COMPARING THE KINEMATICS OF GRASPING VS. PLACING IN HUMANS

Niousha Por Davoody

A Thesis Submitted to the Faculty of Graduate Studies in Partial Fulfillment of the Requirements for the Degree of

MASTER OF ARTS

GRADUATE PROGRAM IN PSYCHOLOGY
YORK UNIVERSITY
TORONTO, ONTARIO

November 2024

ABSTRACT

While many studies have examined reach-to-grasp movements, the placement component remains less explored. Grasping and placing tasks share some common characteristics, such as precise localization and orientation of the hand, but differ in cognitive intent and sensory feedback, with grasping relying more on visual input and placing on somatosensory feedback relative to surroundings. This study employs a within-subjects 2x2x2 design, examining the effects of Task (grasp vs. place), Object Orientation (clockwise vs. counterclockwise), and Target Location (left vs. right) in right-handed participants performing in near-total darkness. Each participant completed 160 randomized trials across eight conditions, tracking hand and eye movements via an OptiTrack system and eye tracker.

Results revealed significant main effects for Task, Location, and Orientation, along with notable interactions. Contrary to the hypothesis, placing tasks were faster than grasping tasks and exhibited higher orientation errors. This result contradicts the expectation that placement would require more precise alignment, suggesting that the simplified placement task used in this study may rely more on visual feedback, which was absent, compared to grasping. Movements toward the right showed faster velocities and fewer errors, reflecting hemispheric motor advantages, while clockwise orientations were associated with lower orientation errors compared to counterclockwise orientations. Interaction effects between Location and Orientation influenced certain variables, highlighting the role of spatial and alignment demands in motor control. These findings suggest that while grasping and placing tasks share overlapping motor control processes, they also engage distinct mechanisms under specific spatial conditions.

ACKNOLEDGMENT

I extend my deepest gratitude to my supervisor, Dr. J. Douglas Crawford, whose mentorship has been a cornerstone of my academic journey. Thank you for granting me the privilege of pursuing this path under your guidance. Your unwavering work ethic and dedication to research have been a profound source of inspiration. I am deeply grateful for your patience, kindness, wisdom, and encouragement, which have been invaluable throughout this journey.

A heartfelt thanks to my colleagues and friends, the incredible members of the Crawford lab—Vishal, Gaelle, and Lina. You have shown me that the joy of scientific discovery is only enhanced by a work-life balance filled with shared laughter and even concert outings. I could not have hoped for a more supportive and enriching environment to conduct my research.

I am also immensely thankful to Dr. Xiaogang Yan for his insightful technical and theoretical guidance, and to Saihong Sun for her programming expertise and support. My gratitude extends to Dr. Peter Jes Kohler for his thoughtful guidance on my thesis, and to the members of my examining committee, Dr. Erez Freud and Dr. Jonathan Michaels, for their time and invaluable feedback. Thank you all for shaping this chapter of my academic journey.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABELS

1. GENERAL INTRODUCTION

1.1 Introduction

Centuries ago, Aristotle described the human hand as "an instrument representing several instruments." Unlike the limbs of other animals that evolved for specific tasks such as climbing, running, swimming, and so on, the human hand evolved to perform a range of tasks dexterously. Therefore, brains and hands coevolved (Aristotle 1937). Daily, I perform various movements involving 3D objects, such as reaching for a cell phone, grasping a mug to drink coffee, reaching for an object to lift it, or moving it from one place to another. Importantly, these movement goals are contingent upon different features of an object or target, such as its orientation and design (Smeets et al., 2019). To correctly execute a movement, I must precisely locate the object of interest (Chen & Crawford, 2020). Then, I might move it to another place. Grasping an object entails simultaneous joint movements that bring the arm close to the intended object, align the hand's orientation with the object's tilt, and shape the fingers into a grip that fits (Marotta et al., 2003). Visually locating and acting upon the object is called visuomotor or sensorimotor transformation (Crawford et al., 2011).

1.1.1 Kinematics and Timing of Reach and Grasp

Reaching is a series of planning and movements aimed at achieving a future movement goal (Fisher et al., 2002; Flanagan & Wing, 1993, 1997; Georgopoulos et al., 1981; Hepp-Reymond & Wiesendanger, 1972; Jeannerod, 1984; Johansson et al., 1992; Kazennikov et al., 1994; Sheth & Shimojo, 2002; Westling & Johansson, 1984; Wing et al., 1997; Wing & Fraser, 1983) . Examples of reaching movements include precision grip, pointing, precision lift, and reach-and-grip tasks (Jeannerod, 1984; Johnson et al., 1996; Sheth & Shimojo, 2002; Wing & Fraser, 1983). To encompass this repertoire of movements, the most widely accepted hypothesis for generalizing hand movements describes three significant prehension components: (i) transporting the hand to the location of the object, (ii) orienting the hand according to the object's tilt, and (iii) forming the appropriate finger posture to interact with the object (Desmurget et al., 1996; Jeannerod et al., 1994). My thesis will focus on the first two components: planning transport location and orienting the hand.

The timing elements of these movements are key to understanding reach and grasp dynamics. Reaction time - the time from the cue to movement onset - typically ranges from 150-250 ms, depending on task complexity (Jeannerod, 1984). Movement duration, the time from movement initiation to completion, generally falls between 500 and 700 milliseconds for grasping tasks, influenced by factors like object size, distance, and required accuracy (Fitts, 1954; Flanagan & Wing, 1993). Peak velocity, which is the maximum speed reached during the movement, usually occurs around 50-70% of the total movement duration. This peak speed can vary but often falls around 1-2 m/s for reach-to-grasp actions, with higher speeds typically observed in tasks requiring less precision (Wing & Fraser, 1983).

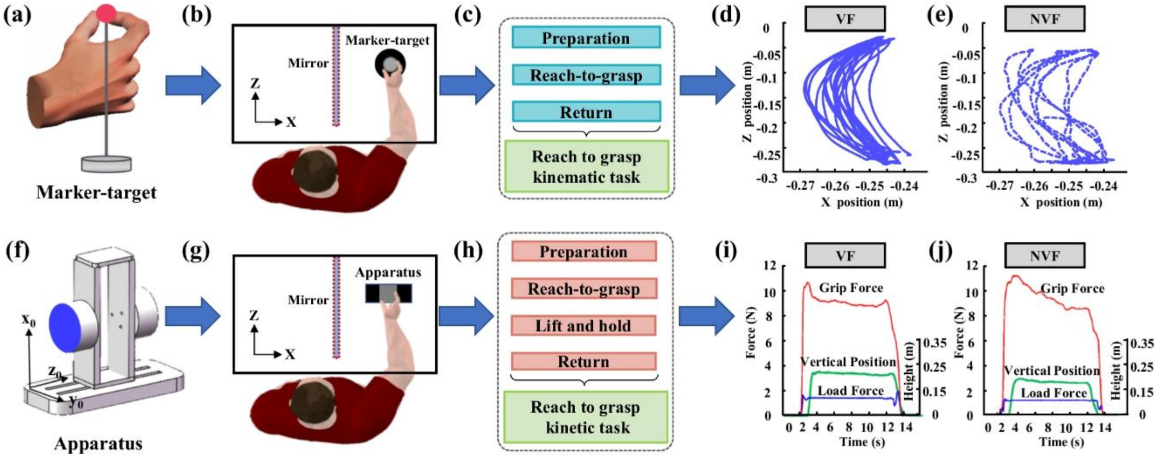

Figure 1. Generalized setup and kinematic analysis framework for reach-to-grasp tasks (adapted from Zhang et al., 2022). This figure illustrates a typical setup and analytical approach used to study reach-to-grasp movements, providing context for similar methods applied in the current study. (a) Marker-Target Setup: Reflective markers are placed on the hand to enable tracking of movement paths. (b) Above View Setup: Shows the experimental configuration with a mirror for aligning hand trajectories in reach-to-grasp tasks. (c) Experimental Task Flow: Depicts the typical phases in a reach-to-grasp task, including preparation, reach, grasp, and return, comparable to the phases used in this study. (d, e) Hand Trajectories: Illustrate example movement paths in visual feedback (VF) and no visual feedback (NVF) conditions, highlighting potential trajectory differences; these are representative examples and not actual trajectories from this study. (f, g) Apparatus and Setup for Kinetic Task: Shows devices used in kinetic analyses, similar to those used to analyze hand forces in this study. (h) Kinetic Task Flow: Outlines phases typically analyzed in kinetic studies, including lift and hold phases, relevant to understanding grip and load forces. (i, j) Kinematic Data: Display grip force, load force, and vertical position for VF and NVF conditions, showing examples of data types relevant to our analysis but not specific results from this experiment..

Figure 1 illustrates the setup and flow of reach-to-grasp tasks, as adapted from Zhang et al. (2022), providing a framework for understanding the components involved in tracking and analyzing reach-to-grasp kinematics in this study. This adapted figure outlines the sequence of the task phases and the tracking setup used, including the use of reflective markers for capturing hand trajectories and the role of visual feedback conditions (VF vs. NVF).

These reach-to-grasp actions, like picking up a glass of coffee, require complex coordination and involve more precise motor control than simpler tasks, such as flipping a switch. Since the foundational work of Marc Jeannerod (1981), reach-to-grasp movements are typically viewed as a combination of hand transport and grip adjustment. In the case of precision grips, this coordination is simplified to adjustments in thumb-index distance, a characteristic that has made it a primary task in studying motor coordination.I

Orientation adjustments typically begin mid-movement, with the hand aligning to the object's orientation in the final approach phase. This anticipatory adjustment ensures the hand is correctly aligned with the object upon contact, showcasing the integration of transport and orientation control in reach-to-grasp movements (Jeannerod, 1984); Marotta et al., 2003).

Initially, Marc Jeannerod (1981) proposed that the use of transport and grip was not only a convenient way to describe behavior but also that this behavior was shaped by an "open-loop control of independent visuomotor channels." He observed that "the hand assumes movements and postures independent of those assumed by the more proximal segments of the limb" (Jeannerod, 1988). Jeannerod interpreted this independence as the posture of the hand being related to intrinsic object properties, such as size and shape (processe d in the temporal lobe of the cerebral cortex). At the same time, the movements of the proximal segments were governed by extrinsic properties, such as location (processed in the parietal cortex). This led him to propose that two specialized input-output modules (visuomotor channels) are anatomically and functionally independent. He argued that this division reduces the problem of visuomotor coordination in grasping the problem of coordinating these two modules.

The idea of dividing tasks into relatively simple modules, for which control seems reasonably straightforward, is widespread in the study of motor control. For instance, the fact that our body has many more degrees of freedom than are strictly required to control the end effector has led several authors to propose solutions for this "degrees-of-freedom problem" (reviewed by Bruton

& O'Dwyer, 2018; Tresch & Jarc, 2009). In doing so, it is assumed that this abundance of possibilities poses a problem for the brain. Control must be simple if the brain's computational power limitations are relevant. Therefore, rather than taking advantage of the abundance of options, the brain restricts itself to a limited set of synergies to construct a repertoire of movements (d’Avella et al., 2006; Ting & Macpherson, 2005; Soechting & Lacquaniti, 1989; Tresch & Jarc, 2009), including reach-to-grasp movements (Grinyagin et al., 2005; Mason et al., 2001). This description of synergies as a limited set of fixed muscle activation patterns (modules) implies that not all theoretically possible movements can be performed. Such synergies can be tested (Berger et al., 2013; Lee, 1984).

A key concept in understanding the relationship between speed and accuracy in movement is Fitts' Law, which describes how movement time (MT) increases as precision demands increase. Fitts' Law can be expressed as:

$$MT = a + b.log_2\left(\frac{2D}{W}\right)$$

Where MT is the movement time, D the distance to the target, and W the width of the target. As movement velocity increases, spatial accuracy often decreases, illustrating a trade-off between speed and precision. In reach-to-grasp tasks, this principle is particularly relevant, as achieving higher speeds may compromise the spatial accuracy of the grasp or contact point selection, impacting grasp orientation and object control.

There are arguments against the assumption that the brain restricts its freedom to choose solutions. The first argument is that if the selected muscle activation patterns were limited to a set of general-purpose synergies, it would be remarkable if such synergies never excluded the optimal solution for various motor tasks. There is clear evidence that humans exploit abundant possibilities when considering task constraints (Latash et al. 2001, 2002; van Beers et al. 2013), presumably searching for better solutions.

A second related argument against the restriction of movement patterns is that studies examining the chosen solutions have generally found that movement strategies are close to optimal in terms of task performance, considering the precision and noise of the motor apparatus (Harris & Wolpert 1998; Trommershäuser et al. 2005; Van Soest et al. 1994). Furthermore, experimental evidence suggests that the spatial characteristics of movements are planned before selecting the muscle activation patterns to produce the desired trajectories (Kistemaker et al., 2014). This hierarchy implies the importance of the spatial trajectory of the end effector in control. Indeed, visual distortions influence the curvature of movement paths (Smeets & Brenner 2004; Wolpert et al. 1994), whereas force-field perturbations leave curvature unaffected (Kistemaker et al. 2010).

A third argument against fixed patterns of muscle activation is that such learned patterns would not transfer across effectors because the anatomical constraints differ, which conflicts with the phenomenon of motor equivalence: many movement characteristics remain invariant when executed by different effectors in writing (Merton 1972; Wright 1990), pointing (Marteniuk et al. 2000), and grasping while walking (Marteniuk & Bertram 2001).

The final argument against fixed muscle activation patterns as the basis of motor control is that even spinal responses to perturbations are flexible and can reverse signs depending on the detailed task constraints (Traub et al., 1980). Taken together, these arguments suggest that movements are controlled in terms of the spatial restrictions of the task (for example, optimal trajectories of the end effector) rather than restrictions at the anatomical level (for example, limited sets of muscle activation patterns or changes in joint angles). Therefore, task constraints rather than neuromuscular constraints limit behavior.

Parallel Visuomotor Processing in Reach and Grasp Movements

A prominent framework for understanding reach-to-grasp actions is parallel visuomotor processing, which suggests that reaching and grasping tasks are divided into distinct functional modules (Arbib, 1981; Jeannerod, 1988). According to this model, each movement—transporting the arm toward the object, orienting the hand, and shaping the fingers to grip—operates as an independent module guided by separate visuomotor processes (Jeannerod, 1984; Jeannerod & Decety, 1990). This modularity allows for simultaneous yet independent adjustments to reach location and grasp orientation, as demonstrated in studies using prism adaptation, where one system can be altered without cross-talk to the other (Marotta et al., 2005).

By segmenting the movement into these distinct modules, the brain can integrate visual feedback to accommodate environmental variables such as object location, size, and orientation. This hierarchy in movement planning promotes efficient and adaptable motor actions, ensuring precision even under changing task demands (Arbib, 1981; Jeannerod, 1988).

Biomechanical Constraints: Donders' Law of the Upper Arm

In contrast to this modular approach, Donders' Law imposes a biomechanical constraint, suggesting that upper arm movements remain within a specific spatial plane during reach-to-grasp tasks. Marotta et al., 2003 explored this principle, finding that upper and lower arm torsional rotations contribute in distinct yet coordinated ways to grasp orientation. For example, when the required grasp orientation shifts from horizontal to vertical, both arm segments undergo torsional rotation, with the lower arm primarily adjusting grasp orientation (42%) and the upper arm contributing 9% (Marotta et al., 2003). These findings highlight the adaptive, coordinated rotation across arm segments, ensuring the hand's final positioning aligns optimally with the object.

Transport Location and Hand Orientation Studies

Studies of transport location have shown that the ability to reach for and grasp objects comprises two key aspects: transport, which is the action of extending the hand towards an object, and grasping, which involves adapting the hand's shape in response to the object's natural features like shape and size. Research has revealed that the orchestration and performance of this complex activity and its components are mapped within specific neural circuits known as the "prehension network" (Turella & Lingnau 2014). All three fundamental elements of a grasping movement (transportation, rotation, and hand opening) share a common visual representation of an object's orientation (Crawford et al., 2004).

Its dependency on visual field positioning emphasizes the close connection between the regulation of grasping actions and vision. For example, the ease of motor control is enhanced when the target object is in the same visual hemifield as the hand being used. Specifically, right-handed people more precisely calibrate their grip width for objects in their right visual field when using their right hand for grasping. Similarly, when using the left hand, individuals adjust their grip width more accurately for objects in the left visual hemifield (Le and Niemeier).

Studies of hand orientation have shown that the orientation of an object can also have distinct effects on our reaching and grasping plans (Cant et al., 2005; Hesse et al., 2008; Rice et al., 2007). In the act of reaching to pick up an object, our hand not only extends towards the accurate location but also adjusts its configuration in response to the anticipated orientation of the target before making contact. An effective grasping mechanism requires the encoding of an object's spatial coordinates and inherent properties (such as size and shape) and the transformation of these properties into a coordinated series of distal (involving fingers and wrist) movements (Crawford et al., 2004).

Orientation studies have demonstrated that as the orientation for the grasp changes from a horizontal to a vertical position, the upper and lower arms undergo a notable clockwise torsional rotation. This suggests that the arms and fingers in the grasp rotate together to create the required torsion for correctly orienting the grasp. Conversely, the aspects of arm torsion during reaching that depend on the workspace operate separately from the grasping action, leading to a specific type of kinematic limitation known as Donders' law. As previously noted, Donders' Law imposes a specific kinematic limitation on arm orientation, dictating a unique arm orientation for every particular location and orientation of the reach and grasp (see page 8; Crawford and colleagues, 2011; Marotta et al., 2003).

When the object has been previously primed with either the same object or a similar object, it leads to facilitation (increase in reaction times) of the visuomotor planning both in memory-guided (Cant et al., 2005) and real-time reaching movements (Hesse et al., 2008). Furthermore, the mass of an object can significantly influence our reaching and grasping movements. In experiments where participants were required to predict an object's center of mass (CM) before grasping it, it was observed that the object's roll/tilt movements were markedly reduced when the participants accurately anticipated the CM. This suggests that predicting the CM allows for a more stable grasp, minimizing the object's roll/tilt post-grasp (Lukos et al., 2007).

1.1.2 The Physiology of Reach and Grasp Systems

Physiological and Neuroimaging studies have shown that sensorimotor tasks activate various brain regions hierarchically arranged for human behaviors (Gallivan & Culham, 2015).

In reach-to-grasp tasks, the brain's motor pathways are generally divided into two complementary systems: one for reaching or transporting the hand and another for grasping or manipulating the object.

Transport System (Reaching Pathways): The transport phase of a reach-to-grasp movement primarily involves reaching networks within the dorsal stream of the visual processing system, often referred to as the "where" or "how" pathway. This network includes the dorsomedial pathway, which is crucial for reaching and extending the arm toward an object. The dorsomedial path connects two key regions in the PPC = posterior parietal cortex the V6A area, identified by Bosco et al. (2010), and the MIP = medial intraparietal sulcus (Johnson et al., 1996). This pathway further connects to the PMD = dorsal premotor cortex (Caminiti et al., 1991), where sensory inputs related to arm position and trajectory are integrated. Together, these areas assimilate somatosensory and visual information to plan and control arm positioning and movement during the transport phase (Turella & Lingnau, 2014; Vesia & Crawford, 2012).

Grasp System (Grasping Pathways): The grasping component of the reach-to-grasp action involves a separate but closely related neural network, which also falls within the dorsal stream but extends toward areas specifically supporting hand orientation and grip formation. Studies indicate that the AIP = anterior intraparietal area within the PPC is highly specialized for encoding grasp-related features such as object size, shape, and orientation. The AIP communicates with the ventral premotor cortex (PMv) to facilitate grip formation by adjusting hand posture and finger positioning in response to object characteristics (Gallivan & Culham, 2015; Culham & Valyear, 2006). The PPC's grasp-specific circuits thus allow for the transformation of object properties into coordinated motor commands essential for grasp execution.

Neuroimaging studies have shown that the ventral visual pathway (often termed the "what" pathway) aids in object recognition and visual perception, while the dorsal pathway facilitates action by transforming spatial information into motor plans (Creem & Proffitt, 2001; Freud et al., 2020; He et al., 2022). The distinction between these networks allows for a division of labor: while reaching movements primarily rely on PPC areas associated with spatial processing, grasping requires both spatial and object-specific processing in interconnected parietal and premotor regions.

By distinguishing these pathways, this section clarifies how specific brain regions contribute to the transport and grasp components of reach-to-grasp actions, with each subsystem integrating necessary sensory inputs for successful hand-object interaction (Vesia & Crawford, 2012; Culham & Valyear, 2006).

Neurophysiological studies provide insights into the neural mechanisms underlying reach-to-grasp movements, emphasizing the role of cortical and subcortical structures in motor control and sensory integration. According to Gentilucci and colleagues (1991), "the primary motor cortex (M1) and premotor cortex are critical for generating and refining motor commands during precision hand movements." The primary motor cortex (M1) is known for initiating voluntary movements and coordinating muscle activity. In contrast, the premotor cortex integrates sensory feedback and visual information to plan and execute motor actions (Jeannerod & Biguer 1982). These cortical regions exhibit functional specialization, with distinct neuronal populations that control proximal and distal muscle groups involved in reach-to-grasp tasks (Jeannerod 1992).

Neurons in PPC = posterior parietal cortex contribute to spatial perception and motor planning by encoding information about object properties such as size, shape, and spatial location (Jeannerod & Decety, 1990). Studies have shown that PPC neurons exhibit selectivity for specific grip types and hand orientations, reflecting their role in guiding precise hand movements during object manipulation (Gentilucci et al., 1991). Physiological and neuroimaging studies have shown that sensorimotor tasks activate various brain regions hierarchically arranged for human behaviors (Gallivan & Culham 2015). Previous reach-to-grasp research has differentiated between perception and movement networks, with the ventral pathway aiding visual perception and the dorsal pathway facilitating action (Creem & Proffitt 2001; Freud et al., 2020; He et al. 2022).

The dorsomedial pathway establishes a connection between two areas within the PP, namely area V6A (Bosco et al., 2010) and the medial intraparietal area (MIP, Johnson et al., 1996), linking these to the dorsal premotor cortex (Caminiti et al., 1991). This pathway is thought to encode information related to reaching movements, playing a critical role in planning and controlling arm positioning during the transport phase through the assimilation of somatosensory and visual inputs (Turella & Lingnau 2014).

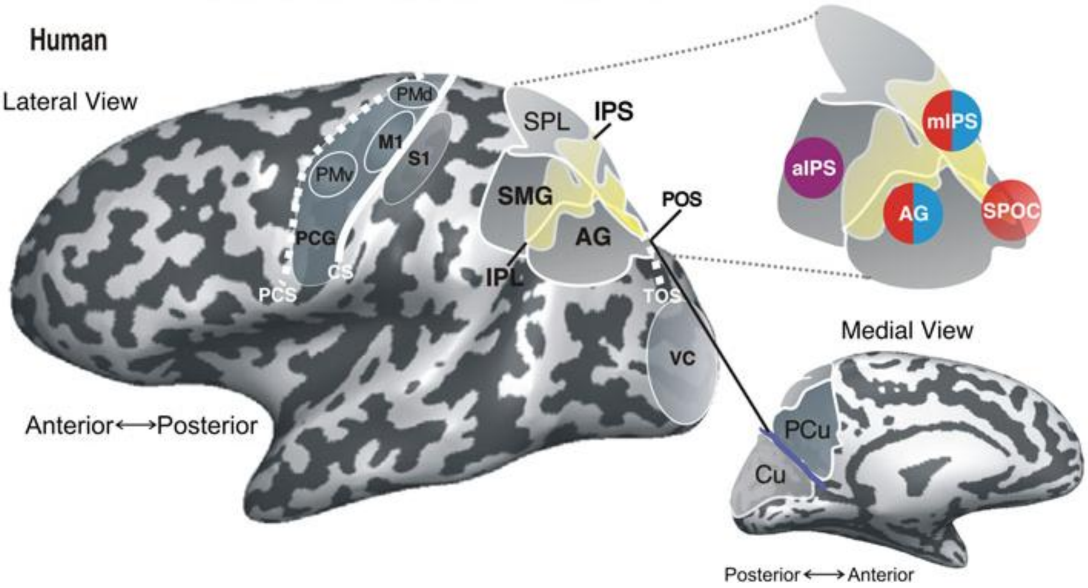

Figure 2. Functional anatomy of visuomotor systems in the posterior parietal cortex (adapted from Vesia & Crawford, 2012). This figure highlights critical regions of the human brain involved in planning and executing reach, saccade, and grasp movements. The lateral view shows transport areas, including MIP (medial intraparietal sulcus) and V6A, which are primarily involved in reaching movements, and grasp areas, such as aIPS (anterior intraparietal sulcus) and AG (angular gyrus), which are responsible for coordinating hand shaping and grasping functions. Additional regions include M1 (primary motor cortex) and S1 (somatosensory cortex), which integrate sensory input for motor control. The superior parietal lobule (SPL) and supramarginal gyrus (SMG) are involved in spatial processing and motor control, supporting both transport and grasp functions. The medial view includes regions like the posterior cingulate cortex (PCU) and cuneus (Cu), which are essential for visuomotor coordination. Overall, this figure illustrates how distinct areas of the posterior parietal cortex specialize in different aspects of movement, providing a framework for understanding how the brain supports reaching, grasping, and eye movements.

As shown in Figure 2, various regions within the posterior parietal cortex play essential roles in visuomotor coordination for grasping and reaching tasks. The physiology and neuroimaging of the brain in grasping objects have been extensively studied, revealing significant insights into the neural substrates involved.

The physiology and neuroimaging of the brain in grasping objects have been extensively studied, revealing significant insights into the neural substrates involved. Functional magnetic resonance imaging (fMRI) studies have shown that "visually guided grasping produces fMRI activation in dorsal but not ventral stream brain areas" (Gallivan & Culham 2015), particularly within the human anterior intraparietal cortex (IPS). This activation highlights the critical role of the dorsal stream in processing the spatial and motor aspects of grasping. Detailed fMRI investigations have identified specific regions within the intraparietal sulcus and frontal cortex engaged during visually guided grasping, emphasizing their involvement in integrating sensory information and coordinating hand movements. Additionally, studies using multivoxel pattern analysis (MVPA) have demonstrated that "recent fMRI work not only adds to the emerging view that the SPL and SPOC, in particular, is involved in the transformation of object-related information into corresponding motor programs for grasping, but also suggests that PMd participates in this transformation process" (Gallivan & Culham 2015).

Moreover, these regions and the PMd = dorsal premotor cortex are pivotal in planning and executing grasping actions. Interestingly, the coding of upcoming hand actions is "surprisingly ubiquitous throughout much of the ventral stream" (Gallivan & Culham 2015). These findings underscore the intricate neural networks facilitating the seamless execution of human grasping movements.

The neurophysiology of grasping objects involves complex interactions among various brain cortical areas, particularly within the posterior parietal cortex, cerebrum, and motor cortex. According to the document, "the PPC, along with corresponding dorsal occipital and PPC sites, integrates visual and other sensory information to guide visuomotor plans" (Gaelle Luabeya et al., 2023). The IPS = anterior intraparietal sulcus also plays a crucial role in grasp formation. At the same time, the SPOC = superior parietal occipital cortex is essential for transport and hand orientation (Luabeya et al., 2023).The influence of gaze on hand movements during grasping is particularly notable, as "gaze position strongly influences reaching and pointing, with gaze direction modulating hand orientation during object placement" (Luabeya et al., 2024). Furthermore, the parietal cortex's integration of saccade and object orientation signals is pivotal for updating grasp plans, underscoring its vital contribution to the reach and grasp functions (Luabeya et al., 2023). These findings highlight the intricate neural mechanisms that enable precise object manipulation and placement, emphasizing the significance of visual and sensory integration in motor planning.

Understanding the neurophysiology of the brain in grasping objects is essential in fields like neuroscience, robotics, prosthetics, and rehabilitation. According to Liu and colleagues (2021), the complexity of the motor control system makes understanding human hand movement challenging, as "some key issues are still in the subject of hot debate, such as the brain activity in the grasping process" (Sereno & Maunsell 1998; Castiello 2005; Goodale 2010). Furthermore, cortical representations of hand movement-related muscles play a critical role, with studies by Schieber and Hibbard (1993) and Sanes et al. (1995) shedding light on this intricate neural activity. Additionally, biomechanical constraints of hand grasping, including tendons and ligaments, are significant factors, as Kapandji (1971) and Santello et al. (2013) discussed. Investigating these neural and biomechanical factors provides a comprehensive understanding of the brain's role in facilitating the complex task of grasping objects (Liu et al., 2021).

1.1.3 Placement

Humans do not only reach for objects; they also place those objects afterward. However, relatively few studies focus on placement compared to reaching and grasping. Placement tasks have been shown to require increased reaction and movement times due to their higher accuracy demands and need for advanced planning (Hesse et al., 2008). In placement, upper limb strength is crucial for maintaining object stability and precise alignment (Parry et al., 2019). While grasping and placement share certain features, such as precise localization and orientation of the hand, they differ in their reliance on sensory information and movement goals. Specifically, grasping relies heavily on visual input to guide hand orientation and grip toward objects identified in the visual field, while placement often involves aligning the object within a designated location or pattern, relying on memory and proprioceptive cues when direct visual feedback is limited (Luabeya et al., 2023).

Milner and Goodale’s two-visual-systems framework (1995) offers a foundational perspective on these differences. According to this model, the dorsal stream primarily guides spatial actions, such as placement, by processing spatial and orientation cues even when visual feedback is restricted or alignment with a target template is required. In contrast, the ventral stream is associated with object identification and perceptual processing, supporting the grasping component through detailed visual analysis. This framework suggests that placement tasks require a mix of real-time control and pre-planned movements. The dorsal stream handles immediate adjustments for precise alignment, while the ventral stream supports placement that relies on recognition and planning. This dual-stream control allows flexibility and accuracy in positioning objects within specific contexts or constraints(A. Goodale et al., 2004)

A recent study by Luabeya et al. (2023) provides further support for these distinctions, examining the roles of gaze, vision, and memory in placement accuracy. The study found that gaze direction and visual feedback significantly impact placement precision, with hand movements tending to overshoot targets when visual input is limited, or gaze is diverted. Additionally, memory delays reduced placement accuracy, highlighting that visual and memory systems are integral to alignment during placement tasks. Although placement and grasping share similar properties, placement may also rely on memory and proprioceptive cues for alignment when visual feedback is constrained, whereas grasping often depends on continuous, real-time visual guidance for adjusting hand orientation and grip.

While reaching primarily utilizes somatosensory information to guide hand transport, placement tasks demand even finer adjustments, involving both visual and somatosensory feedback for precise alignment and stabilization. Somatosensory feedback becomes crucial in placement to refine hand posture and grip strength, meeting spatial constraints and preventing object slippage. Unlike reaching and grasping, placement requires a complex integration of sensory feedback and motor control to achieve the final position accurately.

Placement in sequential pick-and-place tasks involves positioning an object within a specified target area after grasping, requiring greater accuracy and planning than the initial reach and grasp phases. As noted by Hesse and Deubel (2010), “When all movement segments within the sequence were easy to perform, results indeed showed that grip orientation chosen in the early movement segments depended on the forthcoming motor demands, suggesting a holistic planning process.” However, they also observed that making the placing task more difficult resulted in longer reaction times and increased movement times for all segments, indicating that placement draws on additional cognitive and motor resources to achieve precise alignment.

Despite these insights, the specific behavioral and physiological differences between reaching and placing are still underexplored. This highlights an area for future research to deepen our understanding of the unique demands of placement tasks, especially in settings where visual feedback is limited or when objects require exact positioning.

1.1.4 Specific Aims and Hypotheses of the Study

My study aims to investigate the kinematics of reaching/grasping and placement movements in humans, specifically how the intention of the movement (grasp vs. place) influences various kinematic outcomes, including timing, velocity, and different types of errors (e.g., position error, orientation error, depth error). To test this, I developed a task in which participants alternately acquired grasped an object from a template oriented to the left or right of central gaze at clockwise or counterclockwise orientations and then placed the object in a template at a different location and orientation. Given the specific demands and kinematics of grasping versus placing movements, unique neural mechanisms may underlie each action. Additionally, this study serves as an experimental protocol to further explore motor control (Liu et al., 2021).

Hypothesis:

Since it has been suggested that "action context," the forthcoming movement, plays a significant role in the movement kinematics for reaching and grasping (Hesse & Deubel 2010), I speculate that grasp vs. placement goals have unique kinematic properties. Given that the placing task requires more accuracy for aligning the object within a template, I hypothesize that:

Participants might move slower (with increased reaction times) in placement tasks compared to grasping tasks due to the higher control demands required for precise object alignment. This slower movement is expected to improve accuracy in placement tasks, as participants allocate greater attention to achieving exact positioning. However, even with this increased focus on accuracy, the inherent complexity of precisely aligning the object with the target may still introduce small, systematic errors. These minor deviations in location (target alignment) and orientation (object alignment) could arise from the difficulty of maintaining precise control throughout the alignment process, despite careful movements.

2. Materials and Methods

2.1 Materials and Methods

2.1.1 Participants

Seventeen individuals (7 males and 10 females, ages 18 – 31) gave informed consent to participate in the study. This sample size was determined based on an a priori power analysis conducted using G*Power, targeting an effect size of 0.25 with a desired power level of 80% ($\alpha = 0.05$) for detecting differences in kinematic variables between grasping and placing tasks. This analysis indicated a minimum required sample size of 16 participants. All participants were right-handed with no neuromuscular deficits, based on self-report. Participants also reported normal or corrected normal vision and intact color vision. Data from 7 participants was excluded in the preprocessing and further analysis because of noise in the data (see 'exclusion criteria' for details), resulting in 10 participants for analysis. All participants were naïve to the purpose of the experiment and were given monetary compensation for their time. The York Human Participants Review Subcommittee approved the experimental procedures.

2.1.2 Apparatus

The experiment was conducted using a customized table and chair (permanently fixed at a location on the floor) for reaching and placing tasks (Figure. 3a, b) in complete darkness. The table was made the hand positions were tracked using Optitrack while keeping the chin stable on the chin rest.

Apparatus Setup: During experiments, participants were seated so that the nasal point on the face was 32.2 cm from the fixation point directly in front of their eyes, allowing them to maintain focus). To ensure stability and accurate gaze, both the chair and chinrest were adjustable to accommodate each participant's height, ensuring that their gaze remained fixed on the central fixation point without strain.

OptiTrack Camera Placement and Marker Setup: A four-camera OptiTrack system, mounted on the ceiling, recorded hand movements throughout the experiment, capturing the trajectories in 3D space. Reflective markers were attached to the top of the three specific points on each participant's hand: the thumb, the index finger, and the point between these two fingers. This marker setup allowed detailed tracking of the hand's movement path during reach-to-grasp and placement tasks.

Fixation and Eye Tracking: The fixation point, positioned in front of the participant's nasal and aligned with their eyes, served as a constant visual reference throughout the experiment. Participants wore eyeglasses equipped with a camera-based eye tracker, which monitored their gaze to ensure it remained fixed on this point. This setup enabled precise capture of both eye and hand dynamics, providing accurate data for kinematic and spatial analysis essential to the study. The eye tracker used in this study is the MindLink model by AdHawk Microsystems.

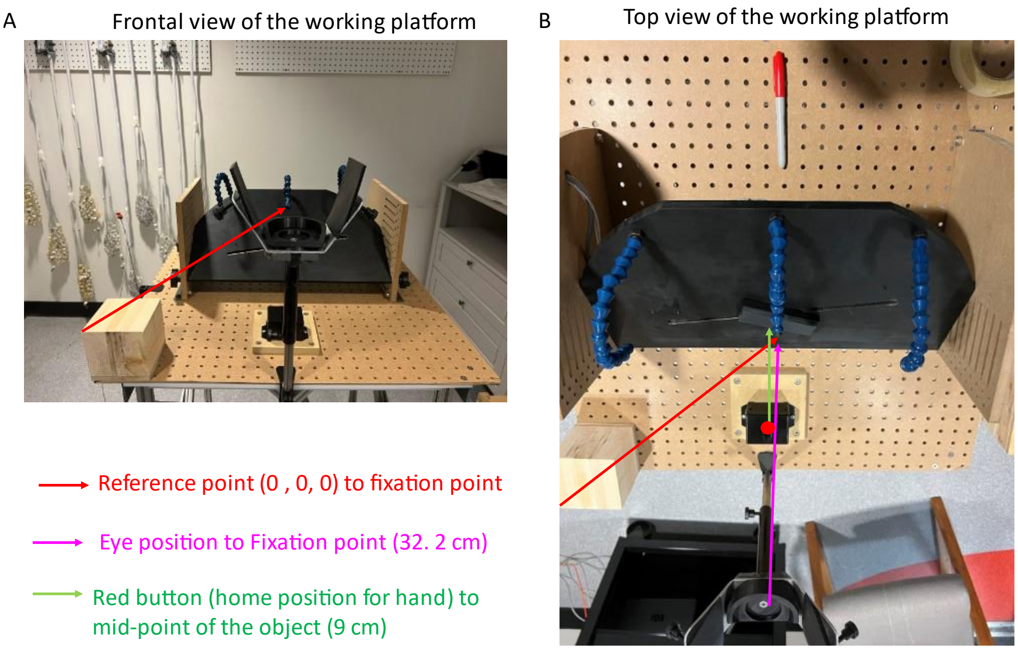

Figure 3. Experimental platform for grasping/placing (and the specific dimensions) in the human. (A) Behind view of the platform. (B) Top view of the platform. The participants were seated on a custom-made chair with their chin on the chinrest 32.2 cm from the eye fixation point (pink arrow), while their hand on the home position (red button) placed 9 cm from the mid-point of the object of the working platform (green arrow). The chinrest base is 35 cm from the base of the reference point block. As the chin rest and eye fixation were changed relative to a participant, the distance between the eye fixation and the base of the chinrest was measured for every participant. Note: The stimulus is accessible to the experimenter through the back side of the platform to change the stimulus orientation and location.

Figure 3 illustrates the experimental setup and specific dimensions used for the grasping and placing tasks, including the positioning of the chair, chin rest, and hand placement. The study was conducted in a nearly completely dark room, only interrupted by a fixation light and flashing light indicating the target location. The fixation light was red for preparation time, i.e., preparing the hand for home fixation. As the fixation light and flashing light turned off, it acted as a ‘go signal’ for movement execution. The movement starts from the home position on the table and returns to the location before the inter-trial interval.

Participants then had a training session lasting between 5 and 10 minutes. They were instructed to grasp a rectangular object or place it on an object holder mounted on the platform in a predetermined location and orientation. The holder was fixed on the platform but could be adjusted by the experimenter to specific orientations (clockwise or counterclockwise) and positions (left or right). The holder was fixed on the platform but could be adjusted by the experimenter between trials. To reposition the object holder, the experimenter used a handle located at the rear side of the platform. This handle allowed for precise adjustments of both the location (left or right) and the orientation (clockwise or counterclockwise) of the object holder. The adjustments were guided by pre-calibrated positions on the platform to ensure accuracy. During the experiment, the experimenter received instructions through a hands-free earpiece, specifying the required position and orientation of the object holder before each trial. This ensured that each trial's setup was predetermined, and the participant could not anticipate the orientation and location of the object before a trial.

The object positions and slots on the platform were intentionally tilted to account for the natural biomechanics of the right hand during reaching and grasping movements. Specifically, the design ensured greater comfort and efficiency for participants: the slots on the left were positioned slightly lower, while those on the right were positioned slightly higher. This adjustment accommodated the natural ergonomic movement of the right hand, making it more comfortable to reach downward on the left side and upward on the right side. This design was implemented to minimize strain and maintain consistency in participants' movements during the grasping and placing tasks.

The experiment alternated between reach-to-grasp and place movements to maximize the amount of data collected within a given timeframe. By intermixing these two task types, we ensured that participants remained engaged and avoided fatigue from performing repetitive movements of the same type. This design allowed for efficient data collection across both conditions while maintaining the participants' focus and consistency throughout the experiment.

2.1.3 Experimental Design

The experiment used a design where each participant performed both grasping and placing tasks under all conditions. It also involved two object orientations (clockwise and counter-clockwise) and two initial locations (left and right), resulting in eight conditions, with each condition repeated 20 times. The experiment involved a repeated measures design, meaning that each participant undergoes all eight conditions in a randomized order to avoid any order effects.

The study was a 2 x 2 x 2 study design with two task types (grasp or place), two possible object orientations (clockwise or counterclockwise), and two target locations (left or right). Thus, the experiment has 8 (2 x 2 x 2) conditions (blocks), outlined as follows:

Condition 1: Grasping – Left – Clockwise

Condition 2: Grasping – Left – Counterclockwise

Condition 3: Grasping – Right – Clockwise

Condition 4: Grasping – Right – Counterclockwise

Condition 5: Placing – Left – Clockwise

Condition 6: Placing – Left – Counterclockwise

Condition 7: Placing – Right – Clockwise

Condition 8: Placing – Right – Counterclockwise

Before the actual experiment began, a calibration stage was run.

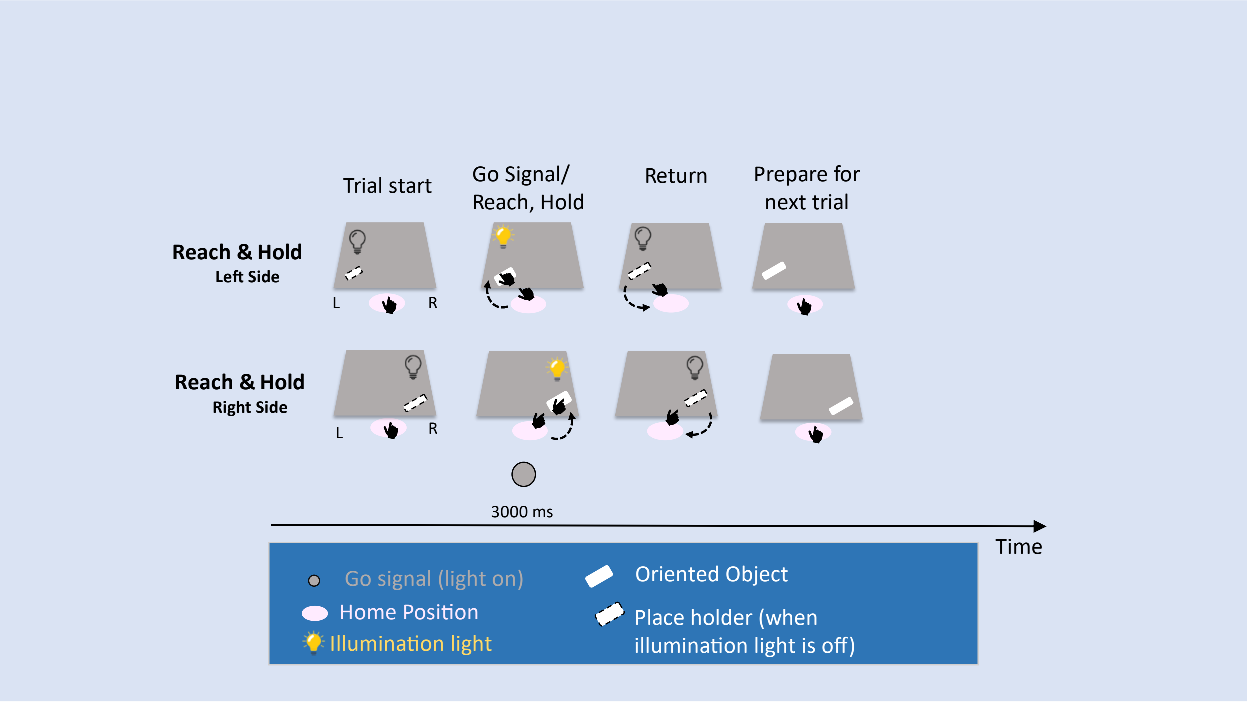

Figure 4. Design and timeline of the calibration. There are two LED lights in the setup, and the participants see these lights, which turn on alternatively during the calibration stage to show participants where the object is (illuminate the object either on the left or right side).

The design and timeline of the calibration process are illustrated in Figure 4, highlighting the sequence of LED signals that guide participants in locating and interacting with the object during the calibration stage. When the LED turns on, it acts as a Go signal, which means the participant looks, reaches, and holds onto the object (for 3 seconds). When the LED gets off, they should return to the home button (by pressing it) and prepare for the subsequent trial. Each participant performs 12 trials in the calibration stage. This figure shows the same movements (reach & hold) in left and right positions.

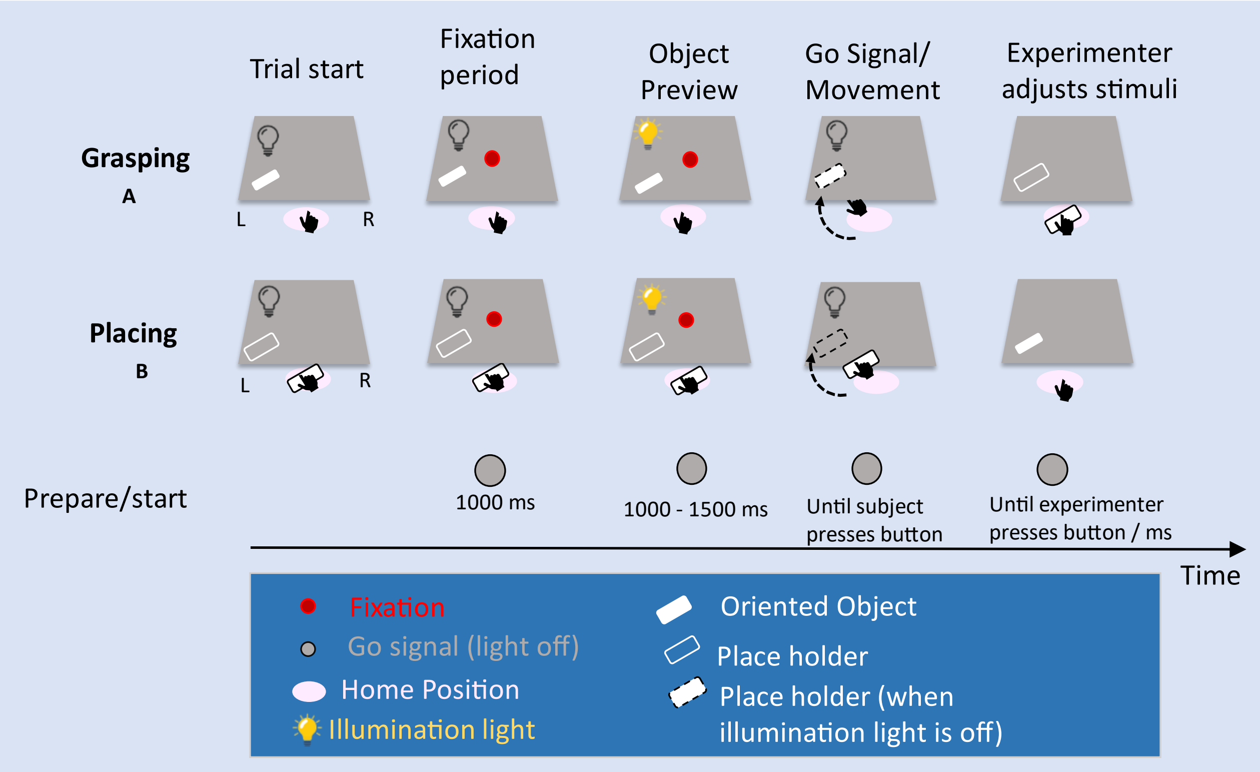

Figure 5. Design and timeline of the experiment. This investigation included two task types: grasping and placing. (A) In the grasping condition, the participant begins the experiment by fixating their hands on the home position (light red bar) and eyes on the red fixation dot. Then, an LED (illumination) lights up to show where the object is (either on the left or right side). Then, the red and LED lights turned off, which meant a go signal. Following variable reaction time (putatively because of inter-participant variations), the participant initiates to look naturally and moves towards the object, then is instructed to return to their home position. (B) It is the same as 'A' except the participant home fixates on the object to be placed in the placeholder on the platform. Note: Here, only one orientation to the left is displayed for representation purposes, but the task contains two orientations and two directions. See text for time details.

The design and sequence of the experimental tasks, including both grasping and placing conditions, are detailed in Figure 5, which outlines the initial hand and eye fixation, LED signaling, and movement phases involved in each trial.

1. Trial Start: At the beginning of each trial, participants were required to either reach and grasp an object or reach and place it onto a specified holder, depending on the assigned task. In the reach-to-grasp task, participants moved their hand from the home position to grasp an object. In the placement task, they moved to place the object on a designated holder in a specific orientation. Tasks were intermingled in a randomized order, ensuring participants could not anticipate the next task type or configuration. Each trial began with the participant fixating on a red dot (Fixation, F) while they also place their hand on the home position (H) on the customized table (in both Grasping/Placing). At this point, the object is not visible in the grasping task or the placeholder for the placement task.

2. Object preview: An LED light is turned on to illuminate the object for a variable time duration between 1000- 1500ms (to control the anticipation effect of the Go signal). Participant continues fixating their eyes and hands on the button.

3. Go Signal / Movement: Then Fixation light and illumination turn off, acting as a Go signal: The participant looks naturally and reaches toward the object (either to the left (L) or right (R) of the participant's midline, depending on where the object for action was displayed).

It is assumed that every individual's reaction time (time between the go signal and the movement initiation) may vary—the movement recorded during the trial. Before participants initiate the movement, they press the button, which signals the hand’s movement.

4. Return: Once the participant’s hand returns to the home position, the experimenter changes the position/orientation based on the instructions to start the new trial. The grasping task and the placing task were altered. In the grasping task, participants were instructed to grasp the object, while in the placing task, they were asked to put the object in an object holder.

Trial Overview: Each participant performed 20 trials in each run for a total of 160 trials. The trials were randomized and tested in 8 separate runs (20 trials in each run, approx. 12s x 20 = 240s). Thus, the anticipated time for a whole experiment was around one hour, including the eye-tracker procedure and calibration stage (1-1.5 hours). During the experiment, the participants did take rest intervals, which extended the total task time to approximately 0.5 hour.

2.1.4 Data Analysis

Behavioral Measurements: All data were pooled across participants for analysis to focus on overall trends across conditions, rather than analyzing individual differences between participants. As participants performed two distinct tasks (grasping and placing), I analyzed each participant's data separately to capture individual variability. A mixed-effects modeling approach was applied to account for participant-level variability within each condition, addressing potential issues with pooling data across participants and allowing a more nuanced analysis of condition effects. An eye calibration was conducted before each experiment to ensure accurate gaze fixation, and trials where participants did not fixate properly (i.e., made errors) were removed from the analysis. Custom-made software in the lab was used to mark successful and unsuccessful trials accurately.

To capture a comprehensive picture of task execution, I selected nine dependent variables that offer insights into the timing and accuracy of movements. These variables are grouped into two main categories: **Timing Variables**—Reaction Time, Movement Duration, Peak Velocity, and Peak Velocity Time—and **Accuracy Variables**—Position Errors (with Depth, Up-Down, and Horizontal components) and Orientation Error. The Timing Variables provide information on how quickly and efficiently participants executed each task, while the Accuracy Variables assess spatial precision and control. Together, these variables facilitate an understanding of the differences in motor control between grasping and placing tasks.

For the hand movement data, sensors tracked the start (home button), endpoint (grasping or placing location), and movement trajectory for each trial. The nine kinematic variables were then analyzed to compare grasp vs placement conditions, as detailed below:

Reaction Time (RT): The time interval between the 'go signal,' marked by the extinguishing of the fixation and target-indicating flashing lights, and the initiation of hand movement. Hand movement initiation was defined as the release of the button at the home position. Reaction time was calculated as the difference in time between the 'go signal' (LED off) and the button release, indicating the onset of hand displacement. RT reflects the speed of a participant's decision-making and motor initiation in response to an external cue. This variable is crucial in motor control studies because it provides insights into the cognitive and sensorimotor processes involved in planning and initiating movement (Schmidt & Lee, 2011). Longer reaction times in the placing task may imply increased demand on attentional resources and motor planning due to the need for greater positional accuracy, a hypothesis supported by prior motor control studies emphasizing the role of reaction time in task complexity (Lili et al., 2021). Researchers measured reach duration to evaluate movement strategies and performance in stroke patients as well (Zaidi & Harris-Love, 2023)

Peak Velocity (PV): Peak velocity was defined as the highest speed reached by the participant's hand during the movement, offering insight into the intensity and dynamics of motor execution. Hand position data were continuously recorded using OptiTrack's motion capture system, tracking the hand's X, Y, and Z coordinates throughout each trial. Velocity was calculated at each time point as the rate of change in the hand’s position between consecutive frames. Peak velocity was identified as the maximum value in the velocity profile for each trial. The timing of peak velocity relative to movement onset was also recorded to determine whether participants reached peak speed early, mid, or late in the movement trajectory. This timing was expressed as a percentage of the total movement duration for each trial.

Calculated as the maximum value in the velocity profile for each trial, peak velocity provides a direct measure of movement vigor and control (Flanagan & Wing, 1997). Tracking this measure is essential in differentiating between tasks with varying precision demands; in tasks requiring precise object placement, participants may intentionally regulate their speed to avoid overshooting or errors (Jeannerod, 1988). In this study, peak velocity is particularly informative for comparing grasping and placing tasks, as it can indicate differences in force application and control. Placing tasks are expected to exhibit lower peak velocities relative to grasping, reflecting the need for greater deceleration and precision in end positioning. Moreover, recording the timing of peak velocity as a percentage of total movement duration offers a further layer of analysis, revealing whether peak speed occurs early, mid, or late in the trajectory. This timing detail helps us understand whether participants adopt a “fast-and-slow” approach—reaching peak velocity early and decelerating as they approach the target, which is often seen in tasks with higher accuracy demands (Hogan & Sternad, 2007).

Peak Velocity Time (PVT): The time peak velocity is the moment during a movement when the participant's hand achieves peak velocity, calculated relative to movement onset and expressed in milliseconds and as a percentage of total movement duration. This measure is informative for understanding acceleration patterns and movement dynamics, offering insights into motor planning and control strategies (Morasso, 1981). Specifically, PVT helps determine whether participants reach peak velocity early, mid, or late in the movement trajectory, which can reveal their approach to task execution (Elliott et al., 2010).

In motor tasks, reaching peak velocity early (e.g., 25-33% of movement duration) suggests a rapid acceleration phase, often seen in tasks with lower accuracy demands. Conversely, reaching peak velocity later in the movement (e.g., 50-75%) may indicate a more controlled, gradual acceleration, suggesting an emphasis on precision and the need to slow down toward the target (Plamondon & Alimi, 1997). Thus, PVT is critical in contrasting grasping with placing tasks, as it may indicate the additional control and precision required in placing, where participants are expected to modulate their speed throughout the movement.

Movement Duration (MD): This is the total time taken from the onset of hand movement (button release) to the completion of the task, marked by hand stabilization at the target location. This measure is essential in motor control research, as it reflects the efficiency and control of movement execution. Movement duration helps us understand how quickly participants complete each task and indicates the degree of planning and control needed for different task demands (Gentilucci et al., 1991).

Longer movement durations often suggest a careful approach, especially in tasks that require precise placement, such as object positioning. By contrast, shorter durations may indicate a more fluid or automatic movement, typically associated with simpler tasks like grasping (Jeannerod, 1997). In this study, we expect placing tasks to exhibit longer movement durations due to the additional accuracy and spatial control required for precise placement, aligning with previous findings that precision tasks generally demand more extended execution times (Fitts, 1954). Movement duration thus provides key insights into the trade-off between speed and accuracy in motor tasks, revealing how task complexity influences the control strategies participants adopt to meet different task demands.

Absolute Position Error (APE): This is defined as the 3D spatial deviation of the participant's hand from a pre-calibrated reference position at the moment of task completion. This measure captures the accuracy of the participant's final hand position in the depth (Z-axis), up-down (Y-axis), and horizontal (X-axis) dimensions. APE is crucial in motor control studies because it reflects spatial precision—how closely participants reach the intended target location—which is particularly important in tasks requiring high accuracy (Soechting & Flanders, 1989).

In tasks such as grasping and placing, where spatial positioning is key, APE allows us to quantify control differences. Placing tasks typically require greater accuracy to achieve correct positioning, whereas grasping tasks may tolerate slight deviations. High APE values in placing tasks would suggest difficulties in spatial precision, aligning with studies indicating that complex motor tasks often involve trade-offs between speed and spatial accuracy (Meyer et al., 1988). By comparing the deviations across the X, Y, and Z axes, APE also provides nuanced insights into specific directional challenges participants may face, such as depth or horizontal misalignments, which can inform theories of sensorimotor integration and control (Haggard & Wing, 1995). Overall, APE helps reveal the spatial accuracy needed for task execution, distinguishing between tasks based on their spatial precision demands at the moment when the finger movement velocity dropped to 0.09 m/s for a sustained duration of 25 ms.

Depth Error (DE): Depth error quantifies the deviation of the participant's hand position along the Z-axis (forward-backward direction) relative to a calibrated reference position at the moment just before contact. This variable is essential for understanding spatial precision in depth, as errors along the Z-axis directly impact successful object manipulation and placement, especially in tasks requiring precise end-point control (Desmurget et al., 1999).

In the context of grasping and placing tasks, DE is particularly informative because accurate depth control is critical for placing tasks, where overshooting or undershooting the target position can result in placement errors. Placing tasks generally require more controlled deceleration along the depth axis to avoid overshoots, whereas grasping tasks may afford more flexibility in this dimension. Studies have shown that movement accuracy in depth (along the Z-axis) is often more challenging to control than in other directions due to perceptual and motor limitations in estimating distances in space (Flanders et al., 1992). Therefore, DE provides insights into participants' depth control capabilities and the precision of hand movements, particularly in tasks with distinct spatial accuracy demands.

Up-Down Error (UDE): Up-down error measures the deviation of the participant's hand along the Y-axis (vertical direction) relative to a calibrated reference position just before contact. This variable is crucial for evaluating vertical accuracy, particularly in tasks requiring precise hand positioning in the vertical plane. Vertical control is an important aspect of motor execution in object manipulation, as misalignment along the Y-axis can impact the stability and accuracy of object placement (Gentilucci, 1992).

In grasping and placing tasks, vertical positioning often requires careful modulation to ensure that the hand aligns correctly with the target's vertical location. Placing tasks may demand tighter vertical control compared to grasping tasks, where some flexibility in vertical position may still allow for successful object contact. Research on vertical movement control has shown that the Y-axis presents unique challenges for motor planning due to the combined demands of balance, proprioceptive feedback, and gravitational factors that influence hand positioning (Smeets & Brenner, 1999). By analyzing UDE, we can gain insights into how well participants adjust their movements to achieve precise vertical alignment, especially when transitioning between grasping and placing tasks with varying demands for vertical accuracy.

Horizontal Error (HE): Horizontal error quantifies the deviation of the participant’s hand position along the X-axis (left-right direction) relative to a calibrated reference position just before contact. This measure is essential for understanding lateral accuracy, which is critical in motor tasks requiring precise hand placement along the horizontal plane. Accurate horizontal positioning is particularly important in tasks such as object placement, where lateral misalignment can lead to task errors or reduced control over object orientation (Haggard & Wing, 1990).

In grasping and placing tasks, lateral control is crucial for successful task execution. Placing tasks, in particular, often demand greater precision in horizontal positioning to avoid errors in final alignment. Studies indicate that the horizontal plane presents unique motor challenges due to lateral biases in movement control and the influence of hand dominance, which can affect the accuracy and consistency of left-right positioning (Sainburg, 2002). By analyzing HE, we gain insight into the participant's lateral control capabilities and can assess the specific horizontal positioning demands associated with each task type.

Orientation Error (OE): Orientation error captures the angular deviation of the participant's hand orientation relative to a calibrated reference orientation just before contact with the target. This measure is essential for evaluating the participant's rotational accuracy and the precision with which they align their hand to the intended orientation, particularly in tasks requiring specific hand orientations for successful completion. Orientation control is critical in object manipulation tasks, as improper alignment can hinder task performance or lead to task failure, especially when precise orientation is necessary for placing objects accurately (Desmurget et al., 1995).

In grasping and placing tasks, rotational alignment (measured by OE) is particularly important for placing tasks, where exact hand orientation impacts object stability and positioning. Research on motor control suggests that orientation adjustments are complex and demand fine motor adjustments to achieve rotational precision, which is often influenced by proprioceptive and visual feedback systems (Krakauer et al., 1999). By examining OE, we gain insights into the participant's control over rotational movements and can assess differences in the control strategies required for tasks that demand precise orientation. OE thus provides critical information on the angular accuracy of participants' hand movements, offering a means to differentiate task-specific demands and highlight the role of rotational control in complex motor actions.

2.2 Data Cleaning and Exclusion Criteria

The original dataset

consisted of 17 participants, each performing 160 trials for a total of 2,720 trials. However, only 10 participants’ data, equating to 1,600 trials, were retained for analysis due to multiple factors that made the remaining data unusable.

Participant Exclusion

The primary reason for excluding data from these 7 participants was ambiguity in decoding hand location and orientation from the wireless marker signals, resulting in bimodal distributions of data that could not be explained or corrected despite refinement attempts. During this process, I also encountered uncertainty regarding whether the stimulus position and orientation were recorded accurately in some trials. To address this, I rejected data points where the trajectories or final positions did not align consistently within a unimodal distribution. This ensured that only reliable and interpretable data were retained for further analysis. Specifically, participants data was removed for the following reasons:

- Noisy or Inconsistent Signals: Marker signals with excessive noise or inconsistency, making it impossible to accurately detect and differentiate hand movements.

- Incomplete or Interrupted Marker Signals: Datasets with non-consecutive or interrupted marker signals, leading to significant gaps in the recorded data.
- Head Movements or Noncompliance: Participants who exhibited frequent head movements or failed to maintain proper positioning on the chin rest, causing motion artifacts that compromised the quality of the data.
- Marker Occlusion or Technical Failures: Persistent loss of hand tracking due to marker occlusion or recurring technical issues with the OptiTrack system.

The exclusion of these participants ensured the integrity and reliability of the dataset, focusing the analysis on high-quality, interpretable data.

Trial-Level Exclusion

For the 10 retained participants, individual trials were excluded based on additional criteria to ensure data quality.

1. Initial MATLAB preprocessing: In the initial preprocessing stage using MATLAB, 100 trials were removed based on pre-defined criteria to exclude trials with significant noise or tracking errors. This step reduced the dataset from 1,600 to 1,500 trials.
2. Handling Missing Values: After exporting the data from MATLAB, rows containing "NA" values, which indicated missing or unusable data, were removed (about 27% of the total data). This step ensured that incomplete or unreliable data did not compromise subsequent analyses.
3. Outlier Detection and Removal: The Interquartile Range (IQR) method was applied to identify outliers. Data points falling below the first quartile (Q1) or above the third

quartile (Q3) by more than 1.5 times the IQR were flagged as outliers. If any dependent variable (DV) within a trial was flagged as an outlier, the entire row for that trial was excluded to maintain a symmetric dataset across all variables. This symmetry is essential for consistent ANOVA and mixed-effects model analyses.

Similar outlier-handling techniques have been effectively applied in motor control and kinematic studies (Liu & Todorov, 2007; Wagner & Smith, 2008).

In cases where any dependent variable (DV) within a trial was flagged as an outlier, the entire row for that trial was excluded. This approach ensured a symmetric dataset across all DVs, which is essential for consistent ANOVA and mixed-effects model analyses.

Retention and Summary

Following the application of all exclusion criteria, a total of 1,050 trials (approximately 66% of the original dataset) were retained for analysis. This pipeline aligns with established practices in kinematic and motor control research, where rigorous preprocessing steps are necessary to ensure data integrity. For example, studies by Madhavan and Ahmed (2013) and Osborne and Overbay (2004) support the approach of removing trial-level outliers to uphold dataset reliability. By retaining only high-quality data, we ensured robust and interpretable results while maintaining symmetry across all dependent variables.

2.3 Statistical Analysis

The statistical analysis focused on examining differences across the eight experimental conditions (Task: Grasp vs. Place; Location: Left vs. Right; Orientation: CW vs. CCW). Given the repeated-measures design, each participant completed all conditions, allowing for a within-subjects comparison across these factors. A repeated-measures ANOVA was employed to capture participant-level variability while evaluating the main effects and interactions among Task, Location, and Orientation. This approach enables us to attribute observed effects to the experimental conditions while accounting for individual differences.

The central hypothesis predicted that placement tasks, due to additional control demands for precise object alignment, would result in slower movements - evident in increased reaction times and movement durations - compared to grasping. Although placement is expected to enhance accuracy overall, the complexity of alignment requirements may introduce subtle, systematic errors in both spatial positioning and orientation.

Following significant ANOVA findings, post-hoc analyses using Tukey’s Honest Significant Difference (HSD) were conducted to pinpoint specific pairwise differences between conditions. This post-hoc test, combined with a False Discovery Rate (FDR) correction, ensured that multiple comparisons were appropriately controlled, allowing us to report only statistically meaningful differences in the effects of Task, Location, and Orientation on the dependent variables.

Overall, the use of a Repeated-Measures ANOVA with participant-level data, followed by FDR-corrected post-hoc comparisons, provided a rigorous approach to testing the hypothesized kinematic differences between grasping and placing tasks, particularly focusing on the anticipated slower movement and the potential for systematic alignment errors in the more demanding placement tasks.

2.3.1 Trajectory Plot

In addition to examining the timing and accuracy of movements, I also analyzed hand trajectories across all conditions. The trajectory data were captured and visualized using both left/right locations and CW/CCW orientations, comparing the grasp and place tasks. The trajectory plots allowed for a detailed understanding of the movement path taken during each condition, revealing insights into the smoothness, variability, and spatial accuracy of these movements. These trajectory analyses complement the statistical findings by providing a visual confirmation of the patterns observed in the kinematic and accuracy-related variables.

2.3.2 Raincloud Plot

Raincloud plots were utilized to illustrate the distribution of participant-level means for each condition, providing an overview of how each dependent variable (DV) varies across participants. These plots integrate multiple graphical elements, including half-violin plots to display the density distribution of participant means, box plots to summarize central tendencies and variability, and individual data points connected by lines to highlight within-participant consistency across tasks. The box plots include the median and interquartile range, while the black dots represent the means, offering a complementary view of central tendency alongside variability. By incorporating density distributions, the raincloud plots allow for a nuanced visualization of multimodality or clustering patterns within the data, emphasizing variability across conditions. This approach facilitates a comprehensive comparison of trends related to Task Type, Orientation, and Location, highlighting overall differences in motor performance metrics. Statistical analyses complement the visual representation by quantifying differences between conditions, supporting interpretations derived from the raincloud plots.

2.3.3 Violin Plot

To provide a qualitative view of the full data distribution, violin plots were generated for each of the nine dependent variables across the eight experimental conditions, based on Location (Left/Right), Orientation (CW/CCW), and Task (Grasping/Placing). The violin plots use pooled data from all trials across participants within each condition, showing the density and spread of the data. These plots reveal the shape of the distribution for each variable, highlighting areas where data points are more concentrated versus where they are sparse, which helps in identifying multimodal distributions or skewness within each condition. By visualizing the full range of each variable, violin plots offer insights into how each DV varies across tasks and conditions, revealing potential patterns influenced by Location, Orientation, and Task Type.

2.3.4 Box Plot

Box plots were generated to display the distribution of subject-level medians for each condition, focusing on how each dependent variable (DV) varies across participants rather than individual trials. For each DV and condition, the median values from the 10 participants are presented, offering a concise summary of central tendencies and variability. The box plots include the median, interquartile range, and any outliers among the participant medians, which visually represents consistency or variability in participant responses under each condition. By focusing on participant medians, the box plots allow for a clear comparison of central tendencies across conditions, emphasizing general trends and differences in motor control related to Location, Orientation, and Task Type. Additionally, statistical analyses support these findings, quantifying differences between conditions and reinforcing trends observed in the box plot distributions.

2.3.5 ANOVA Results

A repeated-measures ANOVA was conducted to examine the main effects of Location (Left vs. Right), Orientation (CW vs. CCW), and Task (Grasping vs. Placing) on the nine movement-related variables. Additionally, two-way interactions (Location × Orientation, Location × Task, and Orientation × Task) and the three-way interaction (Location × Orientation × Task) were evaluated to understand how these factors jointly influenced the measured outcomes. This analysis was based on the median reaction time for each participant within each condition, allowing us to account for individual differences while focusing on overall trends across conditions.

Statistical Significance (p-Value)

Significance was assessed at a level of $p < 0.05$, with results below this threshold indicating statistically meaningful differences between conditions. This approach ensures that the likelihood of observed differences arising by chance is minimized to under 5%.

Degrees of Freedom (DFn and DFd)

In the ANOVA results, degrees of freedom are presented in two parts:

DFn (numerator degrees of freedom) reflects the number of groups or conditions being compared for a given factor or interaction.

DFd (denominator degrees of freedom) represents the variability within participants across conditions and is influenced by the number of participants and the repeated measures design.

For example, in a design with 10 participants, each tested in multiple conditions, DFn = 1 for each factor, and DFd = 9 (total participants - 1). These degrees of freedom values are used to compute the F-statistic for each effect.

F-Value

The F-value in ANOVA is a ratio of the variance explained by a specific effect (or interaction) relative to the variance not explained (error variance). Higher F-values indicate that the factor or interaction explains a larger portion of the variance in the dependent variable, increasing the likelihood that the effect is statistically significant. A larger F-value, combined with a p-value below 0.05, suggests a meaningful difference among conditions.

Effect Size ($\eta^2 p$)

In addition to p-values, partial eta-squared (η^2_p) is reported as a measure of effect size for each significant effect. Partial eta-squared quantifies the proportion of variance explained by each factor or interaction in relation to the total variance, allowing me to interpret the practical importance of each effect. Effect size interpretations follow standard benchmarks:

Small effect: $\eta^2 p \approx 0.01$

Medium effect: $\eta^2p \approx 0.06$

Large effect: $\eta^2p \geq 0.14$

These criteria help interpret whether significant effects are not only statistically meaningful but also practically relevant.

The repeated-measures ANOVA results identified key factors influencing each variable, offering insights into how Location, Orientation, and Task impact different aspects of movement, such as Reaction Time, Peak Velocity, and accuracy. Detailed results for each main effect and interaction are presented in the following chapter, including statistical significance, degrees of freedom, F-values, and effect size interpretations where applicable.

2.3.6 Post-Hoc Results

Following the significant findings from the ANOVA tests, post-hoc analyses using Tukey's HSD (Honest Significant Difference) were conducted to identify specific pairwise differences between conditions. These tests were crucial for determining which particular groups (e.g., Left vs. Right, CW vs. CCW) exhibited statistically significant differences, providing a detailed understanding of how each factor impacted movement performance. Tukey's HSD also controls for Type I errors that could arise from conducting multiple comparisons. The post-hoc analyses revealed key differences between specific conditions, such as differences between Left/Right locations and CW/CCW orientations. These findings offer a more granular understanding of how Location, Orientation, and Task interact to affect movement performance across different conditions.

3. Results

3.1 Results

The primary objective of this study was to investigate differences in performing grasp versus placement tasks across various conditions, including clockwise (CW) vs. counterclockwise (CCW) orientations and left vs. right locations. A vital component of the analysis was to determine whether there were significant variations in hand trajectories, as well as distribution patterns across the nine movement-related variables: Reaction Time, Peak Velocity, Peak Velocity Time, Movement Duration, Absolute Position Error, Orientation Error, Depth Error, Up-Down Error, and Horizontal Error. ,These variables provide insights into both the timing and accuracy of movements. All trials were processed using custom MATLAB software (MatLab R2023a, MathWorks), and trials that did not meet the predefined criteria (e.g., incorrect fixation or early movements) were excluded from the analysis.

3.1.1 Qualitative Hand Trajectory

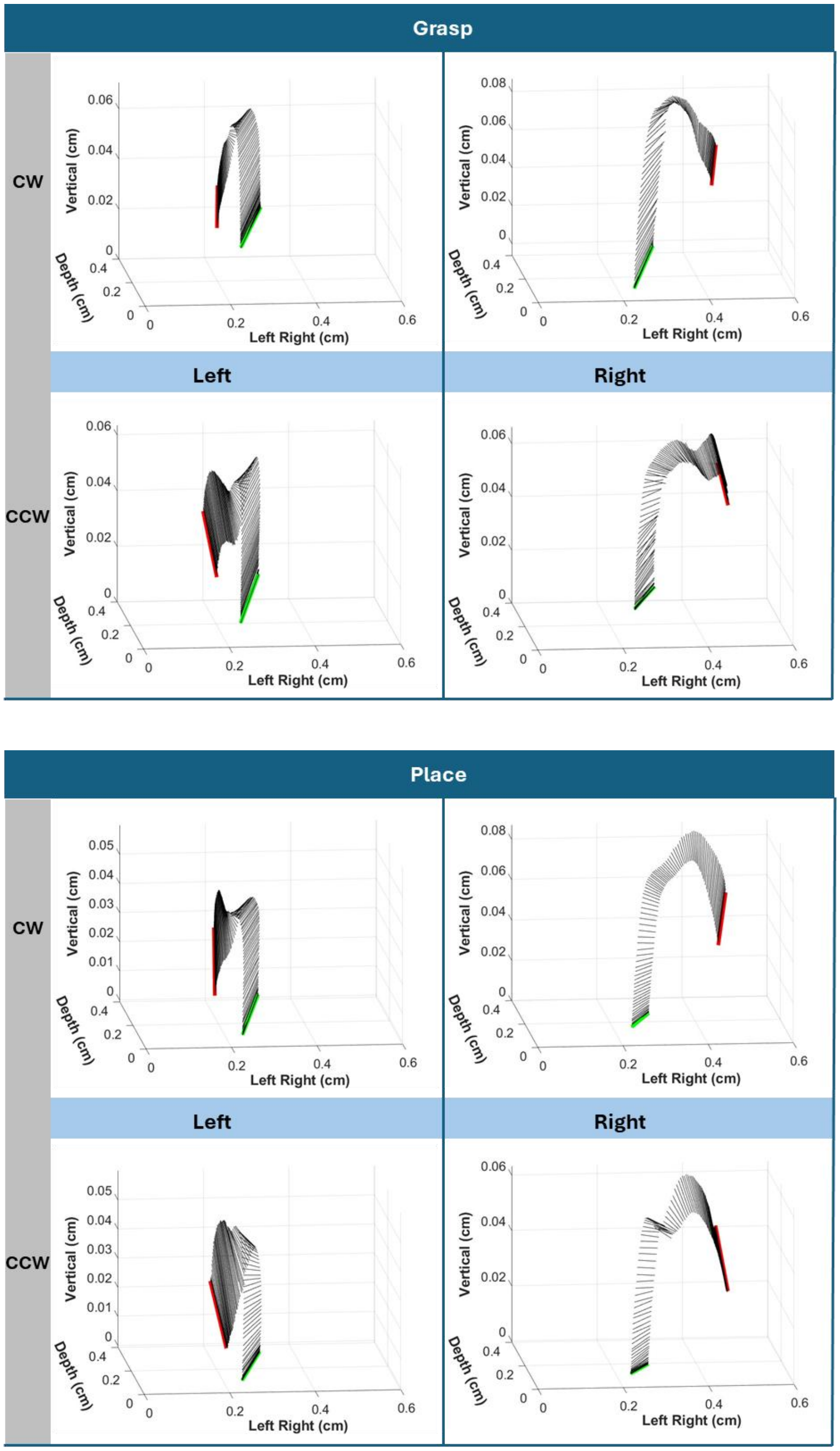

Figure 6. Typical hand trajectories for each of the 8 conditions during grasping and placing tasks, showing individual examples for each combination of target location (Left, Right) and orientation (CW, CCW). It consists of two blocks:

one for the Grasping task and one for the Placing task. The first block contains four graphs, all related to the Grasping task. The top row represents the CW orientation, with the Left location shown first, followed by the Right location. The bottom row represents the CCW orientation, again showing the Left location first, followed by the Right location. The second block contains four additional graphs for the Placing task, structured identically. The top row displays the CW orientation for Left and Right, and the bottom row shows the CCW orientation for Left and Right. Black lines depict the hand trajectory, with the green line representing the home position and the red line marking the hand's position right before contact.

The hand trajectory plots in Figure 6 show typical movement patterns from a single participant for grasping and placing tasks across CW and CCW orientations and Left and Right locations. Each trajectory illustrates the pathway from the initial to the final hand position for each task, with no averaging applied across trials. Each line represents the path of the finger-thumb pinch, starting from the initial position, with visible acceleration as the hand moves toward the target (indicated by the increasing distance between lines). The trajectory curves toward the target location and orientation, reflecting the controlled movement progression of each task.

In the Left Location with CW orientation, both grasping and placing tasks show a largely vertical trajectory with slight adjustments in depth and lateral positioning as the hand approaches the target. In the Right Location with CW orientation, the trajectory takes on a broader arc, reflecting the reach across to the right side.

The figure provides a qualitative overview, illustrating consistent shapes and directions across conditions. Although the general shapes of grasping and placing tasks appear similar, detailed conclusions about trajectory differences between tasks should be reserved for quantified analyses of reaction time, time to peak velocity, and orientation/location errors.

3.1.2 Analysis of “Reaction Time” Across Conditions

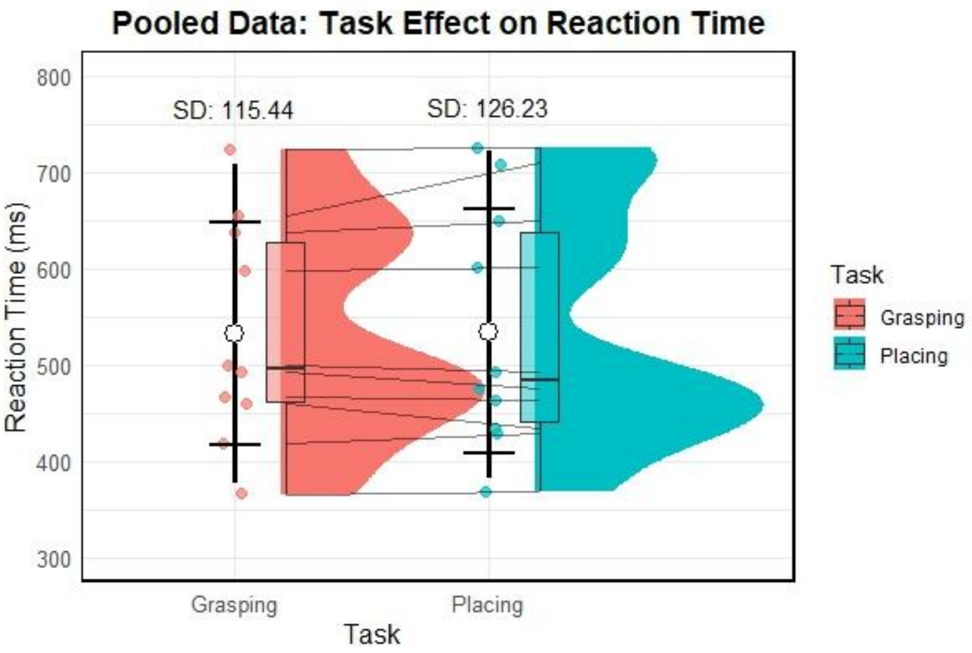

Figure 7. Reaction Time: Pooled Data for Grasping and Placing Tasks. This figure illustrates the distribution of reaction time (in ms) for grasping and placing tasks, aggregated across all participants (P1–P10). Each dot represents the mean reaction time for a single participant, with lines connecting the dots to highlight within-participant consistency across tasks. Red dots correspond to grasping tasks, while teal dots correspond to placing tasks. The half-violin plots display the density distribution of reaction time values, providing insight into the variability of reaction time for each task. The box plots represent the interquartile range (IQR), with the horizontal line inside each box indicating the median reaction time, and the black dot on each vertical black line showing the mean reaction time for the corresponding task group. Whiskers extend to the most extreme data points within 1.5 times the IQR. Standard deviations (SD) are represented by the vertical black lines extending above and below the means, providing a quantitative measure of variability in reaction time for each task.

Figure 7 illustrates the task effect on reaction time. The medians for both grasping and placing tasks, represented by the horizontal lines within the box plots, are at nearly identical levels. However, the mean values, shown as black dots, are slightly higher than the median lines for both tasks and are also nearly identical in value.

The violin plots reveal bimodal distributions for both grasping and placing tasks, suggesting two distinct clusters or peaks in reaction time among participants. This indicates variability in participant response patterns for both tasks. Despite the slight elevation of the mean values compared to the medians, the overall similarity in central tendencies suggests consistent reaction times across tasks.

The variability in reaction times is further captured by the standard deviation (SD) values, represented by the vertical black lines extending above and below the means. The SD for the grasping task is smaller compared to the placing task, indicating that reaction times for the grasping task are slightly less dispersed around the mean. In contrast, the placing task exhibits a larger SD, reflecting greater variability among participants. This highlights that while the central tendencies (mean and median) are similar, the distribution and spread of reaction times differ between the two tasks.

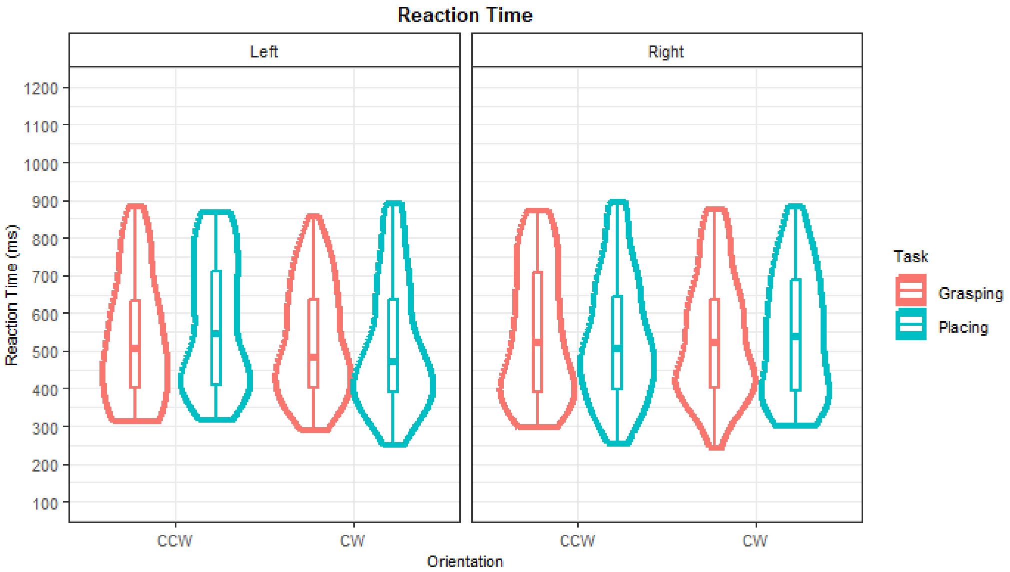

Figure 8. Distribution of “Reaction Time”. This figure presents the distribution of reaction times (in milliseconds) for grasping and placing tasks, segmented by movement direction (Left and Right) and task orientation (CW and CCW). The data are pooled across all participants and show the distribution of data around the median line, with wider sections indicating a higher density of reaction times. The left panel displays reaction times for movements directed to the left, and the right panel shows movements to the right.

Figure 8 shows that reaction times for grasping and placing tasks appear visually consistent across orientations (CW and CCW) and movement directions (Left and Right). Reaction times generally fall within a similar range for each orientation, with placing tasks showing a slightly broader spread and higher median values than grasping tasks. The observed patterns in reaction times across CW and CCW orientations and other conditions are further analyzed and quantified in the ANOVA results section.

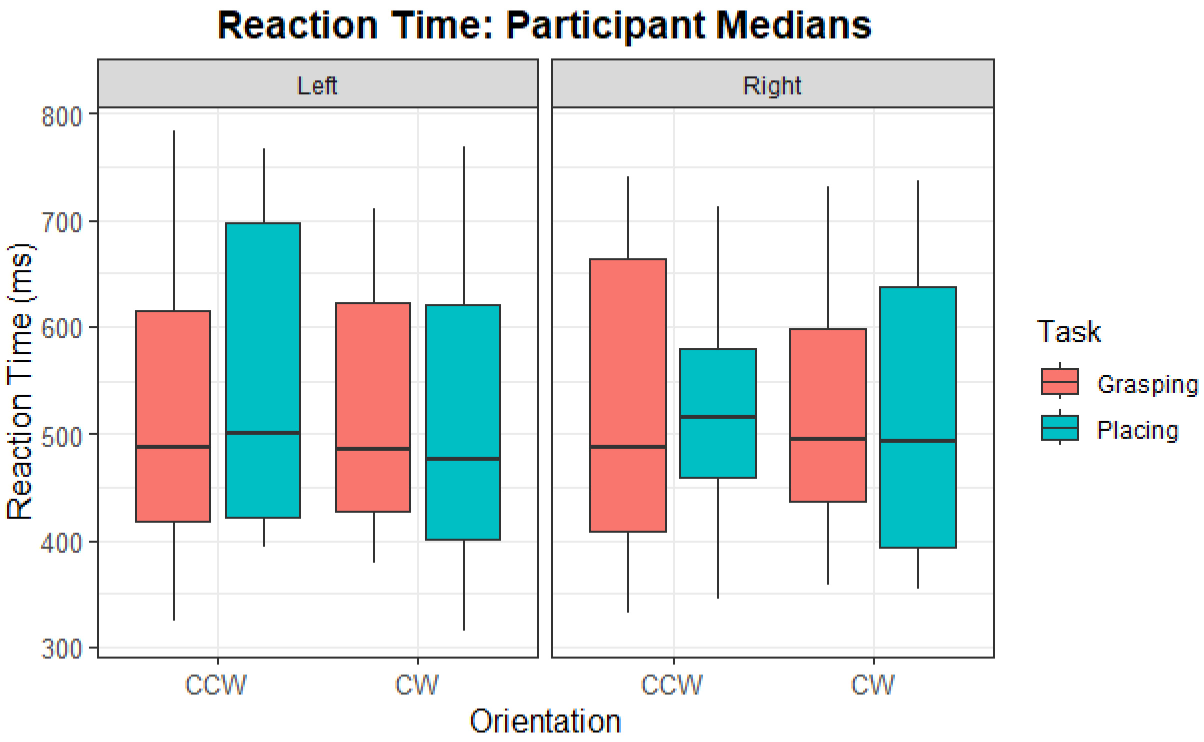

Figure 9. Reaction Time: Participant Medians for Grasping and Placing Tasks. This figure presents the distribution of reaction time (in milliseconds) for grasping and placing tasks across all participants (P1–P10), grouped by task condition and further segmented by Orientation (CCW, CW) and Location (Left, Right). Each box plot includes 10 data points, each representing the median reaction time of a single participant in a given condition. Red boxes indicate grasping, while teal boxes indicate placing. The horizontal line within each box denotes the median reaction time, showing the central tendency for each task condition. The upper and lower edges of each box represent the interquartile range (IQR). Whiskers extend to show the full range of reaction times within 1.5 times the IQR from the quartiles.

Figure 8 displays box plots of median reaction times for each participant across the different task conditions (Grasping and Placing), segmented by Orientation (CCW and CW) and Location (Left and Right). Each box represents the median reaction time of participants within each condition, providing a view of the distribution of subject medians rather than trial-level variability.

In the Left-CCW condition, placing tasks show a higher range and median reaction time than grasping tasks, with a broader distribution, indicating more variability. In the Left-CW condition, reaction times for placing and grasping are more similar, though placing tasks display a slightly wider range and start at a lower reaction time than grasping tasks.

For the Right-CCW condition, grasping tasks exhibit a notably broader range and lower reaction times compared to placing, which has a smaller range. In contrast, in the Right-CW condition, placing tasks have a wider range than grasping, with reaction times starting lower and extending higher than those observed in grasping.

These patterns suggest that reaction times differ based on both task type and specific condition combinations, with variability and median values influenced by both task demands (grasping vs. placing) and orientation/location combinations.

Table 1.ANOVA Results for Reaction Time: Main Effects and Interactions Among Location, Orientation, and Task

Interaction	**DFn**	**DFd**	**F value**	**p-value**	**η2p**
Location	1	9	0.248	0.631	0.027
Orientation	1	9	11.94	0.007	0.570
Task	1	9	1.23	0.297	0.120
Location:Orientation	1	9	1.92	0.198	0.176

Location:Task	1	9	0.60	0.458	0.063
Orientation:Task	1	9	3.41	0.277	0.130
Location:Orientation:Task	1	9	0.86	0.377	0.088

Table 1 presents the ANOVA results for reaction time, examining the main effects of Location, Orientation, and Task, as well as their interactions. Each effect is reported with its degrees of freedom (DFn and DFd), F-value, p-value, and partial eta-squared (η^2p), which provides a measure of effect size for each factor.

There was a significant main effect of Orientation on reaction time, F(1,9) = 11.94, p = 0.007, $\eta^2p = 0.570$, indicating that Orientation significantly influenced reaction times. No significant main effects were observed for Location, F(1,9) = 0.248, p = 0.631, $\eta^2p = 0.027$, or Task, F(1,9) = 1.23, p = 0.297, $\eta^2p = 0.120$ (see Table 10).

The interaction terms (Location × Orientation, Location × Task, Orientation × Task, and Location × Orientation × Task) were also not statistically significant (all p's > 0.10, see Table 10), indicating that the combined influence of these factors did not significantly impact reaction time in this analysis.

Since only the main effect of Orientation was significant, no post-hoc tests were necessary. Orientation consists of only two levels (Clockwise and Counterclockwise), and the ANOVA inherently compares these two groups. The significant result indicates a reliable difference in Reaction Time between the two orientations without requiring further pairwise testing.

3.1.3 Analysis of "Peak Velocity" Across Conditions

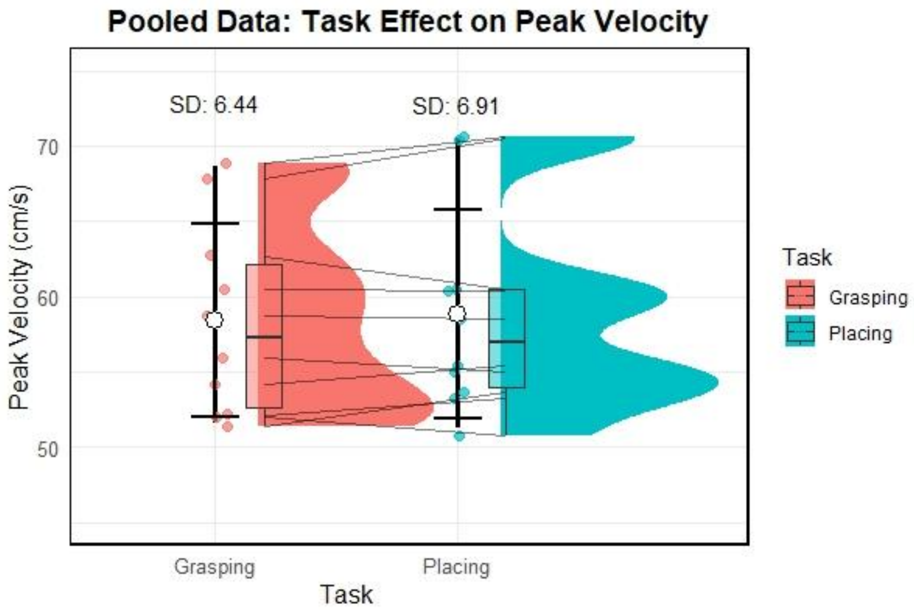

Figure 10. Peak Velocity: Pooled Data for Grasping and Placing Tasks. This figure illustrates the distribution of peak velocity (in cm/s) for grasping and placing tasks, aggregated across all participants (P1–P10). Each dot represents the mean peak velocity for a single participant, with lines connecting the dots to highlight within-participant consistency across tasks. Red dots correspond to grasping tasks, while teal dots correspond to placing tasks. The half-violin plots display the density distribution of peak velocity values, providing insight into the variability of peak velocity for each task. The box plots represent the interquartile range (IQR), with the horizontal line inside each box indicating the median peak velocity, and the black dot on each vertical black line showing the mean peak velocity for the corresponding task group. Whiskers extend to the most extreme data points within 1.5 times the IQR. Standard deviations (SD) are represented by the vertical black lines extending above and below the means, providing a quantitative measure of variability for each task.

Figure 10 illustrates the task effect on peak velocity. Both tasks, grasping and placing, exhibit comparable median values, as indicated by the horizontal lines within the box plots. Similarly, the mean values, represented by the white dots, are at slightly higher levels than the median lines for both tasks and are nearly identical in value.

The violin plots for both grasping and placing tasks demonstrate multimodal distributions, indicating multiple clusters or peaks in the data. These patterns suggest variability in peak velocity across participants for both tasks. The variability in peak velocity is further captured by the standard deviation (SD) values, represented by the vertical black lines extending above and below the means. The SD for the grasping task is slightly smaller compared to the placing task, reflecting a tighter distribution of peak velocity values around the mean for grasping. In contrast, the placing task shows a marginally larger SD, indicating slightly more variability among participants.

Despite these differences in variability, the overall similarity in central tendencies between tasks highlights consistency in peak velocity performance across conditions.

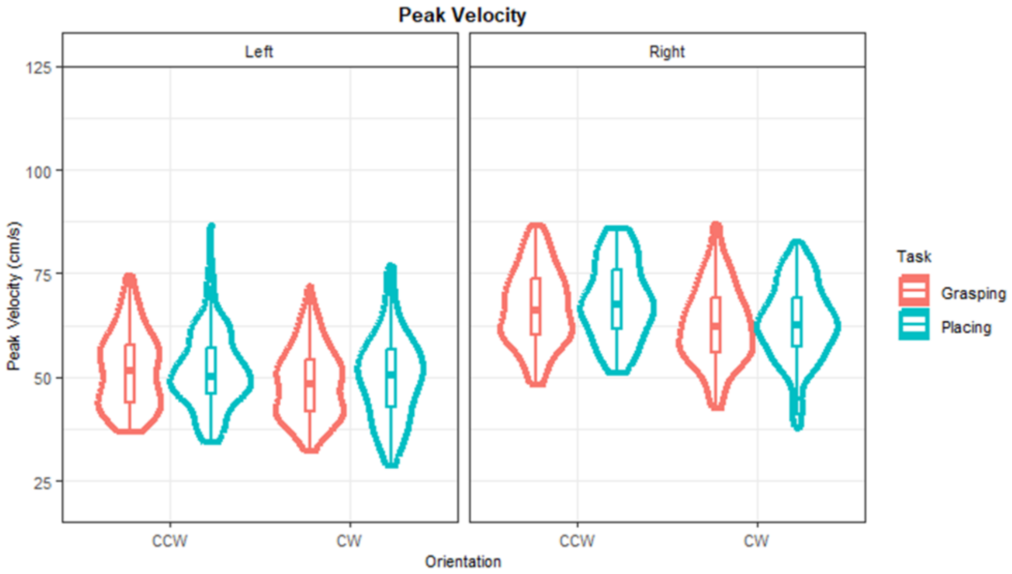

Figure 11. Distribution of "Peak Velocity". This figure presents the distribution of Peak Velocity (in cm/s) for grasping and placing tasks, segmented by movement direction (Left and Right) and task orientation (CW and CCW). The data are pooled across all participants and show the distribution of data around the median line, with wider sections indicating a higher density of reaction times. The left panel displays movements directed to the left, and the right panel shows movements to the right.

Figure 11 shows Peak Velocity has a clear difference between the left and right locations. In the right location, the densities for both grasping and placing tasks are fairly consistent across CW and CCW orientations, with most data concentrated between 50 and 85 cm/s. In the left location, the density distributions for CCW grasping and placing are more spread out, especially for placing tasks, which show a broader range of velocities. The violin plots reveal a higher concentration of values just below the median in some tasks, indicating where most of the data points are clustered. The overall shape suggests a similar distribution pattern across both locations and orientations, with placing tasks in the left location under CCW showing more variability in peak velocities.

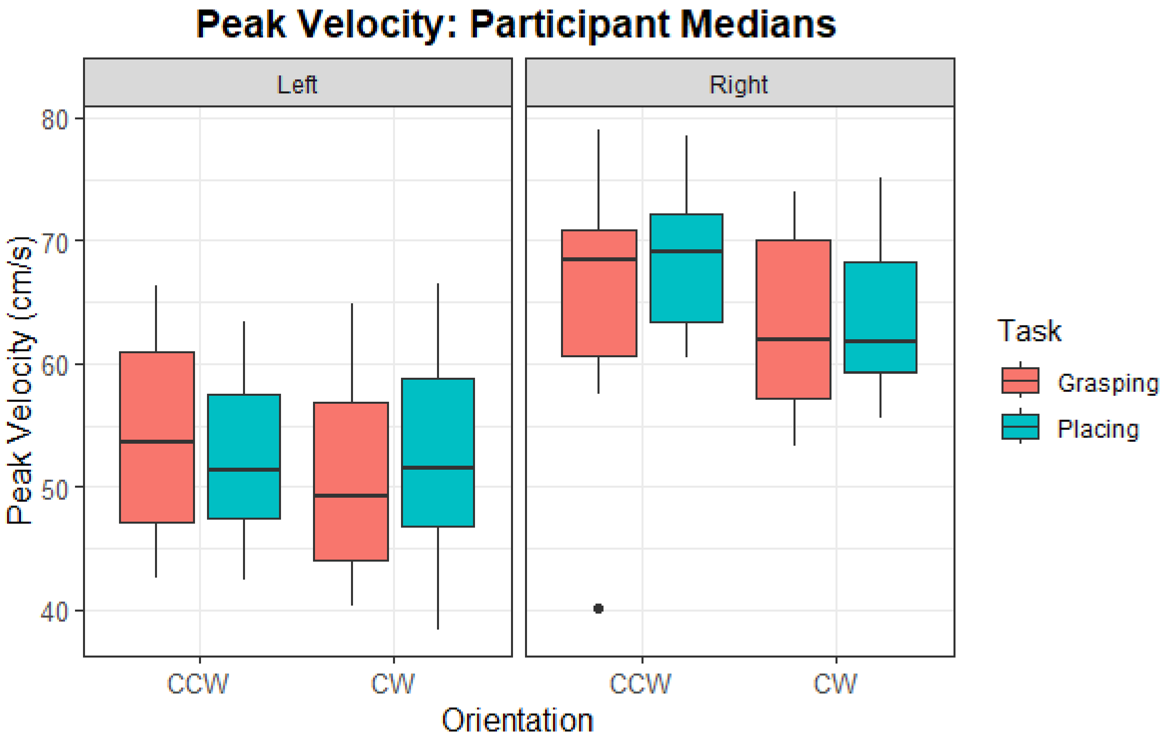

Figure 12. Peak Velocity: Participant Medians for Grasping and Placing Tasks. This figure presents the distribution of peak velocity (in cm/s) for grasping and placing tasks across all participants (P1–P10), grouped by task condition and further segmented by Orientation (CCW, CW) and Location (Left, Right). Each box plot includes 10 data points, each representing the median peak velocity of a single participant in a given condition. Red boxes indicate grasping, while teal boxes indicate placing. The horizontal line within each box denotes the median peak velocity, showing the central tendency for each task condition. The upper and lower edges of each box represent the interquartile range (IQR). Whiskers extend to show the full range of peak velocity within 1.5 times the IQR from the quartiles.

Figure 12 displays box plots of median peak velocities for each participant across the different task conditions (Grasping and Placing), segmented by Orientation (CCW and CW) and

Location (Left and Right). Each box represents the median peak velocity for participants within each condition, providing a view of the distribution of participant medians rather than trial-level variability.

In the Left-CCW condition, grasping tasks exhibit a slightly wider distribution with higher peak velocities compared to placing tasks, whose distribution is narrower and lower. In the Left-CW condition, both grasping and placing tasks show similar variability, though placing tasks have a slightly higher median peak velocity.

For the Right-CCW condition, grasping and placing tasks display similar ranges, with the box lengths nearly equal, but placing tasks are positioned just slightly higher in peak velocity. In the Right-CW condition, grasping tasks have a wider distribution however has the same peak velocities.

Across both CCW and CW Orientations, the Right Location exhibits consistently higher peak velocities than the Left Location for both tasks (Grasping and Placing). The hand movement to the Right Location involves a longer distance from the home position compared to the Left Location. This increased distance likely allows participants to accelerate more, resulting in higher peak velocities when moving to the Right.

Table 2. ANOVA Results for Peak Velocity: Main Effects and Interactions Among Location, Orientation, and Task

Interaction	**DFn**	**DFd**	**F value**	**p-value**	**η2p**
Location	1	9	32.27	$3.01e^{-10}$	0.78
Orientation	1	9	2.97	0.12	0.24
Task	1	9	1.83	0.21	0.17

Location:Orientation	1	9	0.88	0.37	0.08
Location:Task	1	9	1.64	0.23	0.15
Orientation:Task	1	9	0.03	0.87	0.003
Location:Orientation:Task	1	9	2.99	0.12	0.25

Table 2 presents the ANOVA results for peak velocity, examining the main effects of Location, Orientation, and Task, as well as their interactions. Degrees of freedom for each effect are denoted by DFn (numerator) and DFd (denominator), while F-values, p-values, and partial eta-squared (η^2_p) values indicate the strength, significance, and effect size of each factor.

A significant main effect of Location on peak velocity was observed, $F(1,9) = 32.27$, $p = 3.01 \times 10^{-10}$, $\eta^2p = 0.78$. This large effect size suggests that Location accounts for a substantial portion of the variance in peak velocity. No significant main effects were observed for Orientation, $F(1,9) = 2.97$, $p = 0.12$, $\eta^2p = 0.24$, or Task, $F(1,9) = 1.83$, $p = 0.21$, $\eta^2p = 0.17$ (see Table 11).

Additionally, none of the interaction effects (Location × Orientation, Location × Task, Orientation × Task, and Location × Orientation × Task) reached statistical significance, with all p-values exceeding 0.10 (see Table 11). The partial eta-squared values for these interactions indicate small to medium effect sizes, suggesting a limited impact of combined factors on peak velocity.

Since only the main effect of Location was significant, no post-hoc tests were necessary. Location consists of only two levels (Left and Right), and the ANOVA inherently compares these two groups. The significant result indicates a reliable difference in Peak Velocity between the two locations without requiring further pairwise testing.

3.1.4 Analysis of "Peak Velocity Time" Across Conditions

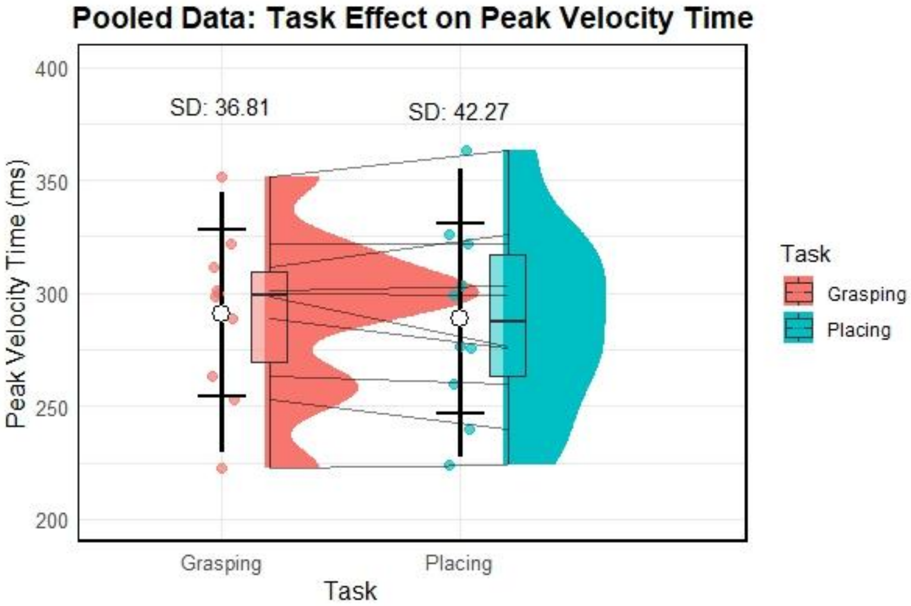

Figure 13. Peak Velocity Time: Pooled Data for Grasping and Placing Tasks. This figure illustrates the distribution of peak velocity time (in ms) for grasping and placing tasks, aggregated across all participants (P1–P10). Each dot represents the mean peak velocity time for a single participant, with lines connecting the dots to highlight within-participant consistency across tasks. Red dots correspond to grasping tasks, while teal dots correspond to placing tasks. The half-violin plots display the density distribution of peak velocity time values, providing insight into the variability of peak velocity time for each task. The box plots represent the interquartile range (IQR), with the horizontal line inside each box indicating the median peak velocity time, and the black dot on each vertical black line showing the mean peak velocity time for the corresponding task group. Whiskers extend to the most extreme data points within 1.5 times the IQR. Standard deviations (SD) are represented by the vertical black lines extending above and below the means, providing a quantitative measure of variability for each task.

Figure 13 illustrates the distribution of peak velocity time for grasping and placing tasks. In grasping tasks, the median (horizontal line inside the box plot) is the highest among all markers, while the mean (white dot) is positioned below the median. For placing tasks, the median and mean are at nearly the same level, and both are aligned with the mean of grasping tasks, all of which are noticeably below the median for grasping.

The violin plot for grasping tasks reveals a multimodal distribution with multiple peaks, indicating variability in participants' performance. In contrast, placing tasks show a more concentrated, single-peaked distribution, reflecting more consistent performance across participants. The variability in peak velocity time is further captured by the standard deviation (SD) values, represented by the vertical black lines extending above and below the means. The SD for the grasping task is 36.81 ms, indicating moderate variability, while the SD for the placing task is 42.27 ms, reflecting slightly higher variability in participant performance for placing.

This figure demonstrates that placing tasks generally result in lower and more consistent peak velocity times, whereas grasping tasks exhibit higher variability, with a distribution where the median exceeds both its own mean and the corresponding markers for placing tasks.

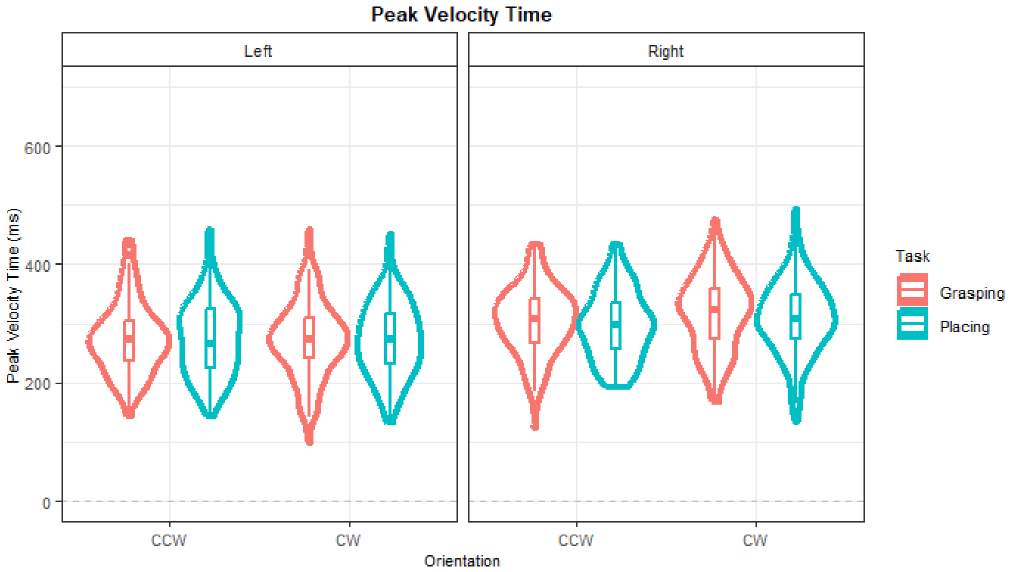

Figure 14. Distribution of "Peak Velocity Time". This figure presents the distribution of Peak Velocity Time (in milliseconds) for grasping and placing tasks, segmented by movement direction (Left and Right) and task orientation (CW and CCW). The data are pooled across all participants and show the distribution of data around the median line,

with wider sections indicating a higher density of reaction times. The left panel displays movements directed to the left, and the right panel shows movements to the right.

Figure 14 shows the distribution of Peak Velocity Time across different locations (left and right) and orientations (CW and CCW). The data appear fairly symmetrically distributed for both grasping and placing tasks. Most distributions show a relatively normal pattern, with a concentration of data points around the median. The density of the data in many conditions is highest around the middle, but the peak of the distribution slightly varies between grasping and placing. Some outliers are visible, especially on the left side, but overall, the distributions reflect consistency in the peak velocity time across locations and orientations.

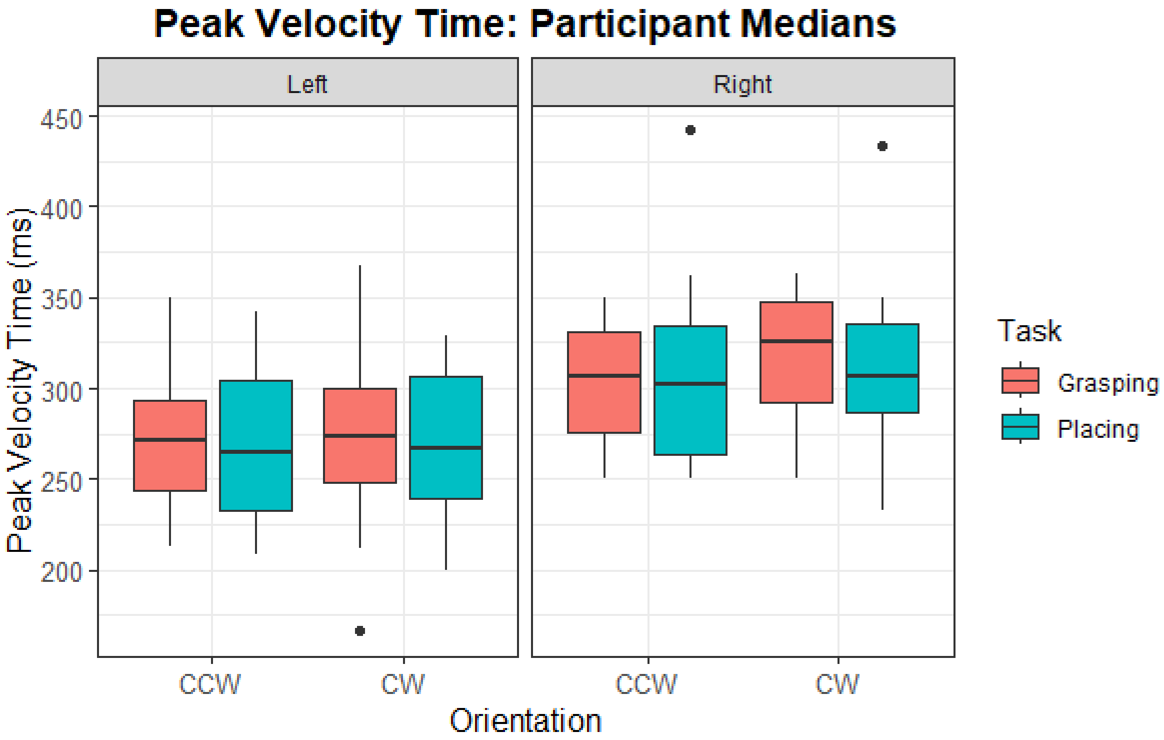

Figure 15. Peak Velocity Time: Participant Medians for Grasping and Placing Tasks. This figure presents the distribution of peak velocity time (in ms) for grasping and placing tasks across all participants (P1–P10), grouped by task condition and further segmented by Orientation (CCW, CW) and Location (Left, Right). Each box plot includes 10 data points,

each representing the median peak velocity time of a single participant in a given condition. Red boxes indicate grasping, while teal boxes indicate placing. The horizontal line within each box denotes the median peak velocity time, showing the central tendency for each task condition. The upper and lower edges of each box represent the interquartile range (IQR). Whiskers extend to show the full range of peak velocity time within 1.5 times the IQR from the quartiles.

Figure 15 displays box plots of median peak velocity time for each participant across the different task conditions (Grasping and Placing), segmented by Orientation (CCW and CW) and Location (Left and Right). Each box represents the median peak velocity time for participants within each condition, offering a view of participant medians rather than trial-level variability.

In the Left-CCW condition, placing tasks show a slightly wider range and a higher median peak velocity time compared to grasping tasks. For the Left-CW condition, placing tasks again exhibit a slightly wider distribution and a marginally higher median than grasping tasks, though the difference is minor.

In the Right-CCW condition, placing tasks have a slightly wider range, but the maximum values for both tasks are nearly equal, suggesting a similar upper limit for peak velocity time in this orientation. In the Right-CW condition, both grasping and placing tasks display similar ranges, though grasping tasks have a slightly higher median peak velocity time.

eak Velocity Time is generally higher in the Right Location compared to the Left Location across both orientations (CCW and CW) and tasks (Grasping and Placing). This aligns with the finding that Peak Velocity is also higher at the Right Location, which likely reflects the longer movement distance to the Right Location allowing participants to reach peak velocity later in the movement.

Table 3. ANOVA Results for Peak Velocity Time: Main Effects and Interactions Among Location, Orientation, and Task

Interaction	**DFn**	**DFd**	**F value**	**p-value**	**η2p**
Location	1	9	30.63	0.00036	0.77
Orientation	1	9	0.39	0.55	0.04
Task	1	9	0.015	0.91	0.001
Location:Orientation	1	9	0.53	0.49	0.06
Location:Task	1	9	0.02	0.88	0.029
Orientation:Task	1	9	0.27	0.61	0.030
Location:Orientation:Task	1	9	0.28	0.61	0.29

Table 3 displays box plots of median peak velocity time for each participant across the different task conditions (Grasping and Placing), segmented by Orientation (CCW and CW) and Location (Left and Right). Each box represents the median peak velocity time for participants within each condition, offering a view of participant medians rather than trial-level variability.

A significant main effect of Location on peak velocity was observed, F(1,9) = 30.63, p = 0.00036, η^2p = 0.77. This large effect size suggests that Location accounts for a substantial portion of the variance in peak velocity. No significant main effects were observed for Orientation, F(1,9) = 0.39, p = 0.55, η^2p = 0.04, or Task, F(1,9) = 0.01, p = 0.91, η^2p = 0.001 (see Table 12).

Additionally, none of the interaction effects (Location × Orientation, Location × Task, Orientation × Task, and Location × Orientation × Task) reached statistical significance, with all p-values exceeding 0.10 (see Table 12). The partial eta-squared values for these interactions indicate small to medium effect sizes, suggesting a limited impact of combined factors on peak velocity.

Since only the main effect of Location was significant, no post-hoc tests were necessary. Location consists of only two levels (Left and Right), and the ANOVA inherently compares these two groups. The significant result indicates a reliable difference in Peak Velocity Time between the two locations without requiring further pairwise testing.

3.1.5 Analysis of "Movement Duration" Across Conditions

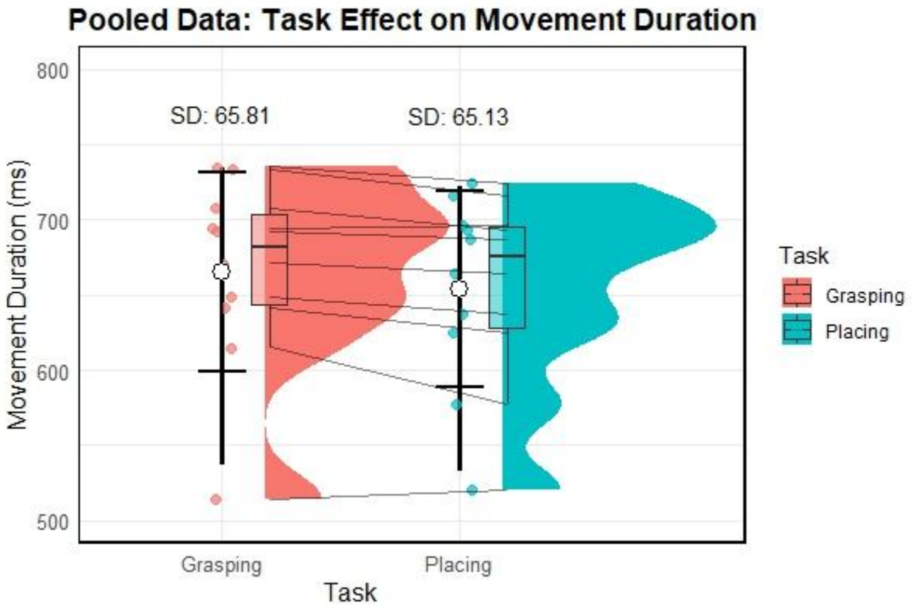

Figure 16. Movement Duration: Pooled Data for Grasping and Placing Tasks. This figure illustrates the distribution of movement duration (in ms) for grasping and placing tasks, aggregated across all participants (P1–P10). Each dot represents the mean movement duration for a single participant, with lines connecting the dots to highlight within-participant consistency across tasks. Red dots correspond to grasping tasks, while teal dots correspond to placing tasks. The half-violin plots display the density distribution of movement duration values, providing insight into the variability of movement for each task. The box plots represent the interquartile range (IQR), with the horizontal line inside each box indicating the median movement duration, and the black dot on each vertical black line showing the mean movement duration for the corresponding task group. Whiskers extend to the most extreme data points within 1.5 times the IQR. Standard deviations (SD) are represented by the vertical black lines extending above and below the means, providing a quantitative measure of variability for each task.

Figure 16 shows the movement duration for grasping and placing tasks. Both tasks display comparable medians and means, with the medians (horizontal lines inside the box plots) positioned slightly higher than the means (white dots on the vertical lines) in both tasks. This consistent positioning suggests that the data for both tasks are slightly skewed, as the means are influenced by lower values.

The violin plot for placing tasks exhibits a multimodal distribution, with multiple peaks indicating distinct clusters of movement duration within this task. In contrast, the violin plot for grasping tasks shows a smoother, less clustered distribution, reflecting a more uniform spread of movement duration values across participants. The variability in movement duration is represented by the standard deviation (SD) values, shown as vertical black lines extending above and below the means. Both tasks have similar SDs, with grasping showing an SD of 65.81 ms and placing showing an SD of 65.13 ms, indicating comparable variability in movement duration across tasks.

Despite the observed distribution differences, the overall central tendency for both tasks, as indicated by the medians and means, remains similar, highlighting comparable movement durations across tasks.

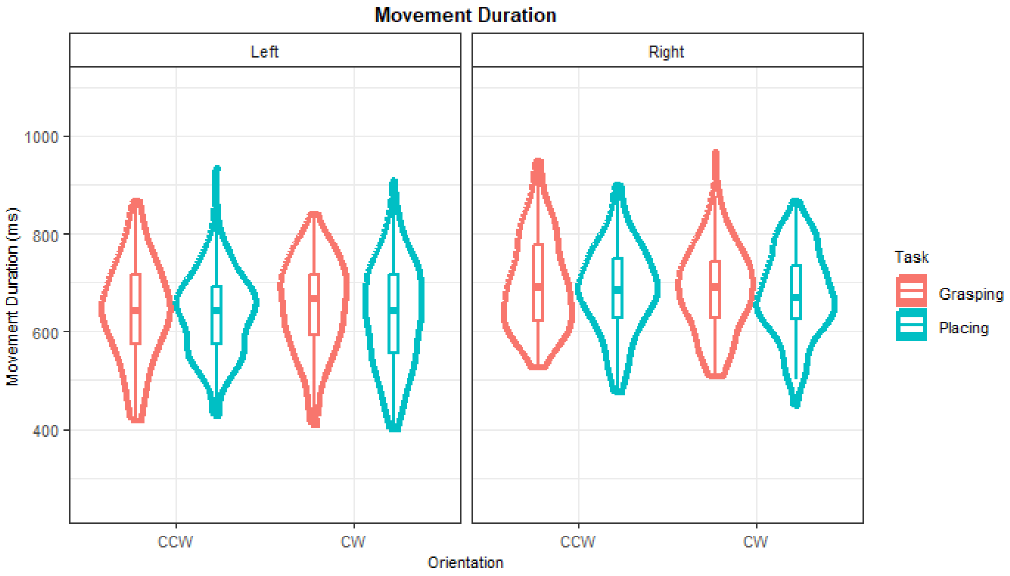

Figure 17. Distribution of “Movement Duration. This figure presents the distribution of Movement Duration (in milliseconds) for grasping and placing tasks, segmented by movement direction (Left and Right) and task orientation (CW and CCW). The data are pooled across all participants and show the distribution of data around the median line, with wider sections indicating a higher density of reaction times. The left panel displays movement duration for movements directed to the left, and the right panel shows movements to the right.

Figure 17 shows the distribution of Movement Duration across different locations (left and right) and orientations (CW and CCW). For both grasping and placing tasks, the data is relatively symmetrically distributed with a notable concentration around the median values, especially in the CCW condition. There are no substantial differences between the left and right locations, although placing tasks on the left location in CW orientation exhibit a slightly wider distribution, indicating more variability.

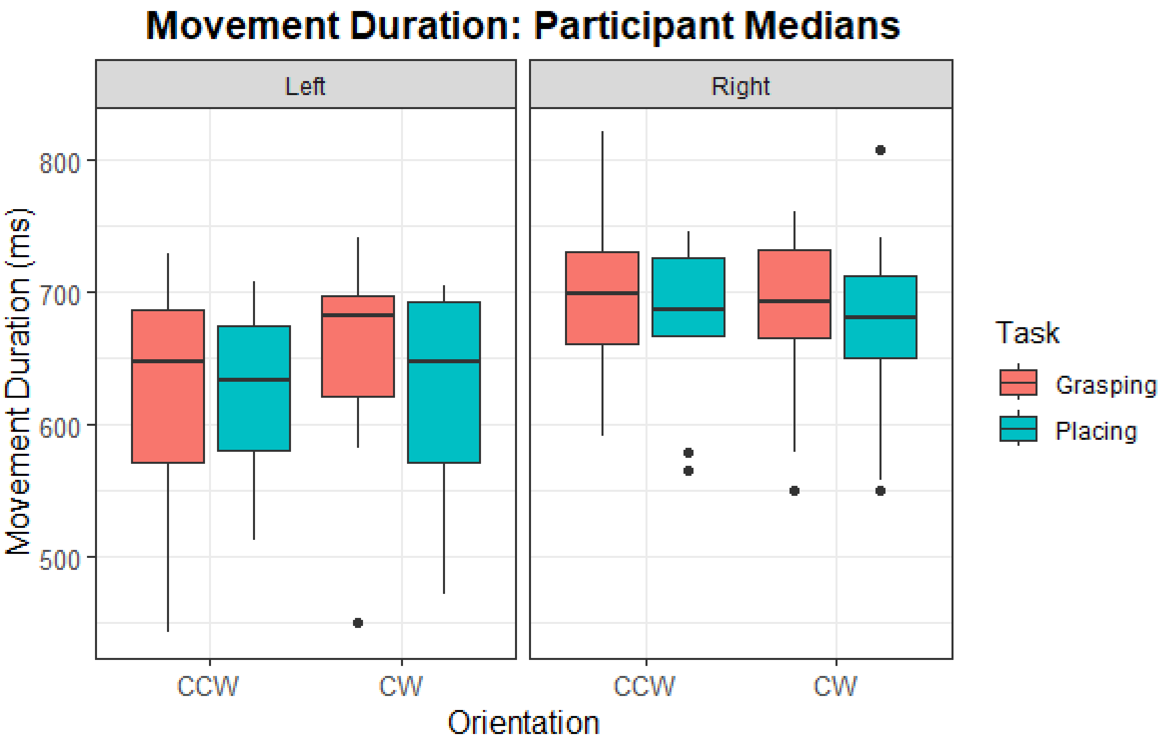

Figure 18. Movement Duration: Participant Medians for Grasping and Placing Tasks. This figure presents the distribution of peak velocity (in cm/s) for grasping and placing tasks across all participants (P1–P10), grouped by task condition and further segmented by Orientation (CCW, CW) and Location (Left, Right). Each box plot includes 10 data points, each representing the median movement duration of a single participant in a given condition. Red boxes indicate grasping, while teal boxes indicate placing. The horizontal line within each box denotes the median movement duration, showing the central tendency for each task condition. The upper and lower edges of each box represent the interquartile range (IQR). Whiskers extend to show the full range of movement duration within 1.5 times the IQR from the quartiles.

Figure 18 displays box plots of median movement duration for each participant across the different task conditions (Grasping and Placing), segmented by Orientation (CCW and CW) and Location (Left and Right). Each box represents the median movement duration for participants within each condition, providing a view of participant-level variability.

In the Left-CCW condition, grasping tasks exhibit a slightly wider range and higher median movement duration compared to placing tasks, though the values are generally similar. For the Left-CW condition, grasping and placing tasks reach similar upper bounds, but placing tasks show a wider range, indicating greater variability. The median for Grasping is higher than for Placing.

In the Right-CCW condition, both grasping and placing tasks have comparable ranges and upper limits, suggesting similar movement durations across these tasks. In the Right-CW condition, the ranges are similar as well, with grasping tasks displaying a slightly higher median than placing tasks.

Movement Duration is slightly longer in the Right Location compared to the Left Location, with this trend consistent across orientations (CCW and CW) and tasks (Grasping and Placing). This finding aligns with the longer movement distance to the Right Location, which likely increases the time required to complete the movement. Variability is more noticeable in the Left Location, particularly in CW Orientation.

Table 4. ANOVA Results for Movement Duration: Main Effects and Interactions Among Location, Orientation, and Task

Interaction	**DFn**	**DFd**	**F value**	**p-value**	**η2p**
Location	1	9	17.62	0.002	0.66
Orientation	1	9	0.007	0.93	0.0007
Task	1	9	5.65	0.04	0.39
Location:Orientation	1	9	6.36	0.03	0.41
Location:Task	1	9	0.01	0.92	0.001
Orientation:Task	1	9	0.55	0.48	0.06
Location:Orientation:Task	1	9	4.53	0.06	0.33

Table 4 presents the ANOVA results for movement duration, examining the main effects of Location, Orientation, and Task, as well as their interactions. Degrees of freedom for each effect are denoted by DFn (numerator) and DFd (denominator), while F-values, p-values, and partial eta-squared (η^2_p) values indicate the strength, significance, and effect size of each factor.

A significant main effect of Task was found, F(1,9) = 5.65, p = 0.04, η^2p = 0.39, idicating that movement duration differs between grasping and placing tasks with grasp longer movement duration than place. Additionally, a significant main effect of Location on movement duration was observed, F(1,9) = 17.62, p = 0.0023, η^2p = 0.66. This large effect size suggests that Location accounts for a substantial portion of the variance in movement duration. Furthermore, a significant interaction effect was found for Location × Orientation, F(1,9) = 6.36, p = 0.033, η^2p = 0.41. This interaction suggests that the effect of Location on movement duration is influenced by Orientation, indicating that the combined influence of Location and Orientation plays a meaningful role in determining movement duration.

No other interaction effects (Location × Task, Orientation × Task, or Location × Orientation × Task) were significant, as all p-values for these interactions exceeded 0.05 (see Table 13). The partial eta-squared values for these non-significant interactions indicate small effect sizes, suggesting limited impact of these combined factors on movement duration.

Since the main effects of Location and Task were significant, no post-hoc tests were necessary for these factors because each consists of only two levels (Location: Left and Right; Task: Grasping and Placing). The ANOVA inherently compares these two groups and indicates reliable differences without requiring further pairwise testing.

For the Location × Orientation interaction, post-hoc Tukey HSD tests were conducted to identify specific pairwise differences; however, no comparisons reached statistical significance after FDR adjustment. This suggests that while the ANOVA detected a significant interaction effect, the overall difference may not be strongly localized to specific pairwise comparisons.

The lack of significant post-hoc results may be attributed to the conservative nature of FDR correction, which reduces sensitivity to detect pairwise differences, especially with a reduced dataset. The ANOVA was conducted using the medians of each participant's trials, resulting in 10 values (one per participant per variable), which inherently limits statistical power for post-hoc tests. Despite the absence of significant pairwise differences, the ANOVA trends highlight the overall influence of Location, Task, and Location × Orientation on Movement Duration, though the findings should be interpreted cautiously given the methodological limitations.

3.1.6 Analysis of "Absolute Position Error" Across Conditions

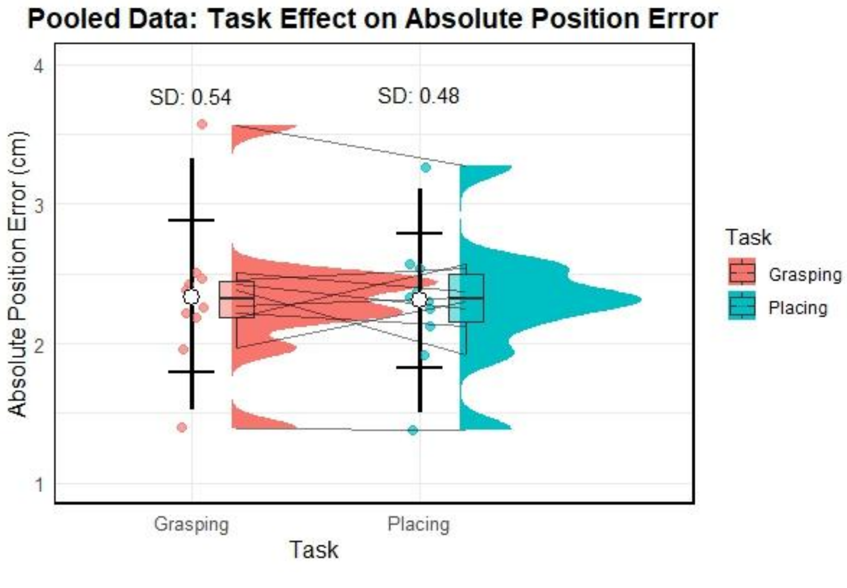

Figure 19. Absolute Position Error: Pooled Data for Grasping and Placing Tasks. This figure illustrates the distribution of absolute position error (in cm) for grasping and placing tasks, aggregated across all participants (P1–P10). Each dot

represents the mean absolute position error for a single participant, with lines connecting the dots to highlight within-participant consistency across tasks. Red dots correspond to grasping tasks, while teal dots correspond to placing tasks. The half-violin plots display the density distribution of absolute position error values, providing insight into the variability of errors for each task. The box plots represent the interquartile range (IQR), with the horizontal line inside each box indicating the median absolute position error, and the black dot on each vertical black line showing the mean absolute position error for the corresponding task group. Whiskers extend to the most extreme data points within 1.5 times the IQR. Standard deviations (SD) are represented by the vertical black lines extending above and below the means, providing a quantitative measure of variability for each task.

Figure 19 illustrates the absolute position error for grasping and placing tasks. The medians and means for both tasks are closely aligned, as shown by the horizontal lines inside the box plots (medians) and the white dots on the vertical lines (means). This alignment indicates comparable central tendencies for absolute position error across tasks.

The violin plots reveal multimodal distributions for both tasks, with distinct peaks visible at the upper and lower ends of the distribution. Notably, the presence of outlier points in both tasks, located at the top and bottom extremes, suggests greater variability among participants in specific trials. The variability is further captured by the standard deviation (SD) values, represented by the vertical black lines extending above and below the means. The grasping task exhibits an SD of 0.54 cm, slightly higher than the placing task's SD of 0.48 cm, indicating marginally greater variability in grasping.

Despite the slightly broader variability in grasping tasks, the overall similarity in medians, means, and central tendencies highlights consistent absolute position error across both tasks.

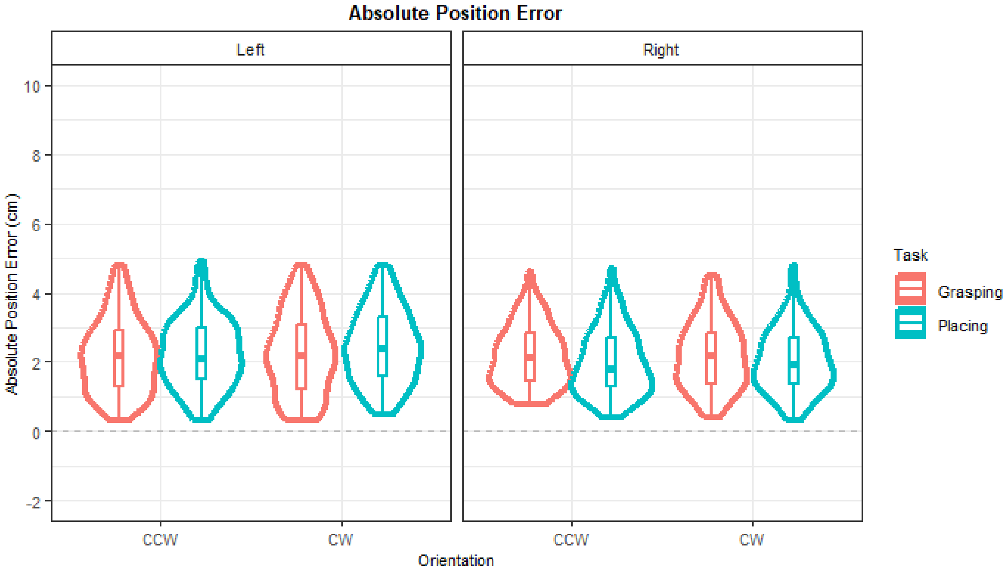

Figure 20. Distribution of "Absolute Position Error". This figure presents the distribution of Absolute Position Error (in cm) for grasping and placing tasks, segmented by movement direction (Left and Right) and task orientation (CW and CCW). The data are pooled across all participants and show the distribution of data around the median line, with wider sections indicating a higher density of reaction times. The left panel displays movements directed to the left, and the right panel shows movements to the right.

Figure 20 shows the distribution of Absolute Position Error across different locations (left and right) and orientations (CW and CCW). The violin plot illustrates a relatively symmetrical distribution for both grasping and placing tasks. Most conditions demonstrate a normal-like pattern, with the majority of the data points concentrated around the median. A slightly broader distribution of errors in the left CW condition for placing tasks suggests more variability in those movements. Overall, the right location exhibits a more consistent distribution across both tasks and orientations, while the left location shows slightly more significant variation, especially in placing tasks.

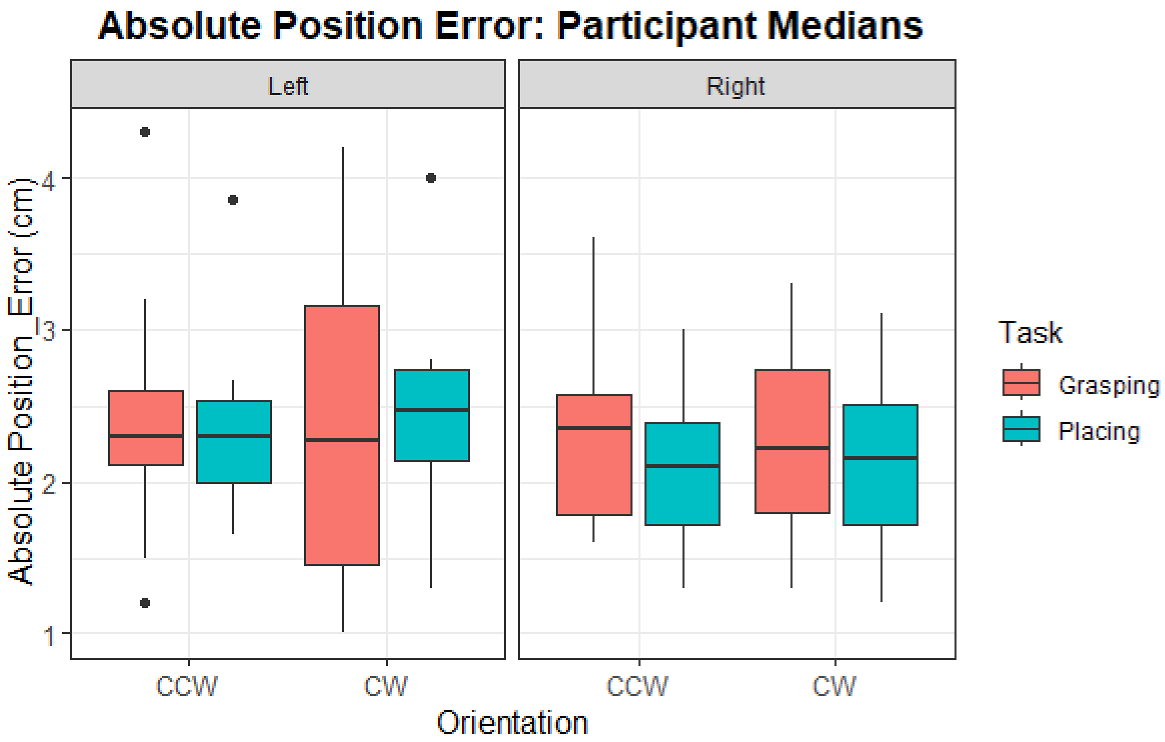

Figure 21. Absolute Position Error: Participant Medians for Grasping and Placing Tasks. This figure presents the distribution of absolute position error (in cm) for grasping and placing tasks across all participants (P1–P10), grouped by task condition and further segmented by Orientation (CCW, CW) and Location (Left, Right). Each box plot includes 10 data points, each representing the median absolute position error of a single participant in a given condition. Red boxes indicate grasping, while teal boxes indicate placing. The horizontal line within each box denotes the absolute position error, showing the central tendency for each task condition. The upper and lower edges of each box represent the interquartile range (IQR). Whiskers extend to show the full range of absolute position error within 1.5 times the IQR from the quartiles.

Figure 21 displays box plots of median absolute position error (in cm) for each participant across different task conditions (Grasping and Placing), segmented by Orientation (CCW and CW) and Location (Left and Right). Each box represents the median absolute position error for participants within each condition, providing an overview of participant-level variability.

In the Left-CCW condition, both grasping and placing tasks exhibit similar ranges, though grasping tasks have a slightly higher median absolute position error than placing tasks. In the Left-CW condition, grasping tasks show a much wider range but lower median compared to placing tasks, which have a narrower range. A few outliers are present, extending the upper range for grasping tasks.

For the Right-CCW condition, grasping and placing tasks display similar ranges, with grasping tasks having a slightly higher median. In the Right-CW condition, both tasks again show comparable ranges, but grasping tasks tend to have higher median values than placing tasks. These patterns suggest that grasping tasks generally result in slightly higher absolute position errors, particularly in the leftward orientations, indicating some variability in accuracy between grasping and placing tasks across orientations and locations.

Table 5. ANOVA Results for Absolute Position Error: Main Effects and Interactions Among Location, Orientation, and Task

Interaction	**DFn**	**DFd**	**F value**	**p-value**	**η2p**
Location	1	9	0.58	0.47	0.06
Orientation	1	9	0.001	0.97	0.0001
Task	1	9	1.47	0.26	0.14
Location:Orientation	1	9	0.11	0.74	0.012
Location:Task	1	9	3.45	0.09	0.28
Orientation:Task	1	9	0.94	0.36	0.09
Location:Orientation:Task	1	9	$3.7e^{-5}$	0.99	$4.1e^{-6}$

Table 5 displays box plots of median absolute position error for each participant across the different task conditions (Grasping and Placing), segmented by Orientation (CCW and CW) and Location (Left and Right). Each box represents the median absolute position error for participants within each condition, offering a view of participant medians rather than trial-level variability.

The ANOVA results for Absolute Position Error revealed no statistically significant main effects or interactions. The main effects of Location F(1,9) = 0.58, p = 0.47, $\eta^2 p$ = 0.06, Orientation, F(1,9) = 0.001, p = 0.97, $\eta^2 p$ = 0.0001, and Task, F(1,9) = 1.47, p = 0.26, $\eta^2 p$ = 0.14, were not statistically significant (see Table 14).

Similarly, all interaction effects (Location × Orientation, Location × Task, Orientation × Task, and Location × Orientation × Task) were non-significant, with p-values well above 0.05. These findings suggest that none of the factors (Location, Orientation, Task) or their combinations have a meaningful impact on absolute position error in this analysis.

The repeated-measures ANOVA for Absolute Position Error did not identify any significant main effects or interactions, as all p-values were greater than 0.05. Since the ANOVA did not reveal any overall significant differences, there was no need to conduct post-hoc pairwise comparisons. This result indicates that neither Location, Orientation, Task, nor their interactions had a statistically significant influence on Absolute Position Error in this analysis.

3.1.7 Analysis of “Depth Error” Across Conditions

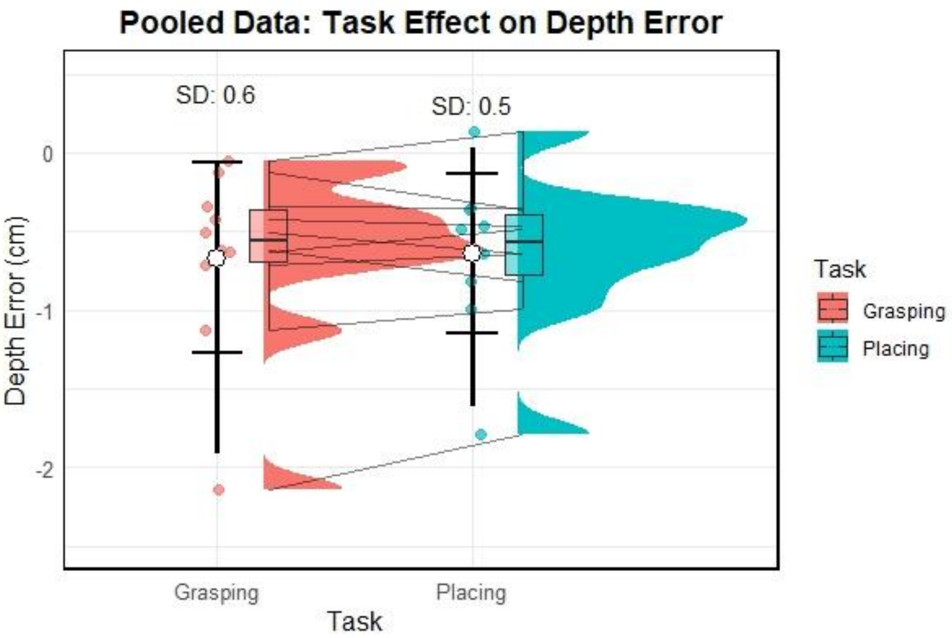

Figure 22. Depth Error: Pooled Data for Grasping and Placing Tasks. This figure illustrates the distribution of depth error (in cm) for grasping and placing tasks, aggregated across all participants (P1–P10). Each dot represents the mean depth error for a single participant, with lines connecting the dots to highlight within-participant consistency across tasks. Red dots correspond to grasping tasks, while teal dots correspond to placing tasks. The half-violin plots display the density distribution of depth error values, providing insight into the variability of errors for each task. The box plots represent the interquartile range (IQR), with the horizontal line inside each box indicating the median depth error, and the black dot on each vertical black line showing the mean depth error for the corresponding task group. Whiskers extend to the most extreme data points within 1.5 times the IQR. Standard deviations (SD) are represented by the vertical black lines extending above and below the means, providing a quantitative measure of variability for each task.

Figure 22 illustrates the depth error for grasping and placing tasks, with both tasks showing very similar medians and means, as indicated by the horizontal lines inside the box plots (medians) and the white dots on the vertical lines (means). This alignment reflects consistency in central tendency across tasks.

The violin plots for both tasks highlight bimodal distributions, suggesting two distinct clusters in depth error across conditions. The variability in depth error is further captured by the standard deviation (SD) values, represented by the vertical black lines extending above and below the means. The SD for the grasping task is 0.6 cm, slightly higher than the placing task's

SD of 0.5 cm, indicating marginally greater variability in grasping.

Despite the small difference in variability, the overall alignment of medians and means and the comparable spread of the distributions reinforce the similarity in performance for depth error across both tasks.

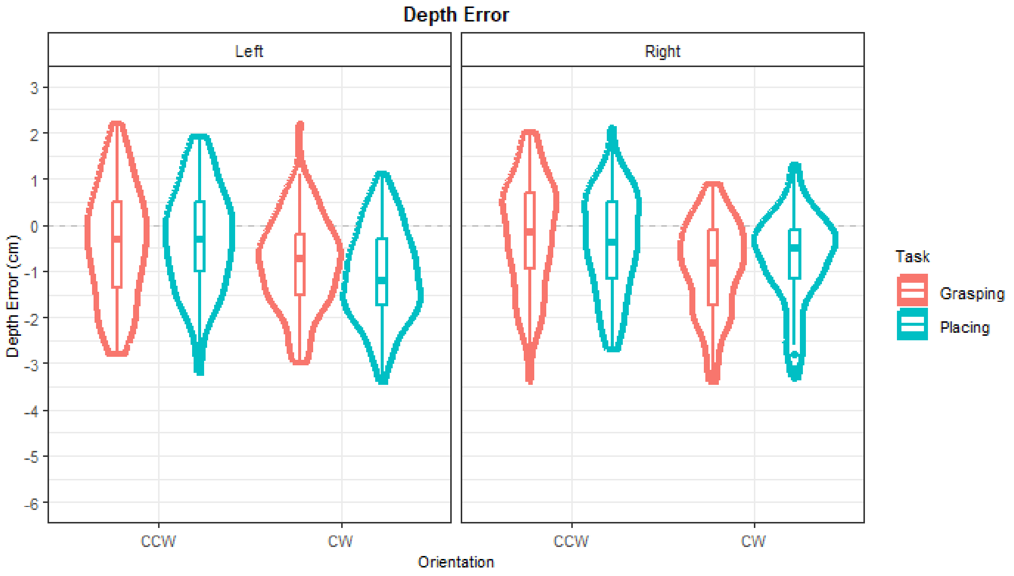

Figure 23. Distribution of "Depth Error". This figure presents the distribution of Depth Error (in cm) for grasping and placing tasks, segmented by movement direction (Left and Right) and task orientation (CW and CCW). The data are pooled across all participants and show the distribution of data around the median line, with wider sections indicating a higher density of reaction times. The left panel displays movements directed to the left, and the right panel shows movements to the right.

Figure 23 show the violin plot for a range of undershoot and overshoot deviations from the calibrated position. On the left side, there is a noticeable variation between the tasks for CW orientation, with placing tasks showing slightly larger errors while grasping tasks are more centered around zero. In contrast, the right side displays more symmetrical distributions, particularly for placing tasks, where errors are closer to zero, suggesting less deviation in these movements. The density peaks for both grasping and placing tasks reveal a higher concentration of movements around zero error, indicating more accurate placement. However, some wider distributions in certain conditions, particularly for grasping on the right side, show greater variability. Overall, the depth error distribution reflects a consistent pattern across conditions, with minor variations in how grasping and placing tasks deviate from the calibrated depth position.

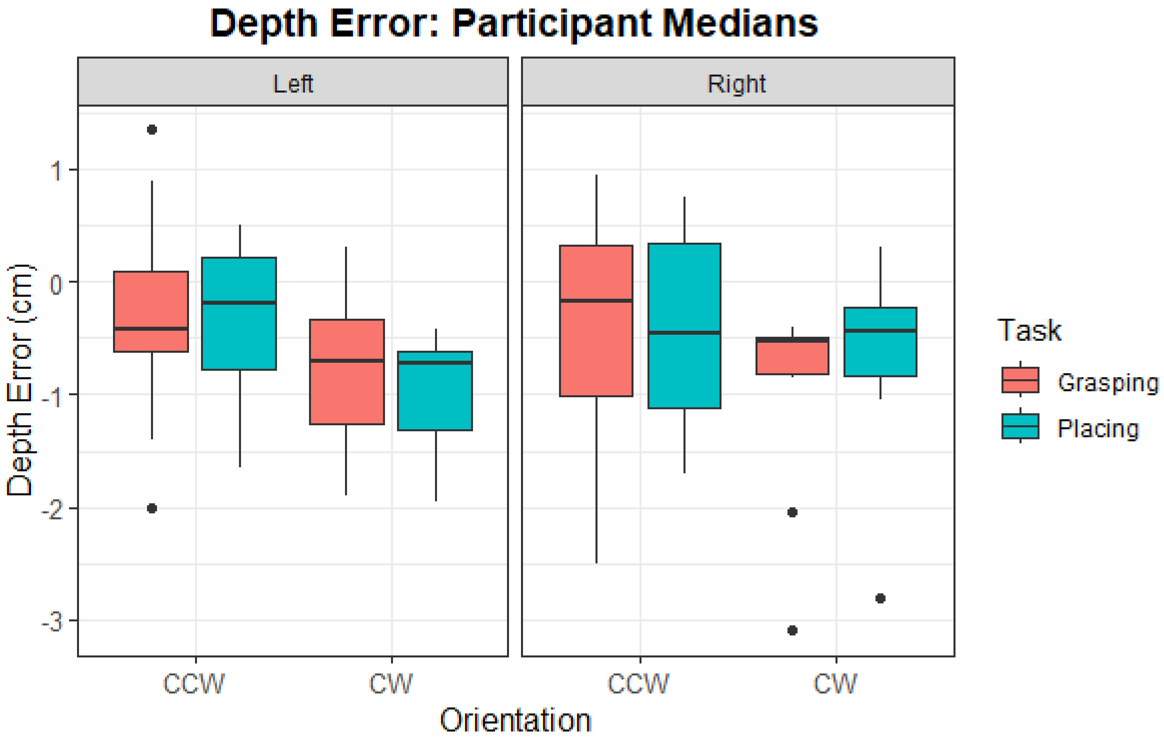

Figure 24. Depth Error: Participant Medians for Grasping and Placing Tasks. This figure presents the distribution of depth error (in cm) for grasping and placing tasks across all participants (P1–P10), grouped by task condition and further segmented by Orientation (CCW, CW) and Location (Left, Right). Each box plot includes 10 data points, each representing the median depth error of a single participant in a given condition. Red boxes indicate grasping, while teal boxes indicate placing. The horizontal line within each box denotes the median depth error, showing the central tendency for each task condition. The upper and lower edges of each box represent the interquartile range (IQR). Whiskers extend to show the full range of depth error within 1.5 times the IQR from the quartiles.

Figure 24 displays box plots of median depth error for each participant across different task conditions (Grasping and Placing), segmented by Orientation (CCW and CW) and Location (Left and Right). Each box represents the median depth error for participants within each condition, providing a view of participant-level variability in depth accuracy.

In the Left-CCW condition, placing tasks exhibit a wider range and slightly upper median depth error compared to placing tasks. For the Left-CW condition, both grasping and placing tasks have similar ranges and similar median depth errors.

In the Right-CCW condition, grasping and placing tasks have similar ranges and median values, suggesting consistent depth errors across these tasks. In the Right-CW condition, placing tasks exhibit a wider range and higher median depth error compared to grasping tasks, indicating more variability and a greater upward shift in depth error for placing.

These patterns suggest that depth error varies slightly between grasping and placing tasks, particularly in specific orientation and location combinations, with placing tasks occasionally showing wider ranges or higher medians in certain conditions.

Table 6. ANOVA Results for Depth Error: Main Effects and Interactions Among Location, Orientation, and Task

Interaction	**DFn**	**DFd**	**F value**	**p-value**	**η2p**
Location	1	9	0.01	0.91	0.001
Orientation	1	9	4.73	0.05766	0.34
Task	1	9	0.33	0.58	0.04
Location:Orientation	1	9	0.40	0.54	0.04
Location:Task	1	9	3.53	0.09	0.28
Orientation:Task	1	9	0.03	0.87	0.002
Location:Orientation:Task	1	9	2.24	0.17	0.20

Table 6 displays box plots of median depth error for each participant across the different task conditions (Grasping and Placing), segmented by Orientation (CCW and CW) and Location (Left and Right). Each box represents the median peak velocity time for participants within each condition, offering a view of participant medians rather than trial-level variability.

The ANOVA results for Depth Error revealed no statistically significant main effects or interactions. The main effects of Location F(1,9) = 0.01, p = 0.91, $\eta^2 p = 0.001$, Orientation, F(1,9) = 4.73, p = 0.05766, $\eta^2 p = 0.34$, and Task, F(1,9) = 0.33, p = 0.58, $\eta^2 p = 0.04$,were all non-significant.

Similarly, all interaction effects (Location × Orientation, Location × Task, Orientation × Task, and Location × Orientation × Task) were non-significant, with p-values exceeding 0.05. These findings indicate that none of the individual factors (Location, Orientation, Task) or their combinations have a meaningful influence on depth error in this analysis.

The repeated-measures ANOVA for Depth Error did not identify any significant main effects or interactions, as all p-values were greater than 0.05. Since the ANOVA did not reveal any overall significant differences, there was no need to conduct post-hoc pairwise comparisons. This result indicates that neither Location, Orientation, Task, nor their interactions had a statistically significant influence on Depth Error in this analysis.

3.1.8 Analysis of “Up Down Error” Across Conditions

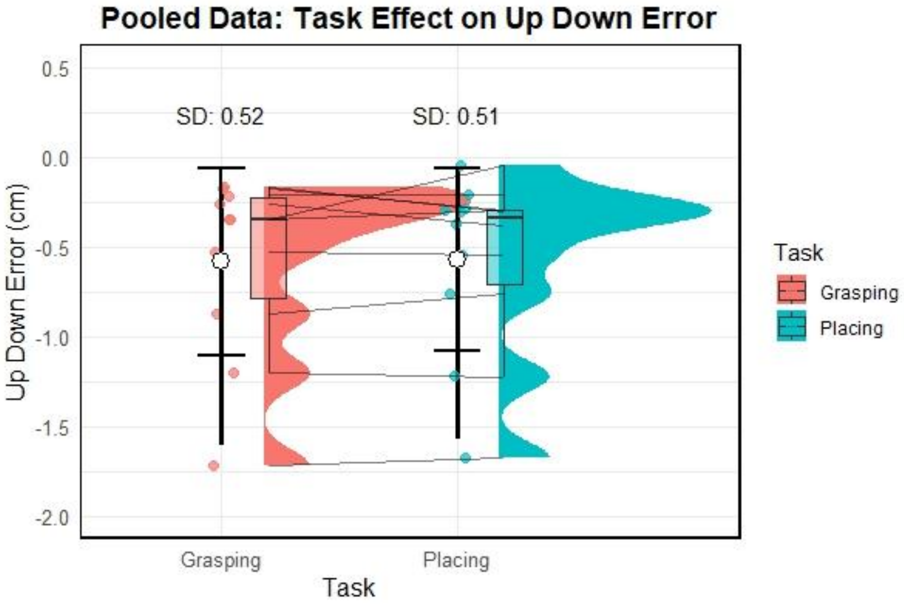

Figure 25. Up Down Error: Pooled Data for Grasping and Placing Tasks. This figure illustrates the distribution of up down error (in cm) for grasping and placing tasks, aggregated across all participants (P1–P10). Each dot represents the mean up down error for a single participant, with lines connecting the dots to highlight within-participant consistency across tasks. Red dots correspond to grasping tasks, while teal dots correspond to placing tasks. The half-violin plots display the density distribution of up down error values, providing insight into the variability of errors for each task. The box plots represent the interquartile range (IQR), with the horizontal line inside each box indicating the median up down error, and the black dot on each vertical black line showing the mean up down error for the corresponding task group. Whiskers extend to the most extreme data points within 1.5 times the IQR. Standard deviations (SD) are represented by the vertical black lines extending above and below the means, providing a quantitative measure of variability for each task.

The results illustrated in Figure 25 show the up-down error for grasping and placing tasks, with both tasks displaying similar medians and means. While the medians for both tasks are aligned, the white dots (means) are positioned slightly lower on the negative axis compared to the median lines, indicating a subtle downward skew in the distribution of up-down errors.

The violin plots reveal multiple peaks in the density distributions for both grasping and placing tasks, highlighting variability in participant performance across conditions. The variability is further quantified by the standard deviation (SD) values, represented by the vertical black lines extending above and below the means. The SD for grasping is 0.52 cm, which is comparable to the placing task's SD of 0.51 cm, reflecting similar variability across tasks.

These observations suggest that although the central tendencies (mean and median) are similar, the positioning of the means below the medians highlights a slight asymmetry in the distribution of vertical positioning errors for both tasks.

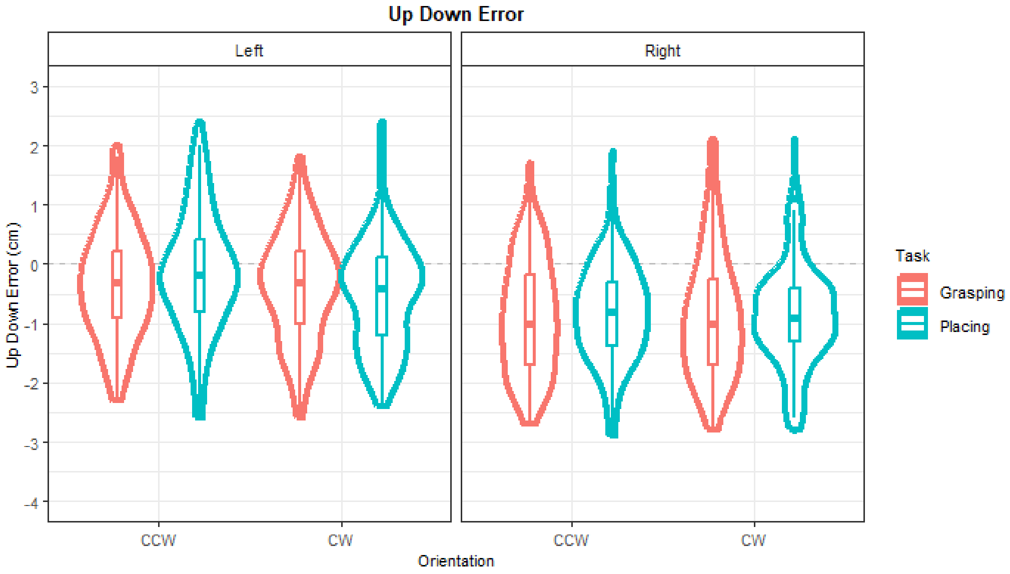

Figure 26. Distribution of "Up Down Error". This figure presents the distribution of Up Down Error (in cm) for grasping and placing tasks, segmented by movement direction (Left and Right) and task orientation (CW and CCW). The data are pooled across all participants and show the distribution of data around the median line, with wider sections indicating a higher density of reaction times. The left panel displays movements directed to the left, and the right panel shows movements to the right.

Figure 26 shows the violin plot for Up Down Error and the data appears relatively symmetrically distributed, with the median generally centered near 0 cm, indicating that participants, on average, had minimal vertical deviations from the calibrated location. This suggests that participants were relatively accurate in controlling their movements in the vertical direction, though some variability is present. A few outliers are visible, particularly on the right side for CW orientation, showing instances where participants deviated more significantly from the calibrated position.

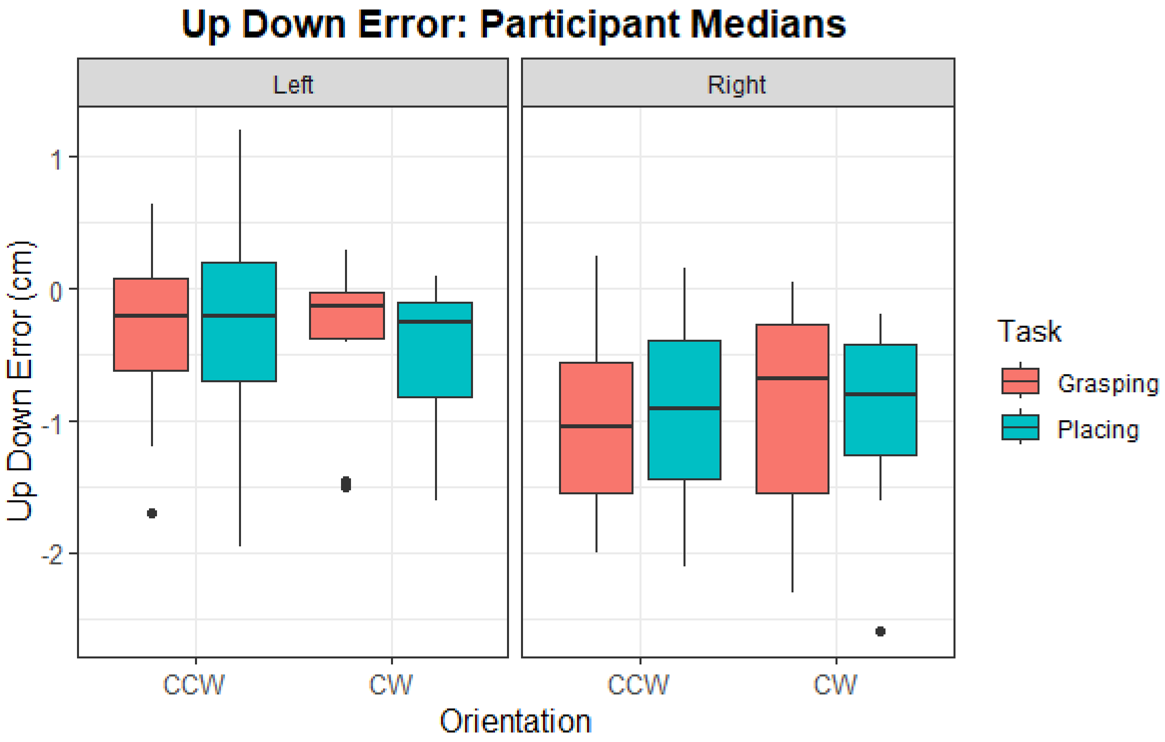

Figure 27. Up Down Error: Participant Medians for Grasping and Placing Tasks. This figure presents the distribution of up down (in cm) for grasping and placing tasks across all participants (P1–P10), grouped by task condition and further segmented by Orientation (CCW, CW) and Location (Left, Right). Each box plot includes 10 data points, each representing the median up down of a single participant in a given condition. Red boxes indicate grasping, while teal boxes indicate placing. The horizontal line within each box denotes the median up down, showing the central tendency for each task condition. The upper and lower edges of each box represent the interquartile range (IQR). Whiskers extend to show the full range of up down within 1.5 times the IQR from the quartiles.

Figure 27 displays box plots of median up-down error for each participant across different task conditions (Grasping and Placing), segmented by Orientation (CCW and CW) and Location (Left and Right). Each box represents the median up-down error for participants within each condition, providing a view of participant-level variability in vertical positioning accuracy.

In the Left-CCW condition, placing tasks exhibit a wider range in comparison to grasping tasks but similar median in both tasks. For the Left-CW condition, placing tasks show a notably wider range, while grasping tasks have a narrower range. However, both tasks have a similar upper range limit.

For the Right-CCW condition, both grasping and placing tasks have comparable ranges, though placing tasks have slightly higher median. In the Right-CW condition, grasping tasks display a wider range and higher upper limit than placing tasks.

Up Down Error shows lower medians in the Right Location compared to the Left Location, indicating greater vertical error in movements to the Right. However, the Right Location also exhibits wider interquartile ranges, suggesting greater variability in performance. In contrast, the Left Location displays higher medians with narrower variability, particularly in the CW Orientation, reflecting less consistent but more precise movements.

Table 7. ANOVA Results for Up Down Error: Main Effects and Interactions Among Location, Orientation, and Task

Interaction	**DFn**	**DFd**	**F value**	**p-value**	**η2p**
Location	1	9	8.64	0.016	0.49
Orientation	1	9	0.04	0.83	0.005
Task	1	9	0.16	0.69	0.02
Location:Orientation	1	9	0.18	0.68	0.02
Location:Task	1	9	0.03	0.87	0.003
Orientation:Task	1	9	2.57	0.14	0.22
Location:Orientation:Task	1	9	0.25	0.63	0.03

Table 7 displays box plots of median up down for each participant across the different task conditions (Grasping and Placing), segmented by Orientation (CCW and CW) and Location (Left and Right). Each box represents the median up-down error for participants within each condition, offering a view of participant medians rather than trial-level variability.

A significant main effect of Location on up down was observed, F(1,9) = 8.64, p = 0.016, η2p = 0.49. This moderate to large effect size suggests that Location accounts for a notable portion of the variance in up-down error, with one location showing consistently higher or lower vertical positioning errors compared to the other. No significant main effects were observed for Orientation, F(1,9) = 0.04, p = 0.84, η2p = 0.004, or Task, F(1,9) = 0.16, p = 0.69, η2p = 0.02 (see Table 16).

Similarly, none of the interaction effects (Location × Orientation, Location × Task, Orientation × Task, and Location × Orientation × Task) were statistically significant, as all p-values exceeded 0.05 (see Table 16). These non-significant results indicate the minimal impact of combined factors on up-down error.

Since the main effect of Location was significant, no post-hoc tests were necessary. Location consists of only two levels (Left and Right), and the ANOVA inherently compares these two groups. The significant result indicates a reliable difference in Up-Down Error between the two locations without requiring further pairwise testing.

3.1.9 Analysis of “Horizontal Error” Across Conditions

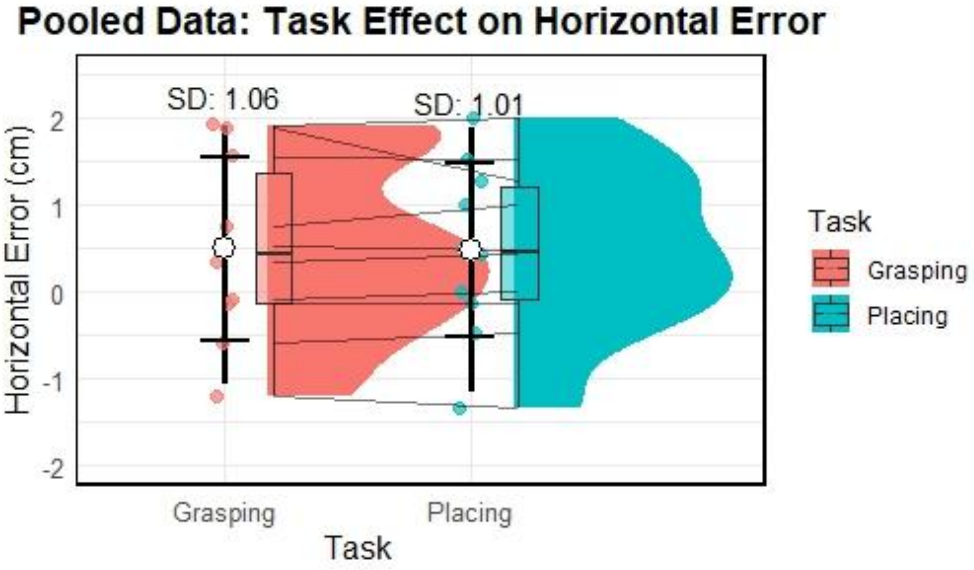

Figure 28. Horizontal Error: Pooled Data for Grasping and Placing Tasks. This figure illustrates the distribution of horizontal error (in cm) for grasping and placing tasks, aggregated across all participants (P1–P10). Each dot represents the mean horizontal error for a single participant, with lines connecting the dots to highlight within-participant consistency across tasks. Red dots correspond to grasping tasks, while teal dots correspond to placing tasks. The half-violin plots display the density distribution of horizontal error values, providing insight into the variability of errors for each task. The box plots represent the interquartile range (IQR), with the horizontal line inside each box indicating the median horizontal error, and the black dot on each vertical black line showing the mean horizontal error for the corresponding task group. Whiskers extend to the most extreme data points within 1.5 times the IQR. Standard deviations (SD) are represented by the vertical black lines extending above and below the means, providing a quantitative measure of variability for each task.

The results illustrated in Figure 28 show the horizontal error for grasping and placing tasks, with both tasks displaying similar medians and means, as indicated by the alignment of the horizontal line inside the box plots (median) and the white dots on the vertical lines (mean).

The violin plots highlight distinct differences in the density distribution of errors. Grasping tasks exhibit a bimodal pattern, with two prominent peaks or clusters, suggesting more variability in participant performance. In contrast, placing tasks display a more uniform distribution with a single peak, indicating a more consistent horizontal error pattern. The variability is further captured by the standard deviation (SD) values, represented by the vertical black lines extending above and below the means. The SD for grasping tasks is 1.06 cm, slightly higher than the placing task's SD of 1.01 cm, reflecting greater variability in horizontal positioning for grasping.

These observations suggest that while the central tendencies (mean and median) are similar between tasks, grasping tasks demonstrate greater variability in horizontal positioning, whereas placing tasks exhibit a more stable but slightly narrower range of errors.

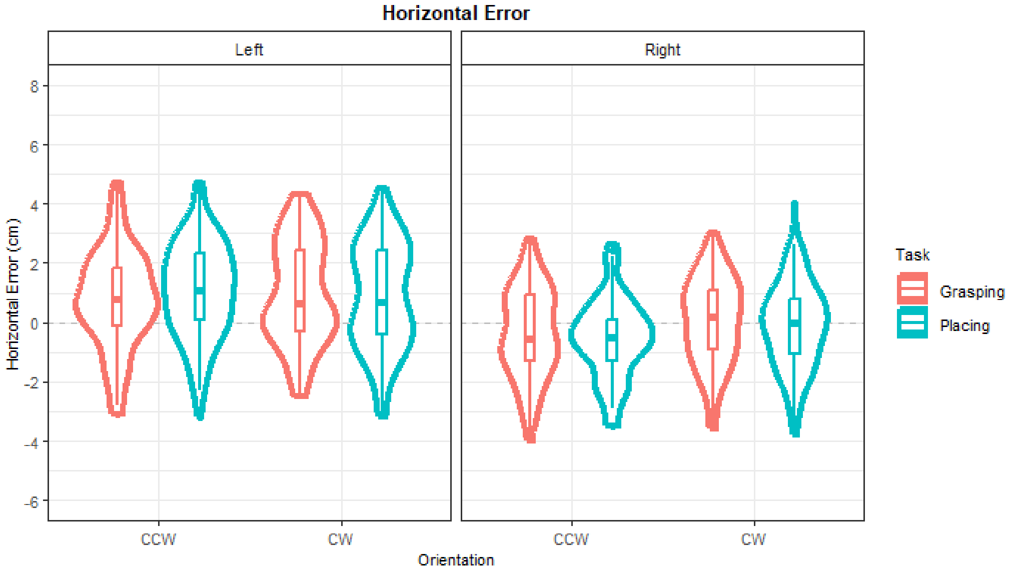

Figure 29. Distribution of "Horizontal Error". This figure presents the distribution of Horizontal Error (in cm) for grasping and placing tasks, segmented by movement direction (Left and Right) and task orientation (CW and CCW). The data are pooled across all participants, with the box plot highlighting the median and interquartile ranges, while the violin plots show the distribution of data around the median line, with wider sections indicating a higher density of reaction times. The left panel displays movements directed to the left, and the right panel shows movements to the right.

Figure 29 shows the violin plot for Horizontal Error and the distribution of errors across different locations (left and right) and orientations (CW and CCW). The distribution appears relatively symmetrical for most conditions, with the median generally centered near 0 cm, indicating minimal horizontal deviations from the calibrated location. Some conditions, such as left CCW for placing tasks, show a broader spread in the distribution, while others, such as right CW for placing tasks, show a more compact distribution. These patterns suggest variability in horizontal error across different orientations and tasks, but the overall trend indicates that horizontal deviations were relatively balanced across the conditions.

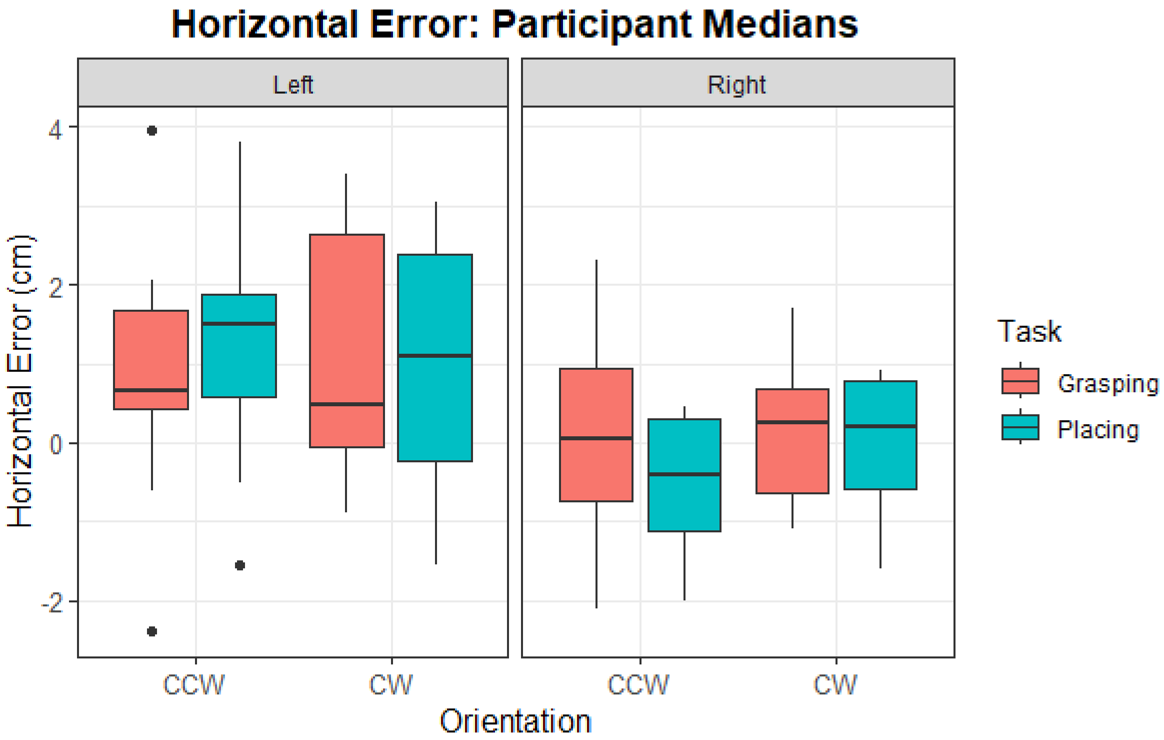

Figure 30. Horizontal Error: Participant Medians for Grasping and Placing Tasks. This figure presents the distribution of horizontal error (in degree) for grasping and placing tasks across all participants (P1–P10), grouped by task condition and further segmented by Orientation (CCW, CW) and Location (Left, Right). Each box plot includes 10 data points, each representing the median horizontal error of a single participant in a given condition. Red boxes indicate grasping, while teal boxes indicate placing. The horizontal line within each box denotes the median horizontal error, showing the central tendency for each task condition. The upper and lower edges of each box represent the interquartile range (IQR). Whiskers extend to show the full range of horizontal error within 1.5 times the IQR from the quartiles.

Figure 30 displays box plots of median horizontal error for each participant across different task conditions (Grasping and Placing), segmented by Orientation (CCW and CW) and Location

(Left and Right). Each box represents the median horizontal error for participants within each condition, providing insights into participant-level variability in horizontal positioning accuracy.

In the Left-CCW condition, both grasping and placing tasks have similar ranges, with placing tasks showing a slightly higher median horizontal error than grasping tasks. For the Left-CW condition, grasping and placing tasks also exhibit comparable ranges, but grasping tasks have a slightly higher median than placing tasks.

In the Right-CCW condition, both tasks display similar ranges, though grasping tasks have a marginally higher median horizontal error than placing tasks. In the Right-CW condition, grasping and placing tasks again have similar ranges, with both showing comparable median.

Horizontal Error is lower in the Right Location compared to the Left Location, with consistently smaller medians across tasks (Grasping and Placing) and orientations (CCW and CW). This indicates greater horizontal precision when reaching the Right Location. The Left Location shows higher medians and greater variability, particularly in the CW Orientation, suggesting increased difficulty in maintaining horizontal accuracy. The Right Location also demonstrates narrower interquartile ranges, reflecting more consistent performance.

Table 8. ANOVA Results for Horizontal Error: Main Effects and Interactions Among Location, Orientation, and Task

Interaction	**DFn**	**DFd**	**F value**	**p-value**	**η2p**
Location	1	9	6.38	0.03	0.41
Orientation	1	9	2.45	0.15	0.21
Task	1	9	1.65	0.23	0.16
Location:Orientation	1	9	0.42	0.53	0.04

Location:Task	1	9	1.79	0.21	0.17
Orientation:Task	1	9	0.01	0.92	0.001
Location:Orientation:Task	1	9	4.17	0.07	0.32

Table 8 displays box plots of median horizontal error for each participant across the different task conditions (Grasping and Placing), segmented by Orientation (CCW and CW) and Location (Left and Right). Each box represents the median peak velocity time for participants within each condition, offering a view of participant medians rather than trial-level variability.

A significant main effect of Location on horizontal error was observed, F(1,9) = 6.38, p = 0.03, η^2p = 0.41, suggesting a moderate effect size, although it did not meet the conventional threshold for significance after correction. The main effects of Orientation, F(1,9) = 2.45, p = 0.15, η^2p = 0.21, or Task, F(1,9) = 1.65, p = 0.23, η^2p = 0.16 were not statistically significant.

Similarly, none of the interaction effects (Location × Orientation, Location × Task, Orientation × Task, and Location × Orientation × Task) were statistically significant, with all p-values exceeding 0.05 (see Table 17). These findings indicate that none of the individual factors or their combinations had a substantial impact on horizontal error.

Since the main effect of Location was significant, no post-hoc tests were necessary. Location consists of only two levels (Left and Right), and the ANOVA inherently compares these two groups. The significant result indicates a reliable difference in Horizontal Error between the two locations without requiring further pairwise testing.

3.1.10 Analysis of “Orientation Error” Across Conditions

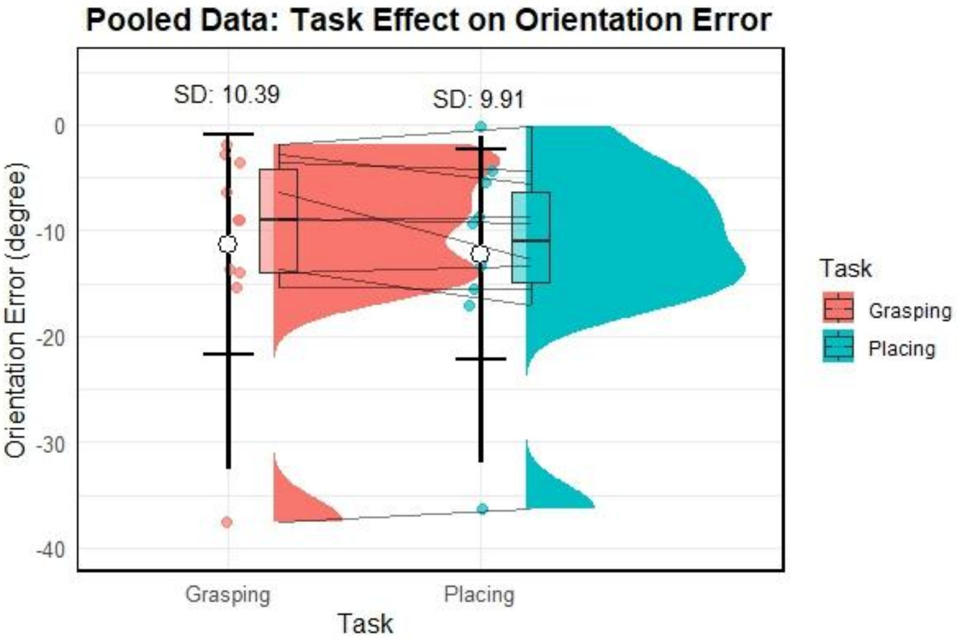

Figure 31. Orientation Error: Pooled Data for Grasping and Placing Tasks. This figure illustrates the distribution of orientation error (in degrees) for grasping and placing tasks, aggregated across all participants (P1–P10). Each dot represents the mean orientation error for a single participant, with lines connecting the dots to highlight within-participant consistency across tasks. Red dots correspond to grasping tasks, while teal dots correspond to placing tasks. The half-violin plots display the density distribution of orientation error values, providing insight into the variability of errors for each task. The box plots represent the interquartile range (IQR), with the horizontal line inside each box indicating the median orientation error, and the black dot on each vertical black line showing the mean orientation error for the corresponding task group. Whiskers extend to the most extreme data points within 1.5 times the IQR. Outliers beyond this range are displayed as individual points outside the whiskers. Standard deviations (SD) are represented by the vertical black lines extending above and below the means, providing a quantitative measure of variability for each task.

The results illustrated in Figure 31 highlight differences in orientation error between grasping and placing tasks. Grasping tasks show median orientation errors closer to zero, as indicated by the horizontal line inside the box plot, reflecting better alignment accuracy. In contrast, placing tasks exhibit medians farther below zero on the negative axis, indicating greater deviation from the target orientation.

The white dots, representing the mean orientation error for each task, are consistently below the median line in the box plots for both tasks, suggesting a slight negative skew in the data, with a few more extreme negative errors pulling the mean downward. The violin plots reveal distinct distribution patterns, with grasping tasks showing a smoother spread of errors clustered closer to zero, whereas placing tasks exhibit a wider spread with more negative values.

The variability in orientation error is further quantified by the standard deviation (SD) values, represented by the vertical black lines extending above and below the means. Grasping tasks exhibit an SD of 10.39 degrees, slightly higher than the placing task's SD of 9.91 degrees, reflecting marginally greater variability in orientation alignment for grasping tasks.

These patterns highlight the distinct accuracy demands and variability characteristics of each task type, with grasping tasks demonstrating closer alignment to the target and placing tasks showing a tendency for greater deviation.

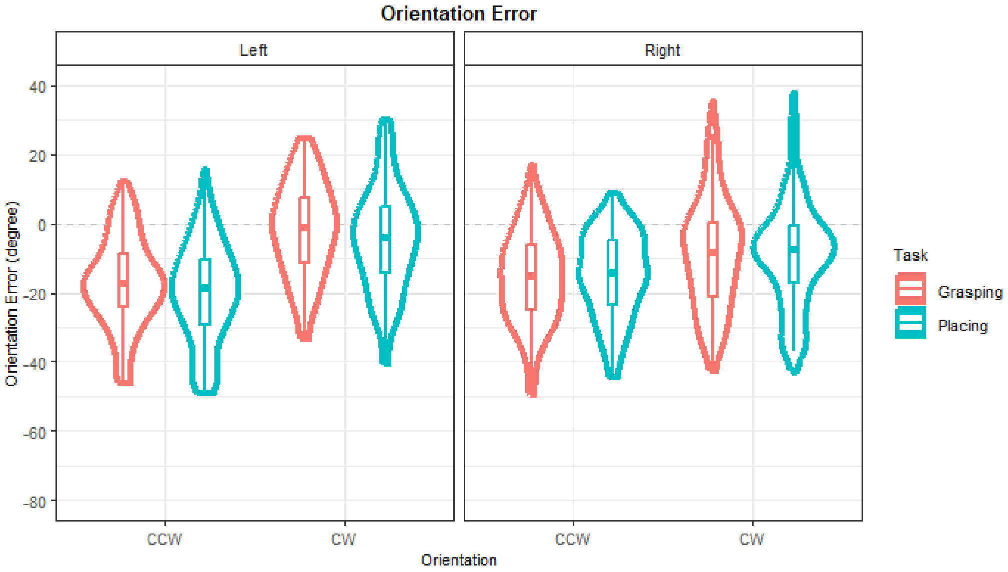

Figure 32. Distribution of “Orientation Error”. This figure presents the distribution of Orientation Error (in degree) for grasping and placing tasks, segmented by movement direction (Left and Right) and task orientation (CW and CCW). The data are pooled across all participants and show the distribution of data around the median line, with wider sections indicating a higher density of reaction times. The left panel displays movements directed to the left, and the right panel shows movements to the right.

Figure 32 for Orientation Error presents the median of the Left CW orientation error is close to 0, while the Left CCW has a median of around -20 degrees. For the right location, CCW orientation has a median of approximately -15 degrees, and CW orientation shows a median of around -10 degrees. There is a noticeable difference in spread between the locations, with the right location showing greater variability, particularly in the CW orientation for both tasks. The left location, in contrast, shows a tighter distribution of orientation errors, suggesting that participants maintained a more consistent orientation when performing movements to the left side.

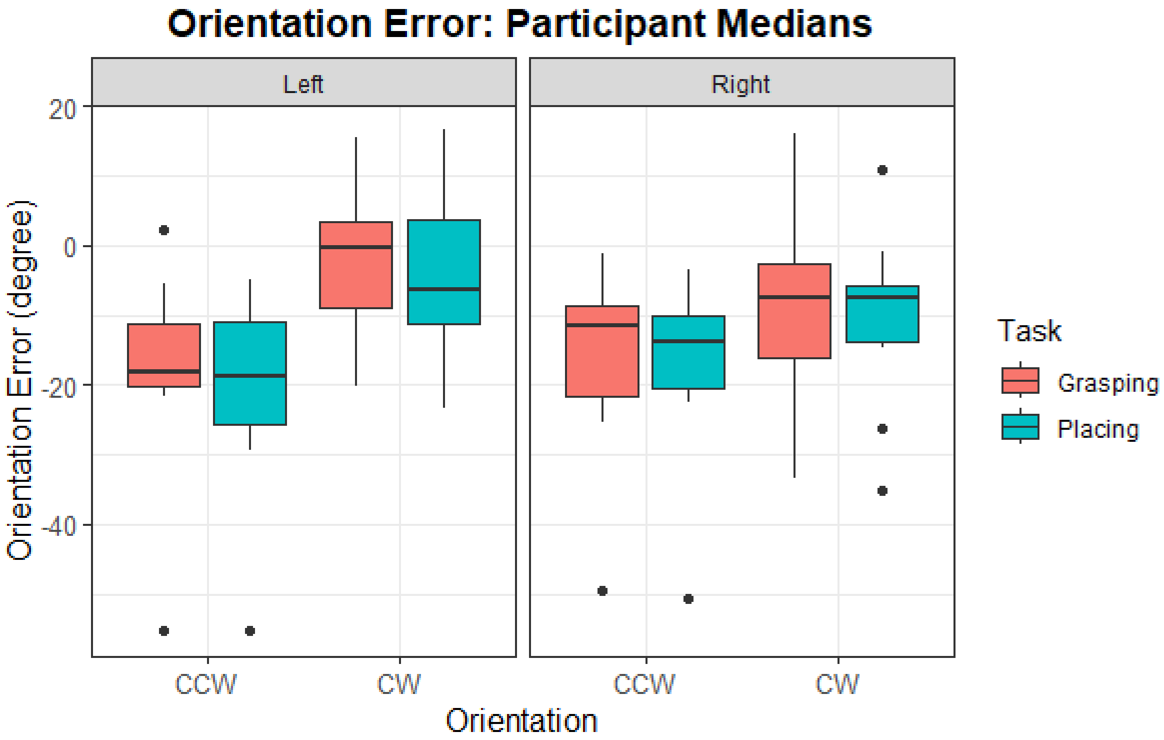

Figure 33. Orientation Erro: Participant Medians for Grasping and Placing Tasks. This figure presents the distribution of orientation error (in degree) for grasping and placing tasks across all participants (P1–P10), grouped by task condition and further segmented by Orientation (CCW, CW) and Location (Left, Right). Each box plot includes 10 data points, each representing the median orientation error of a single participant in a given condition. Red boxes indicate grasping,

while teal boxes indicate placing. The horizontal line within each box denotes the median orientation error, showing the central tendency for each task condition. The upper and lower edges of each box represent the interquartile range (IQR). Whiskers extend to show the full range of orientation error within 1.5 times the IQR from the quartiles.

Figure 33 displays box plots of median orientation error for each participant across different task conditions (Grasping and Placing), segmented by Orientation (CCW and CW) and Location (Left and Right). Each box represents the median orientation error for participants within each condition, providing insights into participant-level variability in orientation accuracy.

In the Left-CCW condition, placing tasks exhibit a slightly wider range than grasping tasks, but both tasks have similar upper edges. For the Left-CW condition, grasping and placing tasks have similar ranges and upper edges, with CW orientations showing generally lower orientation errors than CCW orientations.

In the Right-CCW condition, grasping tasks display a somewhat wider range than placing tasks, though the upper edges are similar for both. For the Right-CW condition, grasping tasks have a wider range and a slightly higher median orientation error than placing tasks. Overall, CW orientations tend to show lower orientation errors compared to CCW orientations in both left and right locations.

Table 9. ANOVA Results for Orientation Error: Main Effects and Interactions Among Location, Orientation, and Task

Interaction	**DFn**	**DFd**	**F value**	**p-value**	**η2p**
Location	1	9	0.79	0.40	0.08
Orientation	1	9	11.70	0.00762	0.57
Task	1	9	5.76	0.04	0.39
Location:Orientation	1	9	4.55	0.06	0.34

Location:Task	1	9	2.82	0.17	0.20
Orientation:Task	1	9	0.02	0.88	0.002
Location:Orientation:Task	1	9	0.04	0.86	0.004

Table 9 Anova result of median orientation error for each participant across the different task conditions (Grasping and Placing), segmented by Orientation (CCW and CW) and Location (Left and Right).

The ANOVA results for Task, F(1,9) = 5.76, p = 0.04, $\eta^2p = 0.39$, indicating a significant effect size. This result suggests that the type of task (grasping vs. placing) plays a role in orientation error. There was also a significant main effect of Orientation on orientation error, F(1,9) = 11.70, p = 0.00762, $\eta^2p = 0.56$. This large effect size suggests that Orientation accounts for a substantial portion of the variance in orientation error.

No other main effects or interaction effects (Location × Orientation, Location × Task, Orientation × Task, and Location × Orientation × Task) reached statistical significance, with all p-values exceeding 0.05. This indicates that the combined effects of Location, Orientation, and Task do not significantly influence orientation error beyond the main effects observed for Orientation and Task.

Since the main effects of Orientation and Task were significant, no post-hoc tests were necessary. Both factors consist of only two levels (Orientation: CW and CCW; Task: Grasping and Placing), and the ANOVA inherently compares these two groups. The significant results indicate reliable differences in Orientation Error between the two orientations and between the two tasks without requiring further pairwise testing.

3.2 Discussion of Results

A key objective of this study was to examine the kinematic differences between grasping and placing tasks and to understand how factors such as target location and object orientation influenced performance. Based on the hypothesis, I expected participants to move more accurately and slower during placement tasks compared to grasping tasks due to the higher control demands required for precise object alignment.

The results revealed significant main effects for task, location, and orientation, along with notable interaction effects, as detailed below:

Task Influence on Movement Duration and Orientation Error

Contrary to the hypothesis, placing tasks were slightly faster than grasping tasks, as indicated by the significant main effect of Task on movement duration. This indicate that if distance is the same, lower duration mean faster average movement during placement.

For orientation error, placing tasks resulted in higher errors compared to grasping tasks. This result also contrary to the hypothesis, maybe placement relies more on visual feedback than grasp.

Influence of Location on Movement Duration and Errors

Movements directed to the right consistently showed longer movement durations and higher peak velocities. This finding aligns with the biomechanics of the right arm in right-handed participants, where rightward movements are more natural and efficient due to reduced mechanical strain and shorter target distances. Additionally, rightward locations tended to reduce errors in depth and horizontal positioning, suggesting that hemispheric dominance for motor control in right-handed individuals may contribute to enhanced precision in rightward movements.

Effect of Orientation on Orientation Error

A significant main effect of Orientation was observed for orientation error, with CW orientations generally producing lower errors compared to CCW orientations. This pattern was consistent across grasping and placing tasks, suggesting that CW orientation may introduce additional demands on spatial alignment.

Non-significant Depth Error and Horizontal Error Effects

Although Location and Orientation effects showed trends toward significance for depth and horizontal error, no statistically significant interaction effects were observed for these variables.

Role of Visual Feedback

The absence of visual feedback likely amplified the observed differences between tasks and conditions. Visual feedback plays a critical role in real-time error correction, and its inclusion could reduce both errors and differences between grasping and placing tasks. For example, visual feedback might enable participants to more effectively align objects during placement, further reducing orientation errors and potentially narrowing the differences in movement duration between tasks.

Broader Implications of Task Differences

The observed task-related differences in movement duration and orientation error suggest that grasping and placing rely on overlapping but distinct neural circuits. These differences could reflect variations in motor planning, where grasping involves goal-directed movements requiring precision for object acquisition, and placing involves more pre-planned movements for target alignment. Additionally, somatosensory feedback may differ between the tasks, with grasping requiring tactile input to stabilize and manipulate the object, whereas placing focuses on spatial alignment with the target.

The finding that placing was faster than grasping could also reflect task-related differences in neural prioritization. For instance, grasping might engage circuits associated with action execution, while placing might emphasize circuits linked to spatial awareness and alignment. The results highlight the need to further explore the neural mechanisms underlying these tasks. Future studies could use neural imaging techniques such as fMRI or EEG to investigate these differences in greater detail. Incorporating visual feedback into such studies could help clarify how visual and somatosensory systems contribute to task-specific performance.

Detailed Analysis of Each Variable

Reaction Time: Reaction time, measuring the interval between the go signal and the start of the movement, is a critical indicator of motor planning and preparation. Shorter reaction times often reflect efficient decision-making and quick readiness, while longer reaction times can indicate a need for additional cognitive processing or adjustments. In this study, a significant effect of Orientation was observed, with CW orientations slightly increasing reaction times compared to CCW orientations. This difference suggests that CW orientation may require more initial preparation, possibly due to its spatial alignment demands. The lack of significant effects for Location and Task implies that participants were equally prepared for grasping and placing tasks across different spatial settings, indicating a robust readiness to act regardless of these variations.

Peak Velocity: Peak velocity represents the highest speed reached by the hand during movement and is an important measure of movement efficiency and control. Higher peak velocities often indicate quicker, more forceful movements, while lower velocities can suggest caution or adjustments made to ensure accuracy. In this study, peak velocity was significantly influenced by Location, with rightward movements consistently reaching higher speeds than leftward movements. This finding likely reflects hemispheric dominance in right-handed participants, enabling more efficient movement execution toward the right. The absence of significant effects for Orientation and Task suggests that, regardless of these factors, participants maintained consistent speed profiles in both grasping and placing tasks, pointing to a stable motor output across conditions.

Peak Velocity Time: Peak velocity time measures the timing of the peak speed within the movement sequence and is crucial for understanding movement dynamics. This variable indicates whether participants reach peak speed early, mid, or late in the movement, which can reflect different control strategies. For instance, an early peak velocity time may indicate rapid acceleration with an emphasis on speed, while a later peak suggests a controlled, gradual approach that prioritizes precision. In this study, peak velocity time was significantly affected by Location, with movements toward the right reaching peak velocity sooner than those toward the left. This pattern aligns with hemispheric dominance effects in right-handed individuals, supporting quicker and potentially more automatic motor planning toward the right. The lack of significant effects for Orientation and Task implies that participants adopted a consistent movement strategy for both grasping and placing tasks, maintaining similar timing profiles regardless of spatial orientation.

Movement Duration: Movement duration measures the total time taken to complete the task, from movement onset to reaching the target, and provides insight into overall efficiency and control. Shorter movement durations generally indicate rapid, efficient movements, while longer durations can reflect a more controlled approach, often necessary for tasks requiring precision. In this study, movement duration was significantly affected by Location, Task, and the Location × Orientation interaction.

Rightward movements showed longer durations, which may reflect the increased control or adjustments required for targets positioned farther away or involving biomechanical challenges specific to rightward movements in this setup. Task effects revealed that placing tasks were slightly faster than grasping tasks, contrary to the hypothesis that placing would require longer durations due to higher control demands for object alignment. This unexpected result could be attributed to the simplicity of the placement task, where alignment with the target holder did not demand the same precision as a grasp.

The significant Location × Orientation interaction suggests that the influence of Location on movement duration depends on the object's orientation, highlighting a combined role of spatial direction and alignment demands in shaping movement timing. The lack of a significant main effect for Orientation alone indicates that participants maintained similar movement durations across CW and CCW orientations, except where spatial direction interacted with Location.

Position Accuracy (Absolute Position Error): Position accuracy, measured by absolute position error, presents the spatial deviation of the participant's hand from the target location at the moment of task completion, providing a direct measure of positional accuracy. Lower position errors indicate high spatial precision, essential for tasks where precise hand placement is required, such as in object manipulation and alignment. In this study, no significant effects were found for Location, Orientation, or Task on absolute position error, suggesting that participants maintained consistent spatial accuracy across all conditions. This consistency implies that participants were able to achieve precise positioning regardless of task type or spatial demands, reflecting a robust level of motor control and accuracy across grasping and placing tasks.

Depth Error: Depth error measures the deviation in the forward-backward (z-axis) positioning of the hand relative to the target, providing insights into control over movement depth. Lower depth error indicates precise control in reaching the correct depth, which is crucial for tasks requiring exact hand alignment with the target in the depth dimension. In this study, depth error showed no significant effects for Location, Orientation, or Task, suggesting that participants maintained consistent control over movement depth across all conditions. This consistency across grasping and placing tasks indicates that participants achieved stable and accurate depth control regardless of spatial demands or task type, reflecting reliable motor coordination in the forward-backward dimension.

Up-Down Error: Up-down error represents the deviation in vertical (y-axis) positioning of the hand relative to the target, providing insight into the control over height-specific accuracy. Lower up-down error indicates precise control in aligning the hand at the correct vertical position, which is essential for tasks that require accurate height adjustments. In this study, a significant effect of Location was observed, with leftward movements generally showing greater up-down error compared to rightward movements. This may reflect spatial asymmetries related to hemispheric dominance, particularly in right-handed individuals. The lack of significant effects for Orientation and Task suggests that, despite the spatial difference, participants maintained consistent up-down control across both grasping and placing tasks and orientation conditions.

Horizontal Error: Horizontal error measures the deviation in the left-right (x-axis) positioning of the hand relative to the target, reflecting control over lateral accuracy. Lower horizontal error indicates precise control in aligning the hand with the target's lateral position, which is important for tasks that require accurate side-to-side adjustments. In this study, no significant effects were found for Location, Orientation, or Task on horizontal error, suggesting that participants maintained consistent lateral accuracy across all conditions. This consistency implies that participants could achieve reliable horizontal positioning regardless of task type, spatial orientation, or target location, demonstrating stable motor control in the lateral dimension for both grasping and placing tasks.

Orientation Error: Orientation error represents the angular deviation of the hand's orientation relative to the target, providing insights into control over hand alignment. Lower orientation error indicates precise control in aligning the hand at the correct angle, essential for tasks requiring specific rotational alignment, such as placing objects in designated orientations. In this study, significant effects were found for Orientation and Task. CW orientations showed consistently higher orientation errors than CCW orientations, suggesting that CW tasks may introduce additional alignment challenges. Additionally, placing tasks exhibited slightly lower orientation errors than grasping tasks, particularly in CW orientations, highlighting subtle task-related differences in rotational accuracy. These findings indicate that both Orientation and Task type play a meaningful role in influencing hand alignment precision, with placing tasks demonstrating improved alignment accuracy, especially in more demanding CW orientations.

General findings: influence of location and orientation

The results from this study, which examined both grasping and placing tasks, align with prior findings in the field of reach-to-grasp movements while also providing new insights into how spatial location and orientation differentially affect task performance. One of the consistent findings across multiple variables is the significant influence of Location. Movements directed to the right generally showed longer movement durations and higher peak velocities, aligning with literature on hemispheric dominance. In right-handed individuals, movements in the right visual and motor fields are often associated with more efficient neural processing, resulting in improved motor performance (Connolly et al., 2003). This rightward advantage in motor control was observed across both grasping and placing tasks in the current study, suggesting that the influence of location extends across different task types, impacting overall movement control and velocity.

Orientation also played a notable role in task performance, particularly for orientation error. Movements performed with CW orientation consistently showed lower orientation errors compared to CCW, suggesting additional alignment challenges when working in CCW orientations. This effect was particularly noticeable in grasping tasks, where orientation accuracy was generally lower than in placing tasks. The observed orientation effect aligns with potential biomechanical challenges and natural hand orientation preferences, where CW orientations might offer a more stable alignment, especially in precision tasks like object placement. While orientation had a less pronounced impact than location, its influence on orientation error highlights the role of spatial orientation in modulating task performance.

Additionally, Depth Error and Horizontal Error showed no significant differences based on task or orientation. These findings suggest that consistent motor control across different orientations and task demands remains robust in terms of spatial positioning.

Future research could explore these effects further by incorporating a variety of object properties, such as shape and size, to examine if location and orientation effects become more pronounced with more complex object demands. Previous studies have shown that object properties, such as shape and height, can influence movement dynamics, resulting in adjustments like larger grip apertures for taller objects and longer movement times for objects positioned farther from the hand (Voudouris et al., 2010). Introducing diverse object conditions could provide deeper insights into how spatial and orientation cues impact task performance in reach-to-grasp actions.

Grasp vs. Placement: Main effects and Trends

The significant main effect of Task on movement duration observed in this study indicates that grasping and placing are not entirely equivalent in their motor demands. Placing tasks were unexpectedly faster than grasping tasks, contrary to the hypothesis that placement would require longer durations due to its higher precision and alignment demands. This result may reflect the relatively simple placement task used in this study, where the absence of visual feedback and low object complexity reduced the control demands typically associated with placement tasks.

Despite the significant Task effect, the overall similarity in kinematics between grasping and placing suggests that under the tested conditions, overlapping motor systems may be employed for both tasks. Fundamental processes such as reaching and hand positioning may dominate task execution, minimizing differences in movement strategies.

One possible explanation for the observed similarities is that participants adapted quickly to the repetitive task structure, generalizing their motor strategies across both actions. Predictive mechanisms in motor control, particularly feedforward adjustments, likely optimized hand movements for both tasks, reducing cognitive load and making the tasks appear kinematically similar (Voudouris et al., 2019).

Additionally, the uniformity of task demands and low variability in object characteristics may have led participants to rely more heavily on motor-driven processes rather than task-specific cognitive strategies. This reliance on shared neural resources could downplay more nuanced kinematic differences between grasping and placing, particularly in the absence of visual feedback, which limits error correction.

Research by Luabeya et al. (2023) highlights the unique demands of placement tasks, including heightened accuracy in spatial location and object orientation, often facilitated by visual feedback and gaze alignment. However, in this study, the lack of visual feedback likely reduced the differentiation between grasping and placing, as participants could not rely on visual cues to refine their movements during placement.

While the significant Task effect on movement duration underscores some differentiation between grasping and placing, the broader interaction trends suggest that placement may engage additional mechanisms under specific conditions. For example, tasks that emphasize spatial precision and orientation alignment may elicit distinct neural processes for placement. Future studies could explore these differences by introducing more complex object properties, increasing task variability, or incorporating visual feedback. Such experimental designs could help delineate the unique contributions of motor and cognitive processes to grasping and placing actions.

Interactions between task, location, and orientation.

Our findings indicate a slight but notable difference in orientation error between grasping and placing tasks, particularly in the left CW condition, where orientation error differed by approximately 5 degrees. This suggests that grasping and placing tasks may involve subtly different control mechanisms for orientation, even though our overall results did not fully align with the initial hypothesis. Contrary to the expectation that placing would show less accuracy due to its higher control demands, the data revealed slightly higher orientation errors in grasping tasks. This finding suggests that orientation control in grasping may be more complex than anticipated, highlighting the intricate demands of motor control and how task-specific orientation requirements may differ from initial predictions.

Previous research has highlighted the distinct motor planning involved in grasping versus placing tasks. Jeannerod (1984) noted that grasping requires precise adjustments in hand orientation and finger placement, aligning with the increased orientation error observed in the grasping task here. Similarly, Goodale et al. (1994) examined placement versus pantomime and found that actions requiring precise manipulation (such as grasping) demand refined visuomotor control. This need for a precise grip may explain the observed increase in orientation error in grasping under specific conditions.

Wing et al. (2003) further supports the notion that while spatial accuracy is critical for placing tasks, hand orientation plays a less central role compared to grasping. Our results echo this, as placing tasks consistently exhibited slightly lower orientation errors, particularly in the left CW condition. This aligns with broader research that emphasizes spatial accuracy in placing and orientation precision in grasping tasks.

The analysis did not reveal a significant three-way interaction between Task, Location, and Orientation for any of the variables. This suggests that while each of these factors individually or in combination with one other factor may influence motor performance, their combined effect does not introduce additional complexity in task execution. The lack of a significant three-way interaction implies that the underlying motor control mechanisms for grasping and placing tasks remain relatively stable across different spatial locations and orientations, without a compounded effect when all three factors vary simultaneously. This stability may indicate that grasping and placing share core motor processes that are adaptable to various spatial contexts without significant performance changes.

Interestingly, although significant ANOVA results for location and location × orientation interactions appeared in certain variables, post-hoc tests did not reveal significant pairwise differences in some cases, such as horizontal error. This suggests that while general trends indicate an effect of these factors, specific differences between conditions may be subtler than anticipated, potentially due to motor variability. Tresilian et al. (2005) also observed that motor variability increases with task complexity, but individual differences between specific conditions may not always reach statistical significance after correcting for multiple comparisons. This pattern held true for both grasping and placing tasks, underscoring the nuanced demands of motor control across varying spatial and orientation conditions.

3.3 Possible Physiological Mechanisms Physiological Mechanisms

While significant task-related differences were observed in movement duration and orientation error, the fundamental motor areas responsible for executing goal-directed actions, such as the primary motor cortex (M1), SMA = supplementary motor area, and premotor cortexare likely involved in the planning and execution of both tasks, treating grasping and placing as variations within a shared motor repertoire. These areas facilitate the coordination of goal-directed motor actions, enabling efficient control across similar tasks.

However, the significant Task effect on movement duration and orientation error points to distinct task-specific demands. Placing tasks, which were unexpectedly faster than grasping tasks, may engage motor strategies optimized for spatial alignment rather than precision grip. This could reflect reduced control demands for object placement under the simplified experimental conditions used in this study, particularly in the absence of visual feedback. Conversely, the higher orientation error observed in grasping tasks highlights the increased complexity of hand orientation adjustments required for precise object acquisition, which involves intricate visuomotor transformations.

The PPC = posterior parietal cortex likely plays a central role in these differences, particularly in placing tasks, which demand spatial transformations for precise alignment. The PPC is critical for integrating sensory information and supporting spatial planning, suggesting its heightened involvement in placement actions compared to grasping. Sensory feedback mechanisms also likely vary between tasks: proprioceptive feedback may be more dominant in placement tasks to ensure accurate hand positioning, whereas visual feedback is typically more critical in grasping to guide real-time adjustments for precise grip.

Additionally, task complexity may influence the involvement of cognitive regions such as the PFC = prefrontal cortex. Placing tasks, with their higher spatial accuracy demands, may recruit additional cognitive resources compared to grasping. This aligns with findings that placing often requires enhanced motor planning and spatial reasoning, particularly when fine alignment is necessary.

In summary, while motor areas such as the primary motor cortex, SMA, and premotor cortex likely contribute similarly to both grasping and placing tasks, the significant differences in movement duration and orientation error highlight task-specific demands that engage distinct sensory and cognitive pathways. These results suggest that grasping and placing rely on overlapping neural circuits but diverge in their reliance on spatial planning and sensory integration. Future neuroimaging studies using techniques such as fMRI or EEG could further delineate the shared and task-specific pathways underlying these actions, particularly under conditions of increased task complexity or enhanced visual feedback.

3.4 Conclusion

This study provides a comparative analysis of the factors influencing motor control in both grasping and placing tasks, highlighting the significant role of task in movement duration and orientation error. I found modest task-related differences but could not reach a firm conclusion due to the underpowered dataset. Tasks performed in the right spatial location exhibited longer movement durations, higher peak velocities, and reduced errors, suggesting advantages potentially related to hemispheric dominance and biomechanical factors. Orientation also influenced performance, particularly in grasping tasks, where CCW orientations were associated with lower orientation errors, emphasizing the impact of spatial alignment and hand orientation preferences.

Grasping and placing tasks differed significantly in their motor demands. The significant main effect of Task revealed that placing tasks were unexpectedly faster than grasping tasks, contrary to the hypothesis that placing would require longer movement durations due to greater alignment demands. This finding suggests that the simplified placement task in this study required fewer adjustments than anticipated. However, placing tasks exhibited lower orientation errors compared to grasping tasks, supporting the hypothesis that placement relies on higher spatial accuracy for precise alignment. In contrast, grasping tasks showed increased sensitivity to orientation demands, particularly in leftward movements, reflecting the heightened complexity of achieving precise hand orientation during object acquisition.

These results suggest modest task-related differences, but the limited dataset prevented me from drawing definitive conclusions.

while grasping and placing share overlapping motor control processes, as evidenced by their similar reliance on core motor areas like the primary motor cortex and premotor areas, distinct sensory and spatial demands differentiate the two tasks. Placing tasks involved greater dependency on absolute position accuracy due to alignment requirements, while grasping tasks exhibited greater sensitivity to orientation errors, likely due to the intricate hand adjustments necessary for gripping.

It is important to interpret these findings cautiously, given potential statistical power limitations. The trends observed provide valuable insights, but a larger sample size or more varied experimental conditions may reveal more robust differences and confirm these results with greater confidence.

Overall, this study advances understanding of how spatial and orientation demands uniquely impact grasping and placing tasks. These insights are particularly relevant for applications in rehabilitation and skill training, where grasping and placing are foundational motor actions. By understanding the nuanced control strategies required for these tasks, interventions can be better tailored to improve motor function. Future research should explore these interactions in more dynamic, real-world environments, incorporating complex objects and varying task demands to deepen our understanding of motor control in everyday contexts.

4. GENERAL DISCUSSION AND CONCLUSIONS

The primary objective of this study was to explore the differences in kinematic patterns between grasping and placing tasks, examining nine specific movement-related variables: Reaction Time, Peak Velocity, Peak Velocity Time, Movement Duration, Absolute Position Error, Orientation Error, Depth Error, Up-Down Error, and Horizontal Error. The study aimed to investigate how task type (grasping vs. placing), object orientation (clockwise vs. counterclockwise), and target location (left vs. right) influenced motor control and precision. The experiment, consisting of 1600 trials with 10 participants, provided detailed insights into the effects of these variables on movement performance.

The results revealed distinct differences in the kinematic patterns of grasping and placing tasks, particularly in movement duration and orientation error. These findings demonstrate that the two tasks engage unique motor control mechanisms under the experimental conditions tested.

Movement duration was significantly shorter for placing tasks compared to grasping tasks, contrary to the hypothesis that placing would require more time due to its alignment demands. This unexpected result may reflect the simplified placement task used in this study, where fewer corrective adjustments were required. In contrast, orientation error was higher in grasping tasks, particularly for CCW orientations, highlighting the increased complexity of achieving precise hand orientation during object acquisition. These findings suggest that placing tasks emphasize spatial accuracy, while grasping tasks demand greater orientation control.

Spatial factors, such as location and orientation, also significantly influenced performance. Rightward movements were associated with longer movement durations, higher peak velocities, and reduced spatial errors, reflecting advantages likely related to hemispheric dominance and biomechanical factors in right-handed individuals. Orientation effects were most prominent in orientation error, where CCW orientations generally resulted in lower errors compared to CW orientations. This aligns with biomechanical preferences that facilitate more stable alignment in CCW orientations.

These findings underscore that grasping and placing engage overlapping motor systems, such as the primary motor cortex and premotor areas, but differ in their reliance on task-specific sensory and spatial demands. Placing tasks required greater absolute position accuracy for alignment, while grasping tasks showed heightened sensitivity to orientation demands, reflecting the unique motor strategies required for each action.

4.1 Limitations

4.1.1 Sample Size

Although the study initially included 17 participants, after the preprocessing step, the final analysis was conducted on data from 10 participants. Based on power calculations, this sample size may lack sufficient statistical power to detect smaller effects and to generalize the findings to a broader population. Increasing the sample size in future studies would help improve the generalizability of the results and might reveal more subtle effects that could not be detected with the current sample.

4.1.2 Data Quality and Noise in Signal Processing

Noise in the OptiTrack data presented challenges during data collection and preprocessing.

Due to limitations in refining the data, it was difficult to isolate main signals entirely from noise, which affected data quality and led to the exclusion of some participant data. This issue may have impacted on the accuracy of kinematic measurements, potentially obscuring subtle effects. Future studies might benefit from enhanced filtering techniques or equipment adjustments to reduce noise and improve signal fidelity, enabling a clearer analysis of movement patterns.

4.1.3 Alternating Tasks and Hysteresis Effects

The alternating order of grasping and placing tasks in this study may have influenced participants' error rates due to hysteresis effects—where previous movements influence subsequent ones. Performance could also have been affected by fatigue or task adaptation as the experiment progressed. Future analyses should investigate how performance evolves over time within participants and conduct pairwise comparisons of coupled grasp-place (or place-grasp) sequences to test for potential hysteresis effects.

4.1.4 Analysis Approach

This study utilized pooled data across participants for violin plots and overall distribution analyses, while median values from each of the 10 participants were used for box plots and repeated-measures ANOVA. This approach allowed for a comprehensive view of both individual trends and group-level distributions. However, focusing on overall distributions and participant medians may have limited the ability to capture finer-grained within-participant variations and individual adaptive strategies. Future research could benefit from additional individual-level analyses, such as mixed-effects modeling, to explore unique patterns across participants and within-participant variations. Such methods could further reveal individual differences and enhance the understanding of motor control mechanisms beyond the group-level trends observed in this study.

4.1.5 Template vs. Non-Template Task Requirements

This study involved both grasping and placing tasks, with placement requiring precise alignment with a template. While this design resembles real-world tasks that require specific positioning (such as placing an object in a designated slot or position), it may limit the generalizability of the findings to tasks where such precise alignment is not necessary. In contexts without templates, both grasping and placing might exhibit greater variability in location and orientation, as the precision demands would be lower. Future studies could explore grasping and placing tasks without templates to understand how different alignment requirements affect kinematic patterns and error rates.

4.1.6 Task Complexity

The grasping and placing tasks were relatively simple and highly controlled. While this was essential for isolating specific kinematic variables, it might not fully capture the complexity of real-world tasks where objects vary in weight, size, and texture. Future studies could consider including more complex, dynamic tasks that reflect everyday scenarios.

4.1.7 Movement Symmetry and Dominance

This study focused exclusively on unimanual (one-hand) reaches, which are inherently asymmetric. Testing both dominant and non-dominant hands could determine whether findings are consistent across hands or whether motor performance differs due to hemispheric dominance or biomechanical factors.

4.1.8 Data Loss Due to Limited Tracking Setup

This study utilized four cameras and three markers for motion tracking, which may have contributed to occasional data loss in some conditions. While this setup provided adequate coverage for the experimental design, increasing the number of cameras and markers in future studies could improve tracking accuracy and reduce the likelihood of data gaps, ensuring more robust and reliable measurements.

4.1.9 Stimulus Order Recording Accuracy

Ensuring accurate recording of stimulus order is critical for maintaining the integrity of the experimental design and data analysis. In this study, efforts were made to randomize and document the stimulus order; however, future studies should implement additional checks and redundancy measures to verify that the stimulus order is consistently and correctly recorded. This will help avoid potential errors and enhance the reliability of the findings.

4.1.10Environmental Conditions

The experiment was conducted in near-total darkness, which ensured controlled visual conditions but could have limited ecological validity. In real-world settings, participants often rely on visual feedback when grasping and placing tasks. The absence of such feedback may have influenced how participants executed movements in this study.

4.2 Implications:

Disclaimer: If these results are born out in a larger sample size, they could have the following implications and applications:

1. **Neuroscience and Rehabilitation:** This study provides valuable insights into motor control, particularly the distinct demands of grasping and placing tasks. Future neuroimaging studies using techniques such as EEG or fMRI could build on this work to explore the neural mechanisms underlying task-specific motor control strategies. These insights could inform rehabilitation programs by tailoring interventions to improve spatial alignment in placing or orientation control in grasping, helping individuals recover fine motor skills after injuries or strokes.

2. **Human-Computer Interaction (HCI):** For technologies like virtual reality (VR) or augmented reality (AR), these results could help in designing interfaces that consider the kinematic differences between different types of hand movements. Understanding that users may perform slower and more variably in tasks requiring precise placement could inform interface designs, making them more intuitive and user-friendly.

4.3 Applications:

1. **Assistive Technology:** The insights from this study could be applied to developing assistive devices for people with motor impairments. Devices that compensate for the increased difficulty of placement tasks, such as smart prosthetics or exoskeletons, could be designed to support fine motor control.

2. **Virtual and Augmented Reality Training:** For fields like surgical training or precision manufacturing, VR/AR platforms could incorporate this data to simulate real-world kinematic challenges more accurately, providing users with more realistic task scenarios and improving their training outcomes.

4.4 Future Directions:

1. **Neural Correlates of Kinematic Variations:** Future research could employ EEG or fMRI to explore the neural mechanisms that underlie the observed differences in grasping and placing tasks. Identifying specific brain areas or networks involved in these motor tasks would provide valuable insights into the neural basis of movement control, which could inform both basic neuroscience and clinical applications.

2. **Task Complexity and Object Properties:** Extending the study to include more complex objects of different shapes, sizes, and weights would provide a richer understanding of how object properties affect movement kinematics. Introducing

dynamic elements (e.g., moving targets) could also more closely mimic real-world grasping and placing tasks.

3. **Expanded Movement Planes:** Additional movement planes (e.g., sagittal or diagonal movements) could offer new insights into how hand trajectories vary in multi-dimensional space. Additionally, varying the initial hand position (e.g., above or below the object) might influence the movement trajectory, which would be important for robotics and other fields where precise hand-object coordination is crucial.

4. **Contextual Feedback and Vision-Based Tasks:** Future experiments could incorporate visual feedback or real-time adjustments based on visual stimuli to better reflect real-world tasks. This would allow researchers to examine how participants integrate visual information into movement control, particularly in placing tasks where alignment and precision are critical.

5. **Longitudinal and Clinical Studies:** Longitudinal studies could explore how these kinematic differences evolve with practice or skill acquisition. Moreover, applying these findings to clinical populations, such as individuals recovering from motor impairments, could help tailor rehabilitation programs that specifically target difficulties in placement tasks.

6. **Addressing Hysteresis Effects:** Future analyses should investigate how alternating

grasp-place tasks influence errors and performance over time. Pairwise comparisons of sequential task transitions could uncover potential hysteresis effects and inform better experimental designs.

REFERENCES

Arbib, M. A. (1981). Perceptual structures and distributed motor control. In V. B. Brooks (Ed.), *Handbook of Physiology: The Nervous System II* (pp. 1449–1480). American Physiological Society. https://doi.org/10.1002/cphy.cp010112

Aristotle. (1937). *Parts of Animals. Movement of Animals. Progression of Animals* (A. L. Peck & E. S. Forster Trans.; Revised ed.). Harvard University Press.

Berger, D. J., Gentner, R., Edmunds, T., Pai, D. K., & d'Avella, A. (2013). Differences in adaptation rates after virtual surgeries provide direct evidence for modularity. Journal of Neuroscience, 33(30), 12384–12394. https://doi.org/10.1523/JNEUROSCI.0122-13.2013

Bosco, G., Breveglieri, R., Chinellato, E., & Galletti, C. (2010). Neural coding of 3D object features in the posterior parietal cortex. Nature Neuroscience, 13(8), 997-1003. https://doi.org/10.1038/nn.2602

Bruton, M., & O'Dwyer, N. (2018). Review of solutions to the degrees-of-freedom problem in human motor control. Progress in Motor Control, 15(3), 1-15. https://doi.org/10.1002/cphy.cp010112

Caminiti, R., Johnson, P. B., & Urbano, A. (1991). Making arm movements within different parts of space: The premotor and motor cortical representation of a coordinate system for reaching to visual targets. Journal of Neuroscience, 11(5), 1182-1197. https://doi.org/10.1523/JNEUROSCI.11-05-01182.1991

Cant, J. S., Westwood, D. A., Valyear, K. F., & Goodale, M. A. (2005). No evidence for visuomotor priming in a visually guided action task. Neuropsychologia, 43(2), 216–226. https://doi.org/10.1016/j.neuropsychologia.2004.11.008

Chen, Y., & Crawford, J. D. (2019). Allocentric representations for target memory and reaching in the human cortex. *Annals of the New York Academy of Sciences*, 1464(1), 142–155. https://doi.org/10.1111/nyas.14261

Crawford, J. D., Henriques, D. Y. P., & Medendorp, W. P. (2011). Three-dimensional transformations for goal-directed action. *Annual Review of Neuroscience*, 34, 309–331. https://doi.org/10.1146/annurev-neuro-061010-113749

Crawford, J. D., Medendorp, W. P., & Marotta, J. J. (2004). Spatial Transformations for Eye–Hand Coordination. Journal of Neurophysiology, 92(1), 10–19. https://doi.org/10.1152/jn.00117.2004

Creem, S. H., & Proffitt, D. R. (2001). Defining the cortical visual systems: "What," "where," and "how." Acta Psychologica, 107(1-3), 43–68. https://doi.org/10.1016/S0001-6918(01)00019-6

d'Avella, A., Portone, A., Fernandez, L., & Lacquaniti, F. (2006). Control of fast-reaching movements by muscle synergy combinations. Journal of Neuroscience, 26(30), 7791–7810.

https://doi.org/10.1523/JNEUROSCI.0830-06.2006

Desmurget, M., Prablanc, C., Arzi, M., Rossetti, Y., Paulignan, Y., & Urquizar, C. (1996). Integrated control of hand transport and orientation during prehension movements. Experimental Brain Research, 110(2), 265–278. https://doi.org/10.1007/BF00228557

Fisher, R. J., Galea, M. P., Brown, P., & Lemon, R. N. (2002). Digital nerve anaesthesia decreases EMG-EMG coherence in a human precision grip task. *Experimental Brain Research*, 145(2), 207–214. https://doi.org/10.1007/s00221-002-1113-x

Fitts, P. M. (1954). The information capacity of the human motor system in controlling the amplitude of movement. Journal of Experimental Psychology, 47(6), 381–391. https://doi.org/10.1037/h0055392

Flash, T., & Hogan, N. (1985). The coordination of arm movements: An experimentally confirmed mathematical model. Journal of Neuroscience, 5(7), 1688-1703. https://doi.org/10.1523/JNEUROSCI.05-07-01688.1985

Flanagan, J. R., & Wing, A. M. (1993). Modulation of grip force with load force during point-to-point arm movements. Experimental Brain Research, 95(1), 131–143. https://doi.org/10.1007/BF00229662

Flanagan, J. R., & Wing, A. M. (1997). The Role of Internal Models in Motion Planning and Control: Evidence from Grip Force Adjustments during Movements of Hand-Held Loads. Journal of Neuroscience, 17(4), 1519–1528. https://doi.org/10.1523/JNEUROSCI.17-04-01519.1997

Freud, E., Plaut, D. C., & Behrmann, M. (2020). 'What' is happening in the dorsal visual pathway. Trends in Cognitive Sciences, 24(10), 1–16. https://doi.org/10.1016/j.tics.2020.07.001

Gallivan, J. P., & Culham, J. C. (2015). Neural coding within human brain areas involved in actions. Journal of Neuroscience, 35(43), 14457–14476. https://doi.org/10.1523/JNEUROSCI.2795-15.2015

Gentilucci, M., Chieffi, S., Daprati, E., Saetti, M. C., & Toni, I. (1991). Visual illusion and action. Neuropsychologia, 34, 369–376. https://doi.org/10.1016/0028-3932(96)00102-3

Georgopoulos, A. P., Kalaska, J. F., & Massey, J. T. (1981). Spatial trajectories and reaction times of aimed movements: Effects of practice, uncertainty, and change in target location. Journal of Neurophysiology, 46(4), 725–743. https://doi.org/10.1152/jn.1981.46.4.725

Gribble, P. L., Ostry, D. J., Sanguineti, V., & Laboissière, R. (1998). Are complex control signals required for human arm movement? Journal of Neurophysiology, 79(3), 1409-1424. https://doi.org/10.1152/jn.1998.79.3.1409

Grinyagin, I. V., Biryukova, E. V., & Maier, M. A. (2005). Kinematic and dynamic synergies of human precision-grip movements. Journal of Neurophysiology, 94(4), 2134-2144. https://doi.org/10.1152/jn.01310.2004

Harris, C. M., & Wolpert, D. M. (1998). Signal-dependent noise determines motor planning. Nature, 394(6695), 780–784. https://doi.org/10.1038/29528

He, C., Liu, Y., Tian, Y., & Yang, J. (2022). Neural representation of object manipulation skills in the human parietal cortex. Nature Communications, 13, 1–15. https://doi.org/10.1038/s41467-022-28654-7

Hepp-Reymond, M.-C., & Wiesendanger, M. (1972). Unilateral pyramidotomy in monkeys: Effect on force and speed of a conditioned precision grip. Brain Research, 36(1), 117–131. https://doi.org/10.1016/0006-8993(72)90770-6

Hesse, C., & Deubel, H. (2010). Advance Planning in Sequential Pick–and–Place Tasks. Journal of Neurophysiology, 104(1), 508–516. https://doi.org/10.1152/jn.00097.2010

Hesse, C., de Grave, D. D. J., Franz, V. H., Brenner, E., & Smeets, J. B. J. (2008). Planning movements well in advance. Cognitive Neuropsychology, 25(7–8), 985–995. https://doi.org/10.1080/02643290701862399

Hoff, B., & Arbib, M. A. (1993). Models of trajectory formation and temporal interaction of reach and grasp. Journal of Motor Behavior, 25(3), 175–192.

https://doi.org/10.1080/00222895.1993.9942044

Jeannerod, M. (1981). Intersegmental coordination during reaching at natural visual objects. In J. Long & A. Baddeley (Eds.), Attention and Performance IX (pp. 153–168). Lawrence Erlbaum Associates.

Jeannerod, M. (1984). The Timing of Natural Prehension Movements. Journal of Motor Behavior, 16(3), 235–254. https://doi.org/10.1080/00222895.1984.10735319

Jeannerod, M. (1988). The Neural and Behavioural Organization of Goal-Directed Movements. Clarendon Press.

Jeannerod, M. (1992). Neural simulation of action: A unifying mechanism for motor cognition. NeuroImage, 14, S103–S109. https://doi.org/10.1006/nimg.2001.0832

Jeannerod, M., Decety, J., & Michel, F. (1994). Impairment of grasping movements following a bilateral posterior parietal lesion. Neuropsychologia, 32(4), 369–380. https://doi.org/10.1016/0028-3932(94)90084-1

Jeannerod, M., & Biguer, B. (1982). Visuomotor mechanisms in reaching within extrapersonal space. In D. J. Ingle, M. A. Goodale, & R. J. W. Mansfield (Eds.), Analysis of Visual Behavior (pp. 387–410). MIT Press. https://doi.org/10.7551/mitpress/9780262518420.003.0020

Jeannerod, M., & Decety, J. (1990). The neural and behavioural organization of goal-directed movements. Trends in Neurosciences, 13(1), 67–71. https://doi.org/10.1016/0166-2236(90)90125-

Johansson, R. S., Hager, C., & Riso, R. (1992). Somatosensory control of precision grip during unpredictable pulling loads. III. Impairments during digital anesthesia. Experimental Brain Research, 56, 550–564. https://doi.org/10.1007/BF00237997

Johnson, P. B., Ferraina, S., Bianchi, L., & Caminiti, R. (1996). Cortical networks for visual reaching: Physiological and anatomical organization of frontal and parietal arm regions. Cerebral Cortex, 6(2), 102-119. https://doi.org/10.1093/cercor/6.2.102

Kazennikov, O., Wicki, U., Corboz, M., Hyland, B., Palmeri, A., Rouiller, E. M., & Wiesendanger, M. (1994). Temporal Structure of a Bimanual Goal-directed Movement Sequence in Monkeys. European Journal of Neuroscience, 6(2), 203–210. https://doi.org/10.1111/j.1460-9568.1994.tb00262.x

Kistemaker, D. A., Wong, J. D., & Gribble, P. L. (2014). The cost of moving optimally: kinematic path selection. Journal of Neurophysiology, 112(8), 1815–1824. https://doi.org/10.1152/jn.00383.2014

Latash, M. L., Scholz, J. P., & Schöner, G. (2001). Toward a new theory of motor synergies. Motor Control, 5(2), 167–188.

Latash, M. L., Scholz, J. P., & Schöner, G. (2002). Motor control strategies revealed in the structure of motor variability. Exercise and Sport Sciences Reviews, 30(1), 26–31. https://doi.org/10.1097/00003677-200201000-00006

Liu, Y., Jiang, L., Liu, H., & Ming, D. (2021). A Systematic Analysis of Hand Movement Functionality: Qualitative Classification and Quantitative Investigation of Hand Grasp Behavior. Frontiers in Neurorobotics, 15, 658075. https://doi.org/10.3389/fnbot.2021.658075

Lukos, J. R., Ansuini, C., & Santello, M. (2007). Choice of contact points during multidigit grasping: Effect of predictability of object center of mass location. The Journal of Neuroscience, 27(14), 3894–3903. https://doi.org/10.1523/JNEUROSCI.4693-06.2007

Marteniuk, R. G., & Bertram, C. P. (2001). Self-organizing processes: Does human movement lawfully produce invariant global properties? In G. E. Stelmach & J. Requin (Eds.), Tutorials in Motor Neuroscience (pp. 213–228). Kluwer Academic Publishers. https://doi.org/10.1007/978-94-011-3965-8_12

Marteniuk, R. G., MacKenzie, C. L., Jeannerod, M., Athenes, S., & Dugas, C. (2000). Constraints on human arm movement trajectories. Canadian Journal of Physiology and Pharmacology, 68(2), 499–505. https://doi.org/10.1139/y90-071

Mason, C. R., Gomez, J. E., & Ebner, T. J. (2001). Hand synergies during reach-to-grasp. Journal of Neurophysiology, 86(1), 2896-2910. https://doi.org/10.1152/jn.00260.2001

Merton, P. A. (1972). How I control the contraction of our muscles. Scientific American, 226(5), 30–37. https://doi.org/10.1038/scientificamerican0572-30

Parry, R., Macias Soria, S., Pradat-Diehl, P., Marchand-Pauvert, V., Jarrassé, N., & Roby-Brami, A. (2019). Effects of Hand Configuration on the Grasping, Holding, and Placement of an Instrumented Object in Patients With Hemiparesis. Frontiers in Neurology, 10, 240. https://doi.org/10.3389/fneur.2019.00240

Rice, N. J., Valyear, K. F., Goodale, M. A., & Milner, A. D. (2007). Orientation sensitivity to grasping objects: An fMRI study. Journal of Cognitive Neuroscience, 19(2), 226-241. https://doi.org/10.1162/jocn.2007.19.2.226

Rosenbaum, D. A., Loukopoulos, L. D., Meulenbroek, R. G., Vaughan, J., & Engelbrecht, S. E. (1995). Planning reaches by evaluating stored postures. Psychological Review, 102(1), 28-67. https://doi.org/10.1037/0033-295X.102.1.28

Rosenbaum, D. A., Meulenbroek, R. G. J., Vaughan, J., & Jansen, C. (2001). Posture-based motion planning: Applications to grasping. Psychological Review, 108(4), 709-734. https://doi.org/10.1037/0033-295X.108.4.709

Sanes, J. N., Donoghue, J. P., Thangaraj, V., Edelman, R. R., & Warach, S. (1995). Shared neural substrates controlling hand movements in human motor cortex. Science, 268(5218), 1775-1777.

Schieber, M. H., & Hibbard, L. S. (1993). How somatotopic is the motor cortex hand area?

Science, 261(5120), 489-492. https://doi.org/10.1126/science.8342024

Sheth, B. R., & Shimojo, S. (2002). How the lack of visuomotor feedback affects even the early stages of goal-directed pointing movements. Experimental Brain Research, 143(2), 181–190. https://doi.org/10.1007/s00221-001-0977-5

Smeets, J. B. J., & Brenner, E. (1999). A simple model for coordinating a reach-to-grasp movement. Human Movement Science, 18(1), 17-31. https://doi.org/10.1016/S0167-9457(98)00043-1

Smeets, J. B. J., & Brenner, E. (2004). The difference between the perception of absolute and relative motion: Movement planning in the presence of a task-irrelevant object. Vision Research, 44(4), 573-581. https://doi.org/10.1016/j.visres.2003.09.027

Smeets, J. B. J., van der Kooij, K., & Brenner, E. (2019). A review of grasping as the movements of digits in space. *Journal of Neurophysiology*, 122(4), 1578–1597. https://doi.org/10.1152/jn.00123.2019

Soechting, J. F., & Lacquaniti, F. (1989). An assessment of the role of vision in the control of manual aiming movements. Journal of Neurophysiology, 62(3), 527-548.

Ting, L. H., & Macpherson, J. M. (2005). A limited set of muscle synergies for force control during a postural task. Journal of Neurophysiology, 93(1), 609-613. https://doi.org/10.1152/jn.00681.2004

Traub, M. M., Rothwell, J. C., & Marsden, C. D. (1980). Anticipatory postural adjustments prior to arm movement in man. Journal of Physiology, 261, 77P–78P. https://doi.org/10.1113/jphysiol.1980.sp013943

Tresch, M. C., & Jarc, A. (2009). The case for and against muscle synergies. Current Opinion in Neurobiology, 19(6), 601–607. https://doi.org/10.1016/j.conb.2009.09.002

Trommershäuser, J., Maloney, L. T., & Landy, M. S. (2005). The expected utility of movement. Behavioral and Brain Sciences, 28(6), 753-754. https://doi.org/10.1017/S0140525X05350113

Turella, L., & Lingnau, A. (2014). Neural correlates of grasping. Frontiers in Human Neuroscience, 8. https://www.frontiersin.org/articles/10.3389/fnhum.2014.00686

van Beers, R. J., Brenner, E., & Smeets, J. B. J. (2013). Random walk of motor planning in task-irrelevant dimensions. Journal of Neurophysiology, 109(3), 969–977. https://doi.org/10.1152/jn.00454.2012

Van Soest, A. J., Haenen, W. P., & Rozendaal, L. A. (1994). Analysis of muscle function in human gait. Journal of Biomechanics, 27(1), 89-98. https://doi.org/10.1016/0021-9290(94)90032-9

Verheij, R., Brenner, E., & Smeets, J. B. J. (2012). The influence of target object shape on early reaching behaviour in natural prehension. Experimental Brain Research, 218, 167–179.

https://doi.org/10.1007/s00221-012-3013-1

Westling, G., & Johansson, R. S. (1984). Factors influencing the force control during precision grip. Experimental Brain Research, 53(2), 277–284. https://doi.org/10.1007/BF00238156

Wing, A. M., & Fraser, C. (1983). The Contribution of the Thumb to Reaching Movements. The Quarterly Journal of Experimental Psychology Section A, 35(2), 297–309. https://doi.org/10.1080/14640748308402135

Wing, A. M., Flanagan, J. R., & Richardson, J. (1997). Anticipatory postural adjustments in stance and grip. Experimental Brain Research, 116(1), 122–130. https://doi.org/10.1007/PL00005732

Zhang, Z., Su, M., Wang, X., Wang, Y., Li, S., & Chen, A. (2022). Reach-to-grasp kinematics and kinetics with and without visual feedback in early-stage Alzheimer's disease. Frontiers in Aging Neuroscience, 14, 888837. https://doi.org/10.3389/fnagi.2022.888837

APPENDICES