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Effect of Action Selection Demands on the Execution of Goal-Directed Reaches

James Garrison Riedy

EFFECT OF ACTION SELECTION DEMANDS ON THE EXECUTION OF GOAL-DIRECTED REACHES

by

James Garrison Riedy

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Accepted by:

Jill Stewart, Director of Thesis

Sheri Silfies, Reader

Troy Herter, Reader

Cheryl L. Addy, Interim Vice Provost and Dean of the Graduate School

ABSTRACT

A well-studied model of cognitive motor function is the process of action selection. It is unclear how the planning demands of a reaching movement interact with the added complexity of selection. Therefore, this thesis investigated the effect of adding selection demands to the performance of skilled reaches in a virtual environment. Thirty young, healthy participants reached ipsilaterally or contralaterally with either their dominant (right hand) or non-dominant (left hand) under two conditions: execute only (EO) and action selection (AS). Selection accuracy was higher for the EO condition than the AS condition for both arms and both directions (left arm: ipsilateral reaches $Z = -3.420$, $p < 0.001$, contralateral reaches $Z = -2.695$, $p = 0.007$; right arm: ipsilateral reaches $Z = -3.123$, $p = 0.002$, contralateral reaches $Z = -3.301$, $p < 0.001$). Reaction times for the AS condition were significantly longer than for the EO condition ($p < 0.001$, $\eta^2 = 0.931$). The primary measures of reach performance, movement time and endpoint error, did not differ between the EO and AS conditions. However, peak velocity and peak acceleration, measures of movement speed, were lower for AS compared to EO ($p < 0.001$, $\eta^2 > 0.364$). In summary, we did not find that the AS condition affected primary reach performance variables significantly but did affect secondary variables (movement speed). These findings can inform therapists on the use of selection tasks to improve the reach performance in aging and stroke populations.

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η^2	Partial eta squared of the given variable.
μ	Mean of the given variable.
σ	Standard deviation of the given variable.

LIST OF ABBREVIATIONS

AS...………Action Selection

EO ....…Execute Only

PMd.……………………………………………………………………...…Dorsal Premotor

RT……………………………………………………………………………..Reaction Time

CHAPTER 1: MANUSCRIPT

1.1 INTRODUCTION

A well-studied model of cognitive motor function is the process of action selection (AS). In essence, AS is a process whereby an individual selects a movement or action to perform from a set of choices (Kim et al., 2020). Consistently in the literature, the added requirement to choose is found to be a mediating factor in the changes in planning and performance outcomes for AS tasks. In young adults, task conditions that add AS demands result in increased reaction times and greater engagement of bilateral dorsal premotor (PMd) and parietal cortices (O'Shea et al., 2007).

The dorsal premotor cortex (PMd) is an important neural correlate of goal-directed reaches (Dexheimer et al., 2022; Kim et al., 2020). However, AS tasks call upon frontal and parietal networks, which includes PMd, as well (O'Shea et al., 2007). With the addition of AS demands to movement, there tends to be an increase in planning times and a greater engagement of PMd and parietal areas of the brain (Filimon et al., 2009; Prado et al., 2005; Kim, 2020). These same brain regions engaged in selection overlap with neural correlates of skilled motor behavior. Goal-directed reaches are thought to require internal models for motor planning. Following target selection from the visual field, a motor plan for the reach is chosen based on an individual's internal knowledge of the arm

(Sabes, 2000). Planned movement programs include salient information from visual stimuli including vital information on target location thought to be important for online corrections (Sabes, 2000). Therefore, selection engages PMd which is critical for reach performance, but it is unknown how an AS condition impacts reach performance.

How movements are specified is a widely debated concept within motor control. There is not yet consensus as to whether movement specification governs limb transport (vector coding) or endpoint location of the limb (endpoint coding) (Kim, 2020). Essentially, the specification of endpoint location is independent of vector coding. Vector coding of the limb trajectory is modifiable during movement including specification of the hand path and movement speed. The ability to modify these variables during movement suggests that vector coding is affected by task demands (Kim, 2020). Previous work has been founded on the assumption that selection (decision making) precedes specification (movement parameterization); however, Cisek and Kalaska (2010) have established evidence for parallel integration of selection and specification. The debate over parallel and non-parallel planning could benefit from a deeper understanding of effects of a movement selection demand on the performance of a reach movement.

Direction influences motor behavior as well. Reaches across midline require more coordination at the elbow and shoulder resulting in longer movement times (Wong & Haith, 2017; Kim, 2020; Enachescu et al., 2021; Oliveira et al., 2010; Oostwoud Wijdenes et al., 2016; Gallivan et al. 2017). Although there is modification in reach performance, there are invariants including order of movement, shape of the velocity curve, and optimization of smoothness (Kim, 2020). Following cue interpretation, a movement plan is initiated. Frequently, the path of this plan is the most direct and efficient movement execution. The velocity is bell shaped, reaching its max at the middle of the movement. Movement smoothness is optimized in the movement execution path. These criteria reflect control principles to minimize effort while maintaining performance (Kim, 2020). The system is flexible in that it must be sensitive to the demands of the specific task being performed. Such considerations as the speed of movement, size of the target, and directionality of reaches are all variables that change from task to task (Kim, 2020; Orban, 2017; Fernandez, 2018).

To highlight the relationship between the direction of reaches and the corresponding neural pathways involved with planning those reaches, several studies have begun to incorporate selection tasks. However, it is unclear how the planning demands of the movement interact with the added uncertainty and complexity of AS. Furthermore, there is a gap in the literature as to whether limb control differences between the dominant right arm and the non-dominant left arm play a role in movement during AS. Therefore, the purpose of this thesis was to determine the effects of adding AS demands to the performance of skilled reaches to two targets within a virtual environment. If planning specification is completed in parallel (plans for both reaches planned simultaneously), the addition of planning demands would not affect reach performance. If planning is not completed in parallel, the addition of planning demands may affect reach performance, suggesting that a default reach plan is generated that is modified to meet the final performance demands.

1.2 METHODS

PARTICIPANTS

Thirty participants were recruited from the local university community via word of mouth. Potential participants were eligible to participate if they were at least 18 years old, were right-hand dominant as determined by the Edinburgh Handedness Questionnaire (Oldfield, 1971), and had no current pain in the upper extremities. Fifteen participants completed the experiment task with the dominant, right arm and fifteen participants completed the task with the non-dominant, left arm. This sample size provided approximately 75% power in detecting a significant effect (G*Power 3.1.9; $f = 0.25$, $\alpha = 0.05$). All participants provided written informed consent prior to participation through a protocol approved by the Institutional Review Board at the University of South Carolina.

EXPERIMENTAL TASK

The reach task was completed in a virtual environment where three- dimensional targets were displayed into the space directly in front of the person (Figure 1.1). Participants wore stereoscopic 3D glasses with a sensor attached to indicate head position in the virtual environment. Two red target spheres (5.0 cm diameter) were positioned 14 centimeters away from the home position at a 45-degree angle; one target was positioned to the right of midline while the other target was positioned to the left of midline. Four green 3D shapes were used as visual cues to indicate the initiation of a reach: a large sphere, a small sphere, a large cube, and a small cube (Figure 1.2). A small white sphere (3.0 cm diameter) represented the position of the index finger.

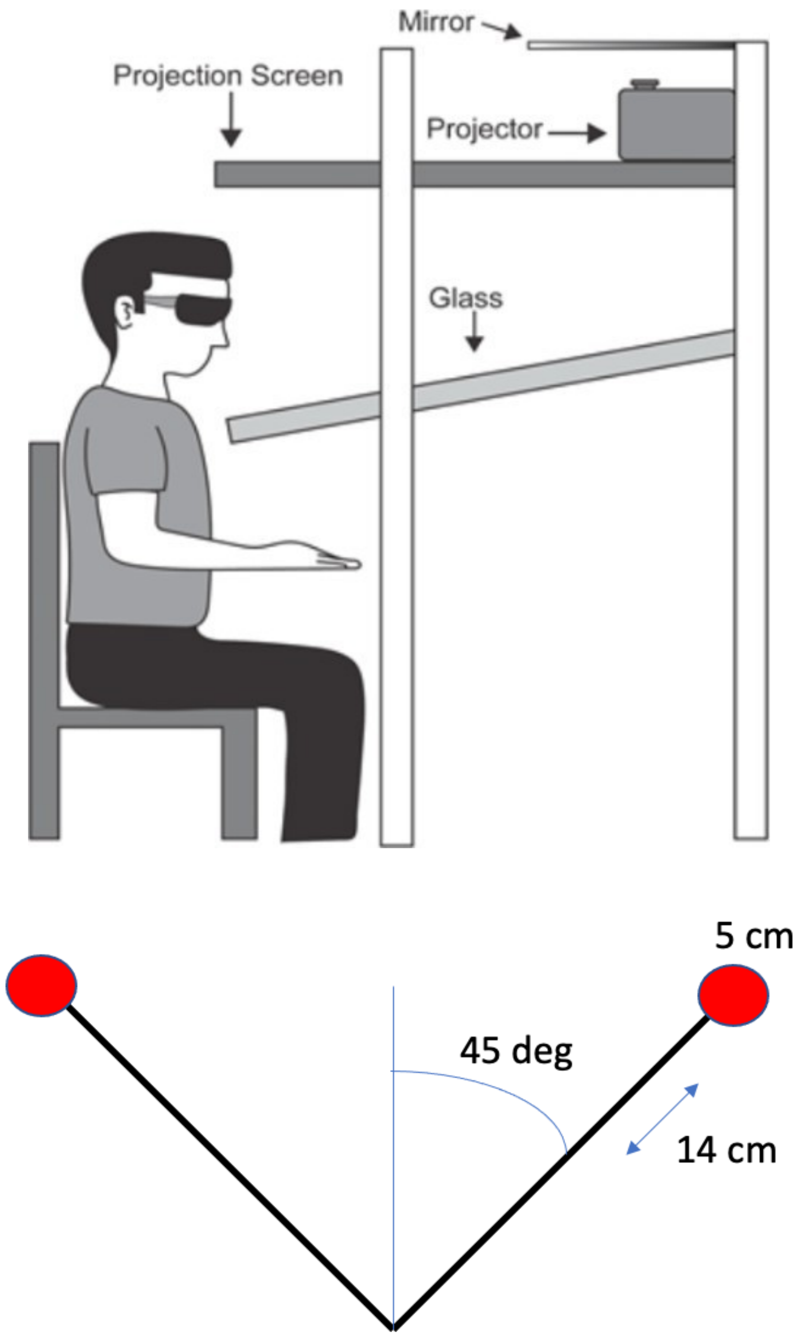

Figure 1.1 A projector and screen were positioned to cast targets onto a mirror. When viewed through stereoscopic glasses, the targets appear in a virtual 3D environment.

Each trial began with the participant positioning the cursor (3.0 cm white sphere representing index finger position) in the home target (3.5 cm blue sphere) located at a fixed position within the virtual environment. Once the participant held the home position (error tolerance:1 cm) for 500 msec, the home target and cursor disappeared, and the cue to reach appeared in the center of the visual field after a varied delay period (800 msec, 1100 msec, or 1400 msec) to reduce anticipatory movements prior cue presentation. Both reach targets (red spheres) were present throughout the trial. No online visual feedback of the moving arm or the cursor representing hand position was provided during the reach; feedback on final cursor position relative to the target was provided after each reach trial.

Data were collected using The MotionMonitor system (Innovative Sport Training Inc., Chicago, IL) using an electromagnetic sensor (Flock of Birds, Ascension Technology Corp, Shelburne, VT) attached to the tip of the index finger. The index finger sensor was used to indicate finger/cursor position in the 3D environment (see Figure 1.1) and for collection of movement throughout the reach trial (120 Hz).

EXPERIMENTAL PROCEDURE

Data was collected in a single session and participants completed the task with only one arm (dominant, right arm or non-dominant, left arm). First, participants had a period of exposure to become familiar with the virtual environment and target locations. Next, four practice trials were completed to allow familiarization with the task and trial sequence. Participants then completed eight blocks of trials (16 reach trials per block). Participants were instructed to reach toward the target as quickly as possible when ready. For the action selection (AS) condition, an abstract rule was utilized: the small cube and large sphere cued a reach to the left target, and the large cube and small sphere cued a reach to the right target. For the execution only (EO) condition, participants were shown

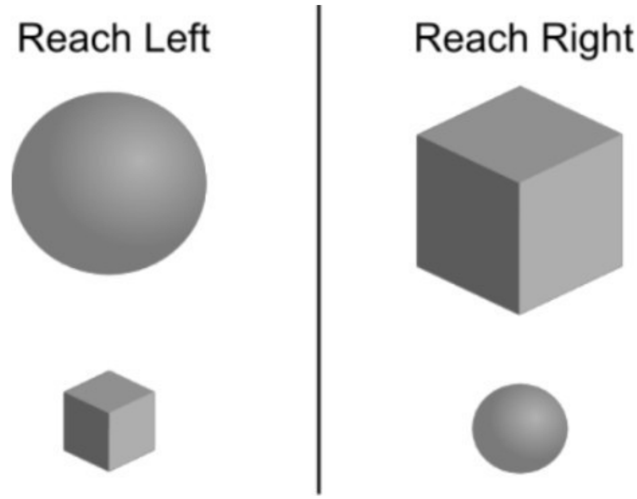

Figure 1.2 Above are the visual cues with corresponding directions. Large sphere or small cube – reach for the left target. Small sphere or large cube – reach for the right target.

the same cues, but reaches to the target were with the predetermined side (left or right) regardless of the cue (Figure 1.2).

The eight blocks consisted of four blocks of AS trials and four blocks consisted of EO trials. The direction of the reaches for the EO blocks alternated between the left and right target (two blocks in each direction). The four AS blocks contained an equal number of randomly ordered right and left target cues. Therefore, the sum of the right and left trials from the AS blocks was equal to those of the EO blocks. The criteria gave four possible orders for completion of the experimental procedure (Figure 1.3).

DATA ANALYSIS

Data was processed using a custom script in MATLAB (MathWorks, Natick, MA). Position data were filtered using a low-pass Butterworth filter (2nd order, 10 Hz cutoff). All kinematic variables were calculated utilizing this filtered data. Velocity was defined as the first derivative of the movement trajectory and calculated by dividing the instantaneous change in 3D linear trajectory by the change in time (Winter, 2005).

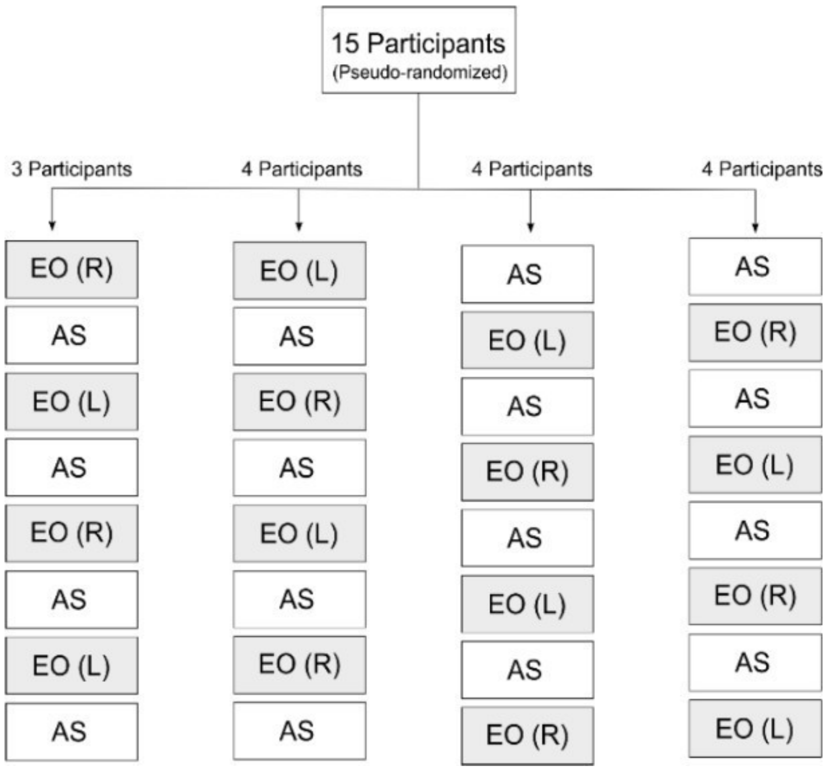

Figure 1.3 Testing block order for both the EO and AS conditions. Trial blocks were counterbalanced.

Acceleration was defined as the first derivative of the movement velocity and calculated by dividing the instantaneous change in velocity by the change in time (Winter, 2005). To locate movement onset, we searched backward in time from the time of peak velocity until movement velocity dropped below 10 cm/sec and either changed direction or the change in velocity was considered low (<3 cm/sec). Movement offset was defined as when movement velocity dropped below a tiered value dependent on the magnitude of peak velocity (20 cm/sec if peak velocity >60 cm/sec, otherwise 10 cm/ sec) and either velocity changed direction or the change in velocity was considered very low (<1 cm/sec).

The primary measures of planning were movement selection accuracy and reaction time. These measures were only analyzed for correct reaches. Movement selection accuracy, defined as the percent of correct reach movements, represents the accuracy of the selected reach. This measure was calculated from the combined accuracy of the movement direction selected based on position at the time of the initial peak velocity and position at movement endpoint. If a reach was initiated in the incorrect direction based on the external cue, then the reach trial was considered an error. Reaction time (sec) was defined as the time from cue presentation to the time of movement onset. The primary measures of reach performance were movement time and endpoint accuracy. Movement time (sec) was defined as the time between movement onset and movement offset. Endpoint error (cm) was defined as the 3D linear distance between the final hand position at the time of movement offset and the center of the target. Secondary measures of reach performance included peak velocity, peak acceleration, hand path ratio, and movement distance. Peak velocity (cm/sec) was defined as the first velocity peak after movement onset. Peak acceleration (cm/ sec^2) was defined as the first peak in acceleration after movement onset. Hand path ratio was defined as the ratio between the total distance traveled by the hand and the 3D linear distance between movement onset and offset. A hand path ratio value of 1 equates to a straight hand path from onset location to offset location; a ratio greater than 1 indicates a curved hand path with the larger the number equating to greater curvature. Movement distance (cm) was defined as the 3D linear displacement of the hand from movement onset to movement offset.

STATISTICAL ANALYSIS

Statistical analysis was completed in SPSS 22.0 (IBM Corp., Armonk, NY). Age was compared between groups with a t-test. Data normality was assessed using a Shapiro-Wilk Test; if data was not normal, it was transformed to achieve normality using

Log10 (peak velocity, peak acceleration, endpoint error) or an inverse transformation (movement distance). A mixed model ANOVA was run with two repeated factors, condition (AS, EO) and direction (right, left), with a between group factor of arm. Two variables could not be transformed to achieve normality (movement selection accuracy, hand path ratio); performance was assessed to determine the effect of condition using a Wilcoxon signed ranks test separately for reach arm and direction. Significance was set at an α of 0.05 for all comparisons. Partial eta squared ($\eta 2$) was used to estimate the effect size of any differences in the primary outcome variables ($\eta 2$ of 0.01–0.059 = small effect; 0.06–0.139 = medium effect; ≥0.14 = large effect) (Cohen, 1988).

1.3 RESULTS

PLANNING VARIABLES

Movement selection accuracy data were not normally distributed; therefore, we used nonparametric tests. These measures were only analyzed for correct reaches. Using a Wilcoxon Signed Ranks Test, we found a significant difference between conditions with greater accuracy for EO than AS conditions for both arms and both directions (left arm: ipsilateral reaches $Z = -3.420$, $p < 0.001$, contralateral reaches $Z = -2.695$, $p = 0.007$; right arm: ipsilateral reaches $Z = -3.123$, $p = 0.002$, contralateral reaches $Z = -3.301$, $p < 0.001$) (Figure 1.4).

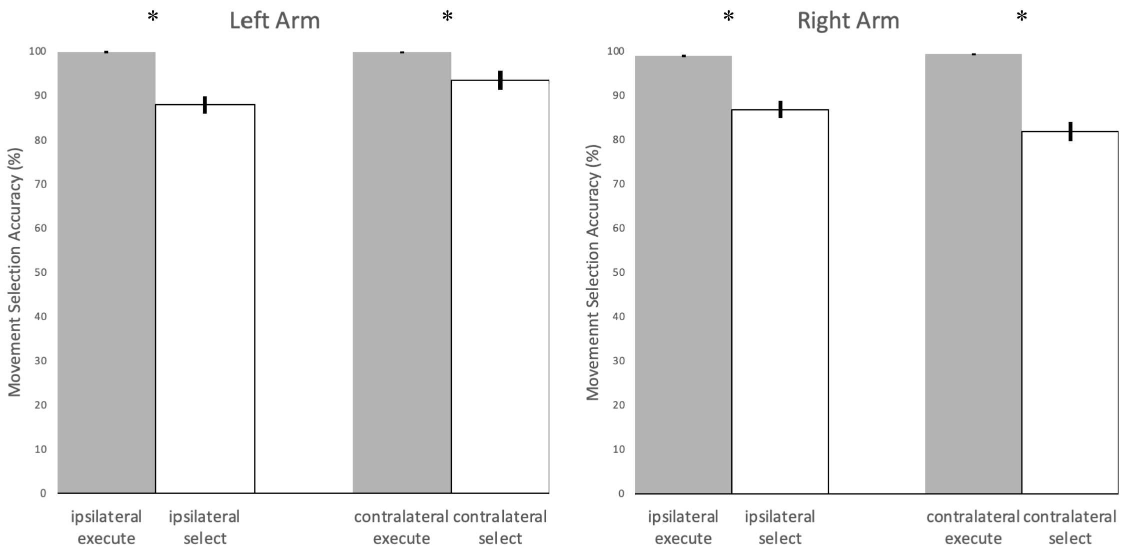

Figure 1.4 Movement selection accuracy for the left and right arms by condition and direction. Mean accuracy is shown with standard error bars. Gray boxes represent EO while open boxes represent AS. *symbolizes a significant difference in accuracy by condition.

As expected, RT for the AS condition was significantly longer than for the EO condition ($p < 0.001$) with a large effect size ($\eta^2 = 0.931$). There was also a direction by arm interaction ($p < 0.001$, $\eta^2 = 0.419$). To better understand this interaction of direction by arm, a post-hoc analysis was run using a t-test for each comparison (EO ipsilateral, A ipsilateral, EO contralateral, AS contralateral). The t-test revealed a significant difference in reaction time between the two arm groups only for the AS contralateral target comparison ($p = 0.005$). For the left arm group, contralateral reaches in the AS condition had significantly longer reaction times compared to the right arm group. For the left arm, the RT means for the EO condition were shorter than the AS condition (EO ipsilateral reaches $\mu = 0.371$ sec, $\sigma = 0.084$; EO contralateral reaches $\mu = 0.403$ sec, $\sigma = 0.140$, AS ipsilateral reaches 0.593 sec, $\sigma = 0.110$; AS contralateral reaches $\mu = 0.650$ sec, $\sigma = 0.142$) (Figure 1.5). Likewise for the right arm, the means for the EO condition were shorter than the AS condition (EO ipsilateral reaches $\mu = 0.337$ sec, $\sigma = 0.071$; EO contralateral reaches $\mu = 0.329$ sec, $\sigma = 0.047$, AS ipsilateral reaches 0.555 sec, $\sigma = 0.070$; AS contralateral reaches $\mu = 0.521$ sec, $\sigma = 0.072$). A significant effect of arm group was also found ($F = 4.730$, $p = 0.038$, $\eta^2 = 0.145$). Overall, the reaction times for the left arm group were longer than reaction times for the right arm group.

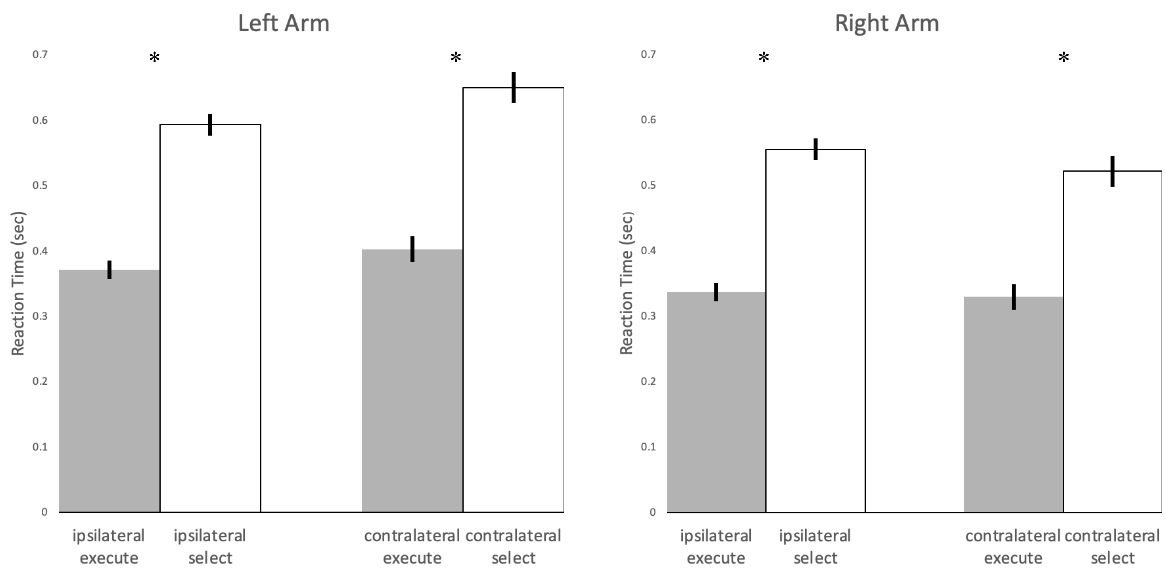

Figure 1.5 Reaction times for the left and right arms by condition and direction. Mean reaction times are shown with standard error bars. Gray boxes represent EO while open boxes represent AS. * symbolizes a significant interaction of direction by arm.

PRIMARY REACH PERFORMANCE VARIABLES

For movement time (Figure 1.6), the effect of condition was not significant ($p = 0.062$, $\eta^2 = 0.119$), but the effect of direction was statistically significant ($p < 0.001$, $\eta^2 = 0.514$). The left arm group had longer movement times than the right arm group, but this difference was not statistically significant ($F = 3.802$, $p = 0.061$, $\eta^2 = 0.120$).

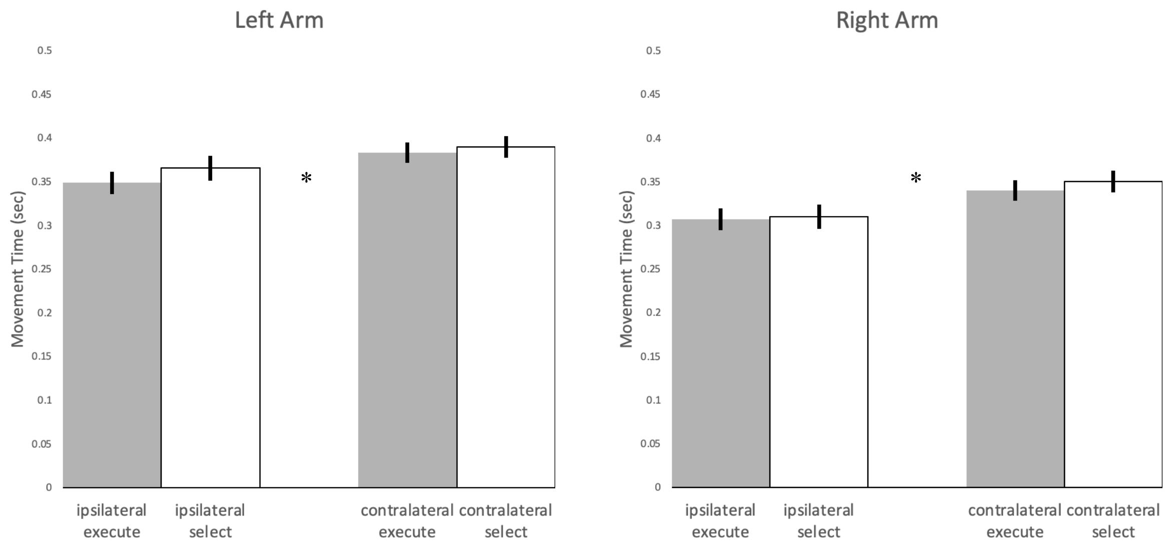

Figure 1.6 Movement time for the left and right arms by condition and direction. Mean movement times are shown with standard error bars. Gray boxes represent EO while open boxes represent AS. * symbolizes the significant difference between ipsilateral and contralateral reaches for both conditions and arm groups.

Our analysis for endpoint error did not show an effect of condition; however, there was a between-subjects effect of arm group ($F = 9.528$, $p = 0.005$, $\eta^2 = 0.254$) (Figure 1.7). Overall, the right arm group was more accurate at the endpoint of movement (mean endpoint error = 4.9 cm) compared to the left arm group (mean endpoint error = 9.1 cm).

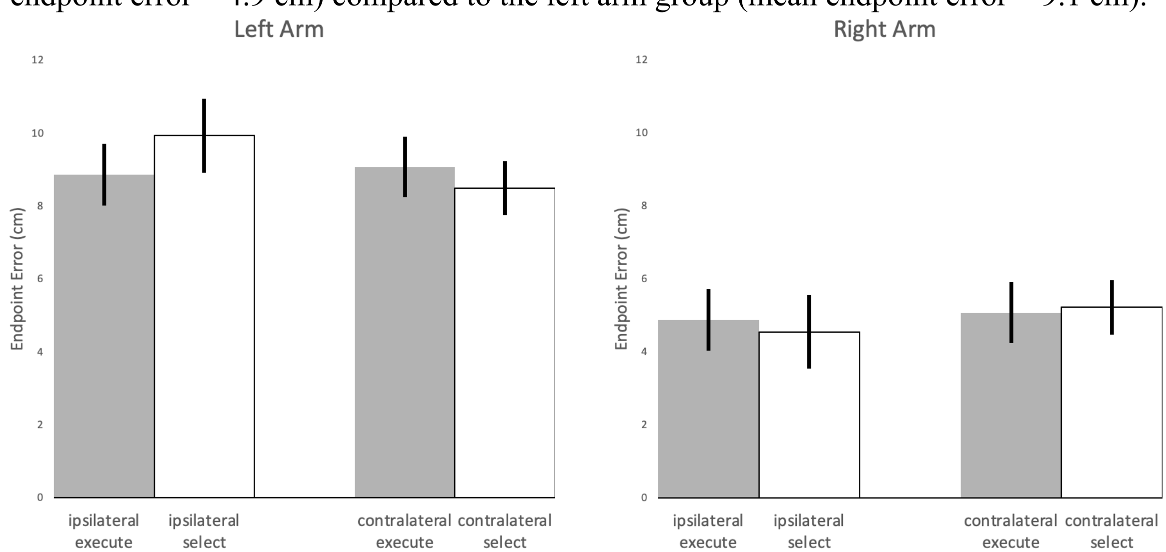

Figure 1.7 Endpoint error for the left and right arms by condition and direction. Errors are shown with standard error bars. Gray boxes represent EO while open boxes represent AS.

SECONDARY REACH PERFORMANCE VARIABLES

Peak velocity (Figure 1.8) was lower for the AS condition compared to the EO condition. This effect of condition was statistically significant ($p < 0.001$, $\eta^2 = 0.533$). There was also an effect of direction ($p < 0.001$, $\eta^2 = 0.743$). Peak velocity was lower for contralateral reaches compared to ipsilateral. Between-subjects effects for arm group were not statistically significant ($F = 3.301$, $p = 0.080$, $\eta^2 = 0.105$).

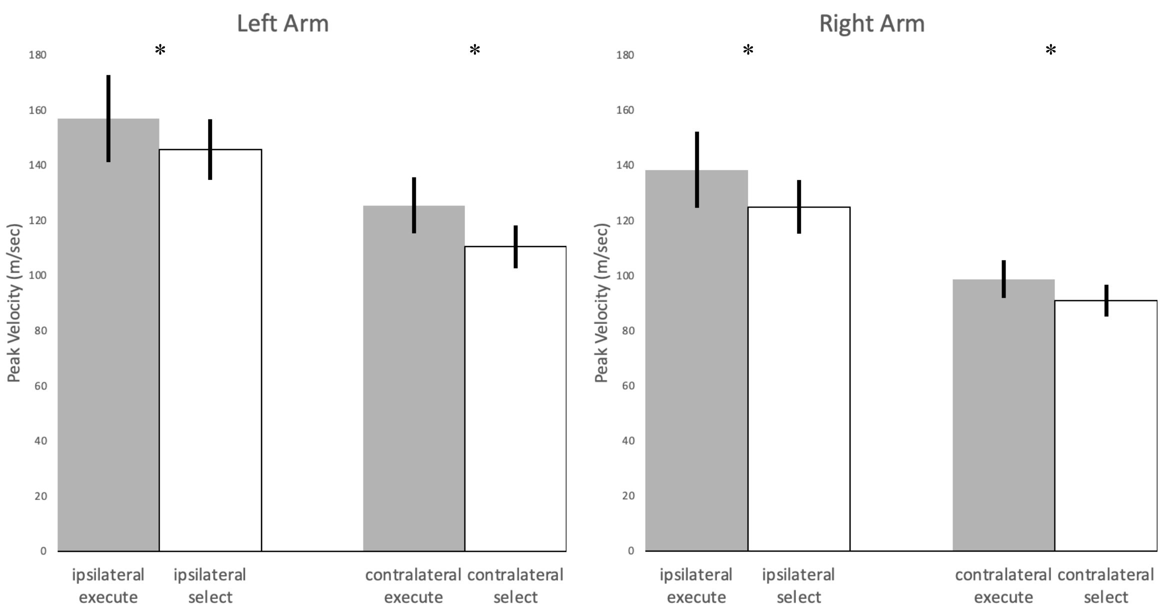

Figure 1.8 Peak velocity for the left and right arms by condition and direction. Velocities are shown with standard error bars. Gray boxes represent EO while open boxes represent AS. * symbolizes a significant difference in velocity by condition.

Peak acceleration (Figure 1.9) was lower for the AS compared to the EO. The mixed model ANOVA revealed an effect of condition ($p < 0.001$, $\eta^2 = 0.364$) and an effect of direction ($p < 0.001$, $\eta^2 = 0.710$). Arm group did not have a significant effect ($F = 0.942$, $p = .340$, $\eta^2 = 0.033$) or an interaction with condition or direction.

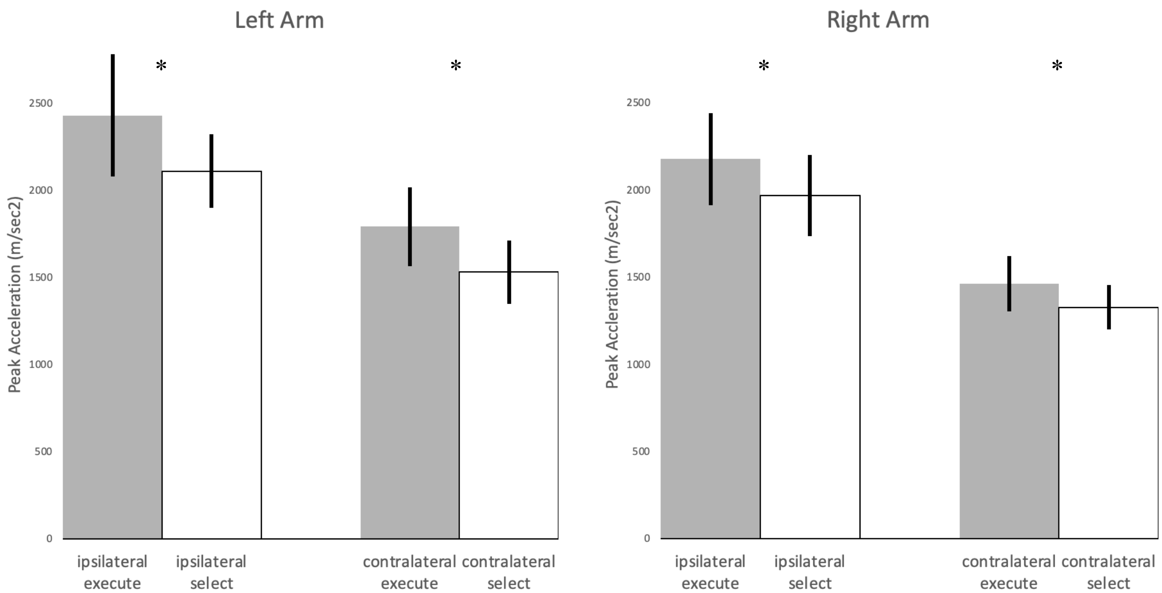

Figure 1.9 Accelerations are shown with standard error bars. Gray boxes represent EO while open boxes represent AS. * symbolizes a significant difference in acceleration by condition.

