How Are Mental Rotation Ability and Postural Stability Related?

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Philipp Hofmann

aus Bayreuth

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Gutachterin (Betreuerin): Prof. Dr. Petra Jansen

Gutachter: Prof. Dr. Dr. h.c. Hans Gruber

Content

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Summary

This thesis explores the relationship between the cognitive skill of mental rotation and the physical ability of postural stability, considering the long-standing knowledge that cognitive and motor tasks can impact one another (Shumway-Cook & Woollacott, 2007). The capacity to mentally rotate objects is known as mental rotation ability. Research in this area has shown that mental and motor rotations share common processes (Wohlschläger & Wohlschläger, 1998) and that mental rotation is considered a covert motor rotation (Wexler et al., 1998). Relationships to complex sports activity (Pietsch & Jansen, 2012; Voyer & Jansen, 2017) and basic motor abilities, like postural stability (Budde et al., 2021; Burcal et al., 2014; Dault et al., 2001; Kawasaki et al., 2014), were discovered throughout time. To better understand the relationship between mental rotation and postural stability, this thesis investigated several possible explanatory factors.

Study 1 examined the effects of simultaneous mental rotation on upright bipedal stance in different standard mental rotation tests, egocentric vs. object-based, with different stimulus material, embodied vs. non-embodied. The simultaneous solution of mental rotation tasks led to postural stabilization compared to a neutral condition. Egocentric mental rotation tasks provoked more postural stability than object-based tasks with cube figures. Furthermore, a more stable stance was observed for embodied stimuli than for non-embodied stimuli. An explorative approach showed the tendency that higher rotation angles in object-based mental rotation task stimuli led to more postural sway.

Study 2 focused on embodied stimulus material to clarify its role in the relationship between mental rotation and postural stability. It was investigated whether the function of the stimulus in postural control influences the amount of the embodiment effect. Therefore, two separate experiments examined the interference of egocentric and object-based mental rotation tasks, with embodied stimuli (foot, hand, whole body), with postural stability. Both experiments showed stabilization of body sway during the mental rotation tasks compared to a neutral control condition and an increased body sway with an increasing angle in the mental rotation tasks. While egocentric mental rotation tasks showed that mental rotation of hand and foot stimuli tended to elicit more body sway than whole-body stimuli, no difference between stimuli could be shown in object-based mental rotation tasks. In addition, reaction time in mental rotation tasks was a good indicator of postural stability in both experiments.

Study 3 attempted to generalize the relationship between mental rotation and postural stability and thereby discover the role of working memory in this relation. In contrast to the clear relationships from the two interference studies, study 1 and study 2, only a descriptