.13ms ± 30.33 PO: 220.83ms ± 211.60 MO: 70.33ms ± 97.16 DO: 22.74ms ± 19.16
Primary axis PA position	Condition	.28	-	8.41**	.28	NO: 212.74pix ± 52.08 PO: 348.65pix ± 149.09 MO: 232.46pix ± 101.72 DO: 179.09pix ± 28.96
Secondary axis PA position	Condition	.20*	.56	1.77	.02	NO: 553.17pix ±44.83 PO: 565.69pix ± 66.49 MO: 543.34pix ± 49.10 DO: 540.73pix ± 27.29

* indicates significance at the $p < .05$ level

** indicates significance at the $p < .001$ level

Appendix C: Summary of results from a 9 (Condition) x 1 (Study) repeated measures ANOVA for Study 2. The conditions include Proximal obstacle (PO), Proximal early (PE), Proximal late (PL), Middle obstacle (MO), Middle early (ME), Middle late (ML), Distal obstacle (DO), Distal early (DE), and Distal late (DL).

DV	Outcome	χ^2	ε	F	ω^2	Mean ± SD
MT	Condition	<.01	-	3.34^{*}	.01	PO: 1354.34ms ± 358.87 PE: 1419.85ms ± 331.08 PL: 1395.30ms ± 355.47 MO: 1318.50ms ± 331.23 ME: 1359.70ms ± 317.38 ML: 1400.72ms ± 361.81 DO: 1331.73ms ± 287.92 DE: 1414.98ms ± 317.20 DL: 1399.92ms ± 323.35
Primary axis end position	Condition	$<.01^{**}$	.29	5.65^{*}	.14	PO: 151.01pix ± 1.76 PE: 151.02pix ± 1.83 PL: 149.10pix ± 2.68 MO: 151.28pix ± 1.73 ME: 151.61pix ± 1.89 ML: 150.31pix ± 1.18 DO: 151.22pix ± 1.53 DE: 151.29pix ± 1.13 DL: 150.16pix ± .72
Secondary axis end position	Condition	$<.01^{**}$	.17	2.38	.01	PO: 552.34pix ± 27.17 PE: 551.50pix ± 25.23 PL: 550.86pix ± 21.32 MO: 547.67pix ± 17.72 ME: 548.12pix ± 17.16 ML: 547.58pix ± 16.82 DO: 544.98pix ± 15.31 DE: 544.26pix ± 15.10 DL: 544.07pix ± 14.71

DV	Outcome	χ^2	ε	F	ω^2	Mean ± SD
Primary axis end position	Condition	.04	-	2.18*	.07	PO: 1608.37pix ± 1.37 PE: 1609.13pix ± 2.19 PL: 1608.45pix ± 1.38 MO: 1608.71pix ± 1.54 ME: 1609.91pix ± 1.89 ML: 1608.82pix ± 2.09 DO: 1609.05pix ± 1.45 DE: 1609.34pix ± 1.26 DL: 1610.58pix ± 2.23
Secondary axis end position	Condition	.01	-	3.63*	.14	PO: 539.11pix ± .77 PE: 538.23pix ± 1.13 PL: 539.82pix ± 1.61 MO: 540.64pix ± 1.60 ME: 539.42pix ± 1.34 ML: 539.80pix ± 1.91 DO: 540.19pix ± 1.71 DE: 540.72pix ± 1.53 DL: 540.51pix ± 2.36
Trajectory distance	Condition	<.01**	.31	1.19	.00	PO: 42.96cm ± 1.94 PE: 43.40cm ± 2.03 PL: 43.18cm ± 1.89 MO: 43.02cm ± 2.05 ME: 43.27cm ± 2.01 ML: 43.10cm ± 1.77 DO: 43.33cm ± 2.47 DE: 43.39cm ± 1.84 DL: 43.54cm ± 1.87
PV	Condition	<.01**	.25	4.38*	.03	PO: 13.92cm/s ± 6.26 PE: 12.81cm/s ± 4.54 PL: 13.11cm/s ± 4.25 MO: 13.16cm/s ± 5.68 ME: 12.77cm/s ± 4.35 ML: 15.54cm/s ± 5.60 DO: 13.94cm/s ± 5.60 DE: 13.56cm/s ± 4.27 DL: 15.95cm/s ± 5.28

DV	Outcome	χ^2	ε	F	ω^2	Mean ± SD
TTPV	Condition	<.01**	.20	6.45*	.19	PO: 383.52ms ± 277.80 PE: 369.27ms ± 256.56 PL: 350.35ms ± 268.22 MO: 210.70ms ± 129.84 ME:167.81ms ± 121.90 ML: 258.59ms ± 92.70 DO: 142.81ms ± 79.75 DE: 146.00ms ± 85.83 DL: 304.63ms ± 86.92
Proportional TAPV	Condition	<.01**	.19	6.22*	.18	PO: .75 ± .15 PE: .77 ± .15 PL: .78 ± .14 MO: .84 ± .10 ME: .86 ± .10 ML: .81 ± .05 DO: .89 ± .07 DE: .89 ± .06 DL: .78 ± .04
Primary axis PV position	Condition	<.01**	.32	7.77*	.25	PO: 659.12pix ± 250.95 PE: 628.37pix ± 214.50 PL: 579.94pix ± 205.40 MO: 516.58pix ± 215.35 ME: 455.51pix ± 202.67 ML: 594.37pix ± 38.90 DO: 454.49pix ± 174.31 DE: 440.29pix ± 135.17 DL: 806.53pix ± 68.55
Secondary axis PV position	Condition	<.01*	.31	5.75*	.04	PO: 565.52pix ± 121.06 PE: 581.18pix ± 117.95 PL: 601.99pix ± 119.91 MO: 573.29pix ± 123.49 ME: 572.17pix ± 119.29 ML: 637.26pix ± 151.81 DO: 553.78pix ± 98.00 DE: 556.64pix ± 94.14 DL: 627.97pix ± 163.65

DV	Outcome	χ^2	ε	F	ω^2	Mean ± SD
PA	Condition	<.01**	.18	28.15**	.37	PO: .20cm/s^2 ± .07 PE: .21cm/s^2 ± .09 PL: .49cm/s^2 ± .24 MO: .22cm/s^2 ± .10 ME: .21cm/s^2 ± .09 ML: .45cm/s^2 ± .21 DO: .25cm/s^2 ± .12 DE: .23cm/s^2 ± .09 DL: .39cm/s^2 ± .15
TTPA	Condition	<.01**	.26	6.21*	.23	PO: 220.83ms ± 211.60 PE: 177.06ms ± 161.57 PL: 114.22ms ± 114.30 MO: 70.33ms ± 97.16 ME: 67.41ms ± 68.93 ML: 161.88ms ± 64.33 DO: 22.74ms ± 19.16 DE: 37.06ms ± 36.27 DL:168.09ms ± 83.90
Primary axis PA position	Condition	<.01**	.27	11.56**	.42	PO: 348.65pix ± 149.09 PE: 301.73pix ± 109.23 PL: 244.79pix ± 79.93 MO: 232.46pix ± 101.72 ME: 236.59pix ± 74.43 ML: 380.43pix ± 76.16 DO: 179.09pix ± 28.96 DE: 198.27pix ± 48.41 DL: 455.79pix ± 148.08
Secondary axis PA position	Condition	<.01**	.22	2.99	.05	PO: 565.69pix ± 66.49 PE: 554.29pix ± 68.82 PL: 573.95pix ± 53.30 MO: 543.34pix ± 49.10 ME: 548.76pix ± 45.46 ML: 600.05pix ± 109.84 DO: 540.73pix ± 27.29 DE: 538.98pix ± 35.47 DL: 575.20pix ± 115.45

* indicates significance at the *p* < .05 level

** indicates significance at the *p* < .001 level

Appendix D: Summary of a 4 (Condition) x 2 (Study) mixed factorial ANOVA. The conditions include No obstacle (NO), Proximal obstacle (PO), Middle obstacle (MO), and Distal obstacle (DO) by Study 1 (S1) and Study 2 (S2).

DV	Outcome	χ^2	ε	F	ω^2	Study	Mean ± SD
MT	Condition	$.56^*$	.71	26.44^{**}	.05	-	NO: 1177.99ms ± 231.82 PO: 1333.89ms ± 306.71 MO: 1302.20ms ± 289.65 DO: 1306.03ms ± 265.77
	Study	-	-	.05	0.0	-	S1: 1267.61ms ± 240.62 S2: 1293.57ms ± 314.31
	Interaction	$.56^*$	.71	1.12	.00	S1	NO: 1185.57ms ± 185.64 PO: 1315.14ms ± 265.05 MO: 1287.25ms ± 259.90 DO: 1282.47ms ± 254.24
						S2	NO: 1169.72ms ± 283.15 PO: 1354.34ms ± 358.88 MO: 1318.50ms ± 331.23 DO: 1331.73ms ± 287.92
Primary axis start position	Condition	$.05^{**}$	.40	6.37^*	.00	-	NO: 169.93pix ± 20.55 PO: 166.09pix ± 19.53 MO: 166.60pix ± 18.82 DO: 169.01pix ± 20.89
	Study	-	-	47.51^{**}	.40	-	S1: 183.27pix ± 15.66 S2: 151.15pix ± 1.53
	Interaction	$.05^{**}$	.40	6.08^*	.00	S1	NO: 187.15pix ± 12.93 PO: 179.93pix ± 17.97 MO: 180.68pix ± 15.93 DO: 185.32pix ± 16.25
						S2	NO: 151.15pix ± 1.26 PO: 150.99pix ± 1.76 MO: 151.25pix ± 1.75 DO: 151.22pix ± 1.53

DV	Outcome	χ^2	ε	F	ω^2	Study	Mean ± SD
Secondary axis start position	Condition	$.03^{**}$	.44	3.51	.03	-	NO: 543.53pix ± 12.17 PO: 553.99pix ± 29.14 MO: 548.06pix ± 19.96 DO: 546.02pix ± 16.97
	Study	-	-	.02	.00	-	S1: 548.41pix ± 21.23 S2: 547.34pix ± 19.58
	Interaction	$.05^{**}$	.44	.59	.00	S1	NO: 541.67pix ± 6.53 PO: 556.27pix ± 31.10 MO: 548.73pix ± 22.41 DO: 546.97pix ± 17.16
						S2	NO: 545.55pix ± 16.44 PO: 551.50pix ± 28.13 MO: 547.34pix ± 17.98 DO: 544.98pix ± 15.31
Primary axis end position	Condition	.85	-	2.62	.03	-	NO: 1608.56pix ± 1.85 PO: 1608.68pix ± 2.27 MO: 1609.29pix ± 2.49 DO: 1609.72pix ± 2.03
	Study	-	-	.98	.02	-	S1: 1609.40pix ± 2.62 S2: 1608.70pix ± 1.55
	Interaction	.85	-	.91	.00	S1	NO: 1608.50pix ± 1.86 PO: 1608.95pix ± 2.90 MO: 1609.80pix ± 3.11 DO: 1610.34pix ± 2.34
						S2	NO: 1608.62pix ± 1.93 PO: 1608.38pix ± 1.37 MO: 1608.73pix ± 1.54 DO: .1609.05pix ± 1.45

DV	Outcome	χ^2	ε	F	ω^2	Study	Mean ± SD
Secondary axis end position	Condition	.65	-	1.74	.02	-	NO: 540.12pix ± 1.83 PO: 539.34pix ± 1.39 MO: 539.82pix ± 2.06 DO: 540.32pix ± 1.65
	Study	-	-	.13	.00	-	S1: 539.82pix ± 1.96 S2: 539.99pix ± 1.53
	Interaction	.65	-	2.14	.03	S1	NO: 540.14pix ± 2.10 PO: 539.63pix ± 1.79 MO: 539.08pix ± 2.22 DO: 540.43pix ± 1.66
						S2	NO: 540.11pix ± 1.59 PO: 539.02pix ± .71 MO: 540.63pix ± 1.60 DO: 540.19pix ± 1.71
Trajectory distance	Condition	$.17^{**}$	.52	34.15^{**}	.06	-	NO: 39.97cm ± 1.61 PO: 41.36cm ± 2.09 MO: 41.39cm ± 2.14 DO: 41.56cm ± 2.43
	Study	-	-	25.11^{**}	.31	-	S1: 39.68cm ± .67 S2: 42.58cm ± 2.20
	Interaction	$.17^{**}$	.52	5.70^{*}	.01	S1	NO: 39.02cm ± .55 PO: 39.90cm ± .67 MO: 39.89cm ± .48 DO: 39.93cm ± .51
						S2	NO: 41.02cm ± 1.75 PO: 42.96cm ± 1.94 MO: 43.02cm ± 2.05 DO: 43.33cm ± 2.47

DV	Outcome	χ^2	ε	F	ω^2	Study	Mean ± SD
PV	Condition	$.08^{**}$	.46	6.09^{*}	.01	-	NO: 10.82cm/s ± 5.30 PO: 9.64cm/s ± 6.10 MO: 9.32cm/s ± 5.58 DO: 9.87cm/s ± 5.72
	Study	-	-	22.63^{**}	.33	-	S1: 6.15cm/s ± 2.08 S2: 14.02cm/s ± 5.38
	Interaction	$.08^{**}$	.46	.51	.00	S1	NO: 6.94cm/s ± 1.96 PO: 5.72cm/s ± 1.95 MO: 5.80cm/s ± 2.17 DO: 6.14cm/s ± 2.26
						S2	NO: 15.04cm/s ± 4.45 PO: 13.92cm/s ± 6.26 MO: 13.16cm/s ± 5.68 DO: 13.94cm/s ± 5.60
TTPV	Condition	$.13^{**}$	.48	14.47^{**}	.17	-	NO: 204.47ms ± 91.77 PO: 352.61ms ± 210.21 MO: 241.77ms ± 112.18 DO: 193.67ms ± 86.59
	Study	-	-	.73	.01	-	S1: 266.14ms ± 93.93 S2: 228.48ms ± 187.77
	Interaction	$.13^{**}$	.48	3.00	.03	S1	NO: 229.75ms ± 56.44 PO: 324.27ms ± 128.01 MO: 270.25ms ± 89.41 DO: 240.28ms ± 65.23
						S2	NO: 176.89ms ± 115.85 PO: 383.52ms ± 277.80 MO: 210.70ms ± 129.84 DO: 142.81ms ± 79.75

DV	Outcome	χ^2	ε	F	ω^2	Study	Mean ± SD
Proportional TAPV	Condition	.28*	.57	13.55**	.17	-	NO: .83 ± .05 PO: .75 ± .11 MO: .82 ± .08 DO: .85 ± .05
	Study	-	-	.50	.04	-	S1: .79 ± .05 S2: .83 ± .11
	Interaction	.28**	.57	2.20	.02	S1	NO: .81± .03 PO: .76 ± .07 MO: .80 ± .05 DO: .82 ± .03
						S2	NO: .85 ± .06 PO: .75 ± .15 MO: .84 ± .10 DO: .89 ± .06
Primary axis PV position	Condition	.58	-	7.16**	.07	-	NO: 641.47pix ± 133.61 PO: 706.54pix ± 191.91 MO: 602.49pix ± 174.08 DO: 568.41pix ± 166.37
	Study	-	-	11.23*	.17	-	S1: 706.44pix ± 78.99 S2: 546.04pix ± 206.70
	Interaction	.58	-	1.35	.00	S1	NO: 721.69pix ± 56.11 PO: 750.01pix ± 109.98 MO: 681.24pix ± 65.60 DO: 672.83pix ± 53.48
						S2	NO: 553.97pix ± 140.23 PO: 659.12pix ± 250.95 MO: 516.58pix ± 215.35 DO: 454.49pix ± 174.31