Using a Wilcoxon Signed Ranks Test, we found a significant difference for the right arm group between AS contralateral and EO contralateral hand path ratios (Z = -2.669, p = 0.008) (Figures 1.10 and 1.11). For these reaches, the AS condition had higher ratios (more curved hand paths) compared to the EO condition.

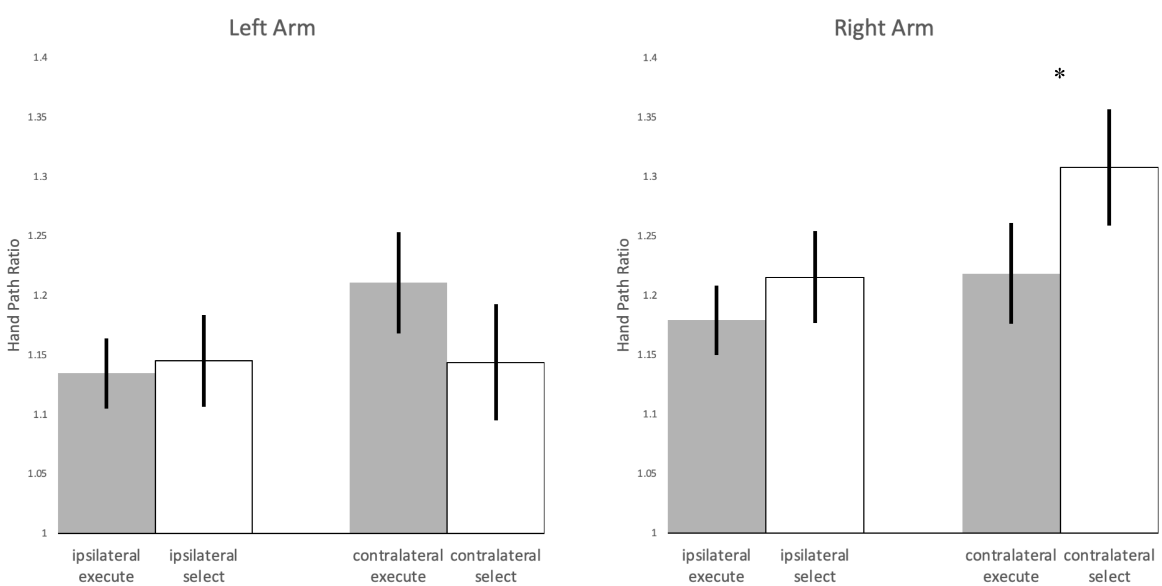

Figure 1.10 Hand path ratio for the left and right arms by condition and direction. Errors are shown with standard error bars. Gray boxes represent EO while open boxes represent AS. *symbolizes significance.

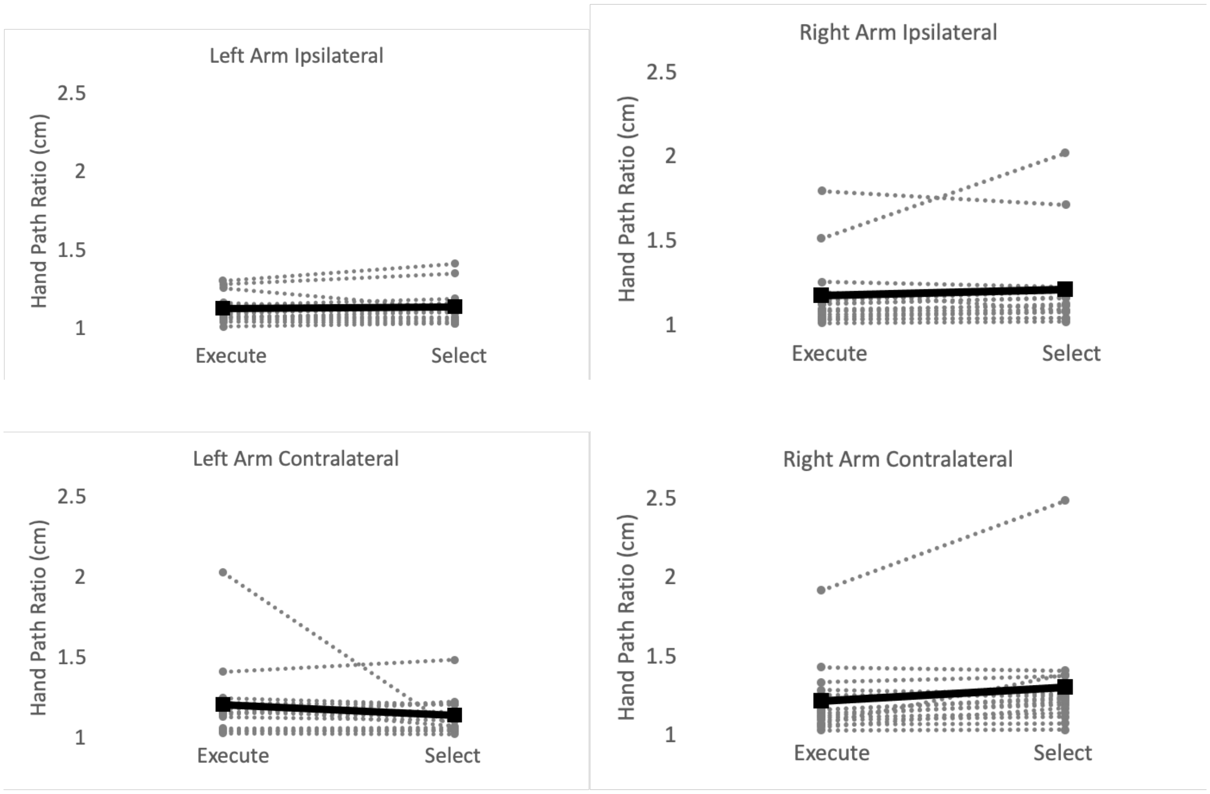

Figure 1.11 Line plots of hand path ratio. Dotted lines depict participant averages and the bold line with square marker depicts the mean of the averages.

Movement distance (Figure 1.12) was examined to better understand the relationship between the conditions and reach performance. There was a condition by direction interaction ($F = 7.918$, $p = .009$, $\eta^2 = 0.220$) which required a follow up paired t-test of condition run separately for each direction. The t-test revealed that the movement distances were shorter for the AS condition compared to the EO condition only for the contralateral reaches but not for the ipsilateral reaches ($t = -4.038$, $p < 0.001$). The left arm group had longer movements than the right arm group. Overall, the left arm group tended to over shoot the target (14 cm) while the right arm group tended to stop at the target or undershoot the target.

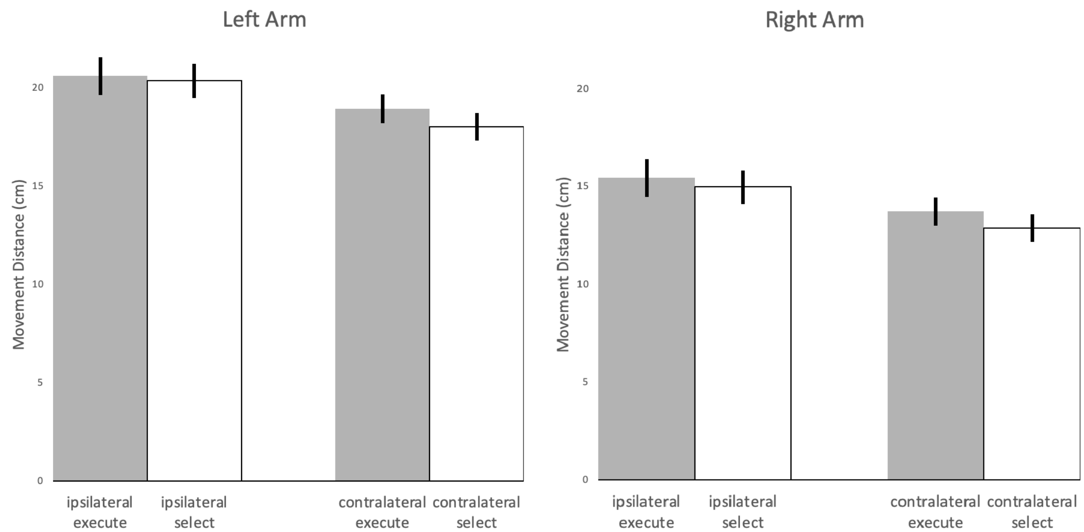

Figure 1.12 Movement distances shown with standard error bars. Gray boxes represent EO while open boxes represent AS.

1.4 DISCUSSION

This thesis investigated the effects of adding AS demands to the performance of skilled reaches within a virtual environment. Consistent with the current literature, the primary planning variables changed with the addition of action selection demands: reaction time increased and movement selection accuracy decreased (Kim, 2020; Enachescu et al., 2021; Oliveira et al., 2010; Oostwoud Wijdenes et al., 2016). Therefore, planning selection was seen to differ by condition as we expected given the current knowledge on AS. Our finding that the additional planning demands of an AS condition impacted secondary reach performance variables (peak velocity and peak acceleration), provides evidence that movement speed is effected. We believe our initial hypothesis is supported because the increase in reaction time and corresponding decrease in movement selection accuracy could be accommodating the increase in planning demands the AS condition requires. If reaction time and accuracy are accounting for the added planning demands, this would explain why we did not see an effect of condition for movement time and endpoint accuracy. Therefore, effects of AS on secondary reach performance variables (movement speed) could support the hypothesis that planning specification is not completed in parallel.

Consistent with the literature, the planning demands quantified by the primary variables movement selection accuracy and reaction time, were affected by the AS condition. Firstly, movement selection accuracy was found to be altered by the AS condition. Namely, accuracy was lower during the AS condition compared to the EO condition. Secondly, the planning variable reaction time was significantly increased in the AS condition compared to the EO condition. To summarize, consistent with previous work, this thesis provides evidence for additional planning demands during AS compared to EO (Kim, 2020; Enachescu et al., 2021; Oliveira et al., 2010; Oostwoud Wijdenes et al., 2016).

With the increased planning demands for the AS condition, we found evidence for effects on reach performance, specifically the speed of movement (velocity and acceleration). Movement time and endpoint error were not affected by condition. Movement time may have not been impacted by the AS condition as much as expected due to compensation of reach movement distance. Perhaps the shorter movement distances we observed for the AS condition compensated for what would have been longer movement times. More research is required to better quantify this compensation since it is not covered in the current literature on AS. Furthermore, understanding participants' rating of perceived exertion could elucidate our findings on why movement distance was altered but not movement time. Additionally, the over-reaching observed in the left arm and under-reaching in the right arm could be analyzed along with acceleration duration and deceleration duration to investigate the effects of AS on reach performance.

Other findings from our analysis are consistent with previous research on reach control. For differences by direction, a common finding suggests reaches across midline require more coordination and thus tend to have longer movement times (Wong & Haith, 2017; Kim, 2020; Enachescu et al., 2021; Oliveira et al., 2010; Oostwoud Wijdenes et al., 2016; Gallivan et al. 2017, Stewart et al. 2014). We found this to be true for contralateral movement times that were significantly higher than ipsilateral. It should be noted that we collected data in left and right directions then flipped the directions to analyze contralateral and ipsilateral directions. Secondary reach performance variables, peak velocity and peak acceleration, were lower for contralateral compared to ipsilateral reaches in agreement with our hypothesis and the literature (Wong & Haith, 2017; Kim, 2020).

From our results, we found some evidence for our main hypothesis. We considered that if planning specification was completed in parallel, the addition of planning demands would not affect reach performance. But if planning was not completed in parallel, the addition of planning demands would affect reach performance, suggesting that a default reach plan was modified to meet the final performance demands. We found significant effects of increased planning demands and this corresponded with impacts on secondary reach performance variables of movement speed (peak velocity and acceleration). Therefore, there is evidence planning was not completed in parallel and modification was required. Although more evidence is required to make adequate conclusions, we suggest there is evidence that planning is not completed in parallel because the increase in RT and decrease in selection accuracy buffered the effect of increased planning demands during AS; but since peak velocity and acceleration were still impacted by the AS condition, there was an effect of AS planning demands on reach performance.

LIMITATIONS

Each participant completed the task with only one arm which may have contributed to variance between the two arm groups. Future studies could have the same participants complete the task with both arms to help control this factor. Our paradigm only includes 1 reach distance and 2 target directions; given the effect of the variables on reach performance measures, future studies could investigate the effect of planning demands the control of reaches to multiple distances and directions. Data collection was completed in a single day – therefore, we cannot determine if practice would impact the planning and performance variables investigated in the current study. When verbally instructing the participants, endpoint error was not required and thus not constrained by condition. The lack of a goal for accuracy at the endpoint of movement could explain why endpoint error did not differ by condition. In summary, we adopted a well-studied experimental procedure that has inherent limitations that should be addressed in future research.

CONCLUSION

In conclusion, this thesis investigated the effect of adding action selection demands to the performance of skilled reaches within a virtual environment. We found significant differences in movement selection accuracy, reaction time, peak velocity, and peak acceleration by condition. These findings all provided evidence that AS increased planning demands which resulted in slower reach performance. Movement selection accuracy, movement time, peak velocity, and peak acceleration differed significantly by direction as well which were likely due to coordination demands for reaches across midline. It is our hope that these findings on planning specification can inform therapists on the use of action selection tasks to challenge reach planning and reach performance in aging and stroke populations. Understanding that reaches will likely be slower when selection is involved could help to inform patient therapy to restore functional reach control and patient rehabilitation for reach performance.

CHAPTER 2: REVIEW OF THE LITERATURE

MOTOR PLANNING AND ACTION SELECTION

Inherent to visually guided reaches are internal models for motor planning. Following target selection from the visual field, a motor plan for the reach is chosen based on an individual's internal knowledge of the arm (Sabes, 2000). The planned movement program includes salient information from visual stimuli; vital information on target location is thought to be important in this phase of planning for online corrections, to determine the direction of reaches and the extent of neural activation (Sabes, 2000; Kim, 2020; Klaes, 2011; Cisek & Kalaska, 2010). To highlight the relationship between the direction of reaches and the corresponding neural pathways involved with planning those reaches, a number of studies have begun to incorporate action selection. In 2010, Cisek and Kalaska reviewed the literature, in part, on action selection. They described an integrative process that deals with altered planning demands as well as movement execution. However, what is still unknown in many populations is the true effects and magnitude of the behavioral effects of altered planning demands. Additionally, there is a gap in the literature as to whether limb control differences between the dominant right arm and the non-dominant left arm play a role in movement during action selection.

In essence, action selection is the process whereby a subject selects a movement or action to perform from a set of choices. When action selection (AS) demands are introduced into a motoric protocol, a competitive process is initiated (Kim, 2020; Klaes, 2011; Cisek & Kalaska, 2010). This competition between choices can have an effect on motor planning – unnecessary actions are inhibited, and the correct action is selected. Motor planning demands are inherently altered in an AS condition with measurable effects on 1) motor behavior and 2) neurophysiological parameters as the brain selects and plans the movement pattern (Kim, 2020; Klaes, 2011; Cisek & Kalaska, 2010). During reaches, there is an aspect of uncertainty on the part of the participant in regard to target selection. The direction of reaches is the most vital information to determine which motor plan to execute – especially when subscribing to the parallel planning hypothesis (Kim, 2020; Cisek, 2007). There may be an interaction between action selection and target selection during reaching that impacts both movement planning and movement execution.

AS is a motor planning process and has been studied from a motor planning perspective in the literature. WhenAS demands are introduced, the time to plan the movement, as measured by reaction time, usually increases (Kim, 2020; Enachescu et al., 2021; Oliveira et al., 2010; Oostwoud Wijdenes et al., 2016). The direction of the targets determines the motor behavior as well; for example, reaches across midline require more coordination and thus tend to have longer movement times (Wong & Haith, 2017; Kim, 2020; Enachescu et al., 2021; Oliveira et al., 2010; Oostwoud Wijdenes et al., 2016; Gallivan et al. 2017, Stewart et al. 2014). Therefore, directionality introduces a greater demand for higher brain centers to control the execution of the reach. However, it is unclear how execution demands interact with the added complexity of AS.

Dorsal premotor cortex is an important neural correlate of visually guided reaches (Dexheimer et al., 2022; Kim et al., 2020). AS calls upon frontal and parietal networks as well, which includes dorsal premotor cortices (O'Shea et al., 2007). With the addition of AS demands, there tends to be an increase in planning times and a greater engagement of dorsal premotor (PMd) and parietal areas of the brain. These brain regions engaged for action selection overlap with neural correlates of skilled motor behavior as measured by velocity, acceleration, and movement trajectory (Filimon et al., 2009; Prado et al., 2005; Kim, 2020).

GOAL-DIRECTED REACHES

Although there is flexibility in movement execution in the human system, there are countless invariants. These immutable variables include order of movement, shape of the velocity curve, and optimization of smoothness (Kim, 2020). Following cue interpretation, a movement plan is initiated. Frequently, the path of this plan is the most direct and efficient movement execution. The velocity is bell shaped, reaching its max at the middle of the movement. Movement smoothness is optimized in the movement execution path. These criteria reflect control principles to minimize effort while maintaining performance (Kim, 2020). The system is also flexible in the sense that it must be sensitive to the demands of the specific task being performed. Such considerations as the speed of movement, size of the target, and directionality of reaches are all variables that change from task to task (Kim, 2020; Orban, 2017; Fernandez, 2018).

A commonly discussed outcome of introducing AS to reaches is a possible interaction with the speed–accuracy trade-off. Fitts's law described an inverse relationship between movement time and target accuracy; overall, as movement time gets faster, accuracy declines (Fitts, 1954). Goal-directed reaches with lower accuracy demands tend to be faster, have straighter trajectories, and single peak velocity and acceleration curves (Sainburg & Schaffer, 2017). It is not known how the addition of AS demands to movement impacts these variables during reaches.

MOVEMENT PLANNING DEMANDS OF REACHES

Increased variability along the axis of movement increases with movement amplitude and varies based on the direction of reaches (Gordon et al., 1994; Vindras et al., 2005). There are two major considerations with directionality: visual requirements as the reaches get further from midline (requiring more peripheral vision) and hand dominance (requiring specialized control). Therefore, investigating the right and left arms separately can shed some light on the importance of direction when planning a movement. Randomizing directionality challenges the subject to quickly interpret visual-motor information and results in increased planning time (especially as the ability to anticipate target location is removed).

Poirier and colleagues (2020) have previously described whole-arm reaches in the vertical direction. Direction-dependency is crucial for arm kinematics in these kinds of skilled reaches. This dependency is common for both vertical (overhead) and horizontal (forward) reaches (Poirier et al., 2020). Pivotal to much of the literature on whole-arm reaches is a discussion of inter- coordination between the elbow and shoulder joints. While humans are adept at utilizing both hands cooperatively, difficulty may arise when specific goals require more complex movement coordination (Ivry et al., 2004). This universal finding in the literature suggests that interference originates upstream of motor planning when translating the cues to motor actions (Derosiere et al., 2018; Klein et al., 2012). Also, there are increased coordination demands for the elbow and shoulder with goal-directed reaches compared to movements of the hand (Sainburg & Schaefer, 2004).

Generalization can narrow the usefulness of learned skills. Conversely, adaptation may have minimal transfer from one arm to the other arm if the context and parameters are similar (Poh et al., 2016; Sainburg & Wang, 2002; Taylor et al., 2011; Werner et al., 2019; Kim, 2020). This type of transfer of adaptation is localized, however, even with high generalizability (Kim, 2020). Although the virtual nature of the experimental environment may not fully generalize to a real-world environment, the benefits of isolating the testing conditions, the visual field, and arm kinematics in a first-person space make this current dataset invaluable for analyzing the effects of added action demands during reaches.

The dynamic dominance hypothesis suggests that the dominant limb is best suited for controlling the reach trajectory, while the non-dominant arm is better at governing endpoint position. Thus, for right-handed individuals, the right hand reaching to right targets would hypothetically result in more consistent and smoother movement trajectories compared to reaches with the left hand. However, the left hand in these same individuals might be better at online corrections and endpoint accuracy compared to the right hand. Although the asymmetry of bimanual limb control is not fully understood, the literature agrees that inter-limb dynamics are crucial to anticipatory responses. One pattern of control used to examine differences between arms is the pulse-step control system. Consisting of two parts: pulse-height and pulse-width, which refer to the peak and duration, respectively, of the initial acceleration pulse (Sainburg and Schaefer, 2004; Pellegrino, 2021; Merrick, 2022; Dexheimer et al., 2021; 2022; Oldfield, 1971). As reported by Sainburg and Schaefer in 2004, the scaling of dominant arm velocities with target distance is reflected by scaling of the first peak in the acceleration profile – symbolizing pulse-height control. The velocity curves presented in the dominant arm reaches reflect the anticipatory responses of the movement while the curves of the non-dominant reaches represent extended profiles symbolizing the corrections stemming from the feedback-loop (Sainburg and Schaefer, 2004; Sainburg and Schaffer, 2017). Accuracy in the final position captures the events occurring at the end of motion. When feedback (somatosensory-based) closed-loop control mechanisms are relied upon, the non- dominant arm outperforms the dominant arm (symbolized by the pulse-width and lower endpoint error) (Sainburg and Schaefer, 2004).

MEASURES OF REACH PLANNINGAND PERFORMANCE

Reaction time is expected to increase with greater task demands introduced with the AS condition. Movement time is an inherent variable in the discussion of speed-accuracy trade-offs because it sheds light on the effects of increased demands. Pulse-height and pulse-width control have been reported to influence open- and closed-loop mechanisms for controlling movement distance. Current studies provide support for this model by demonstrating that the two arms rely differentially on one or the other process. In addition, recent findings suggest specialization of the dominant limb system for pulse-height control and similar specialization of the non-dominant system for pulse-width control. The velocity curves present in the dominant arm reaches reflect the anticipatory responses of the movement while the curves of the non-dominant reaches represent extended profiles symbolizing the corrections stemming from the feedback-loop (Sainburg and Schaefer, 2004; Sainburg and Schaffer, 2017). Measures of reach planning and reach performance are outlined in the table below.

Variable	**Domain**	**Units**
Reaction time	Planning	sec
Movement selection accuracy	Planning	% correct
Peak acceleration	Planning	cm/sec^2
Peak velocity	Performance	cm/sec
Movement time	Performance	sec
Endpoint error	Performance	cm
Hand path	Performance	ratio

Table 2.1 Depicting variables of interest, their domains, and units of measure.

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