DV	Outcome	χ^2	ε	F	ω^2	Study	Mean ± SD
Secondary axis PV position	Condition	.19**	.51	1.88	.01	-	NO: 554.22pix ± 52.22 PO: 583.16pix ± 105.65 MO: 577.51pix ± 109.62 DO: 566.13pix ± 90.55
	Study	-	-	.11	.00	-	S1: 575.91pix ± 81.02 S2: 564.08pix ± 102.29
	Interaction	.19**	.51	1.56	.00	S1	NO: 545.49pix ± 22.01 PO: 599.33pix ± 91.67 MO:581.37pix ± 100.68 DO:577.45pix ± 85.88
						S2	NO: 563.74pix ± 72.63 PO: 565.52pix ± 121.06 MO: 573.29pix ± 123.49 DO: 553.78pix ± 98.00
PA	Condition	.24**	.71	9.41**	.01	-	NO: .18cm/s^2 ± .12 PO: .14cm/s^2 ± .09 MO: .15cm/s^2 ± .10 DO: .16cm/s^2 ± .12
	Study	-	-	22.00**	.32	-	S1: .09 cm/s^2 ± .04 S2: .23 cm/s^2 ± .10
	Interaction	.24**	.71	3.66*	.00	S1	NO: .10cm/s^2 ± .04 PO: .08cm/s^2 ± .05 MO: .09cm/s^2 ± .05 DO: .09cm/s^2 ± .05
						S2	NO: .27cm/s^2 ±.12 PO: .20cm/s^2 ± .07 MO: .22cm/s^2 ± .10 DO: .25cm/s^2 ± .12

DV	Outcome	χ^2	ε	F	ω^2	Study	Mean ± SD
TTPA	Condition	.05**	.42	9.72*	.12	-	NO: 26.77ms ± 25.53 PO: 114.45ms ± 177.00 MO: 40.87ms ± 72.24 DO: 18.49 ± 15.73
	Study	-	-	10.24*	.10	-	S1: 15.21ms ± 13.36 S2: 88.26ms ± 138.57
	Interaction	.05**	.42	9.29*	.11	S1	NO: 15.45ms ± 13.23 PO: 16.94ms ± 16.24 MO: 13.87ms ± 13.86 DO: 14.60ms ± 11.26
						S2	NO: 39.13ms ± 30.33 PO: 220.83ms ± 211.60 MO: 70.33ms ± 97.16 DO: 22.74ms ± 19.16
Primary axis PA position	Condition	.29**	.60	8.52*	.12	-	NO: 206.72pix ± 37.48 PO: 267.62pix ± 128.87 MO: 210.77pix ± 72.67 DO: 189.41pix ± 25.49
	Study	-	-	6.69*	.07	-	S1: 196.07pix ± 17.81 S2: 243.24pix ± 112.09
	Interaction	.29**	.60	9.80*	.14	S1	NO: 201.19pix ± 16.54 PO: 193.33pix ± 20.46 MO: 190.89pix ± 15.98 DO: 198.87pix ± 18.25
						S2	NO: 212.74pix ± 52.08 PO: 348.65pix ± 149.09 MO: 232.46pix ± 101.72 DO:179.09pix ± 28.96

DV	Outcome	χ^2	ε	F	ω^2	Study	Mean ± SD
Secondary axis PA position	Condition	.18**	.53	2.82	.02	-	NO: 547.19pix ± 31.14 PO: 560.67pix ± 51.00 MO: 546.18pix ± 37.33 DO: 544.02pix ± 23.27
	Study	-	-	.03	.00	-	S1: 548.40pix ± 23.04 S2: 550.74pix ± 48.25
	Interaction	.18**	.53	1.08	.00	S1	NO: 541.71pix ± 6.69 PO: 556.06pix ± 33.68 MO: 548.79pix ± 24.09 DO: 547.04pix ± 19.85
						S1	NO: 553.17pix± 44.83 PO: 565.69pix ± 66.49 MO: 543.34pix ± 49.10 DO:540.73pix ± 27.29

* indicates significance at the $p < .05$ level

** indicates significance at the $p < .001$ level

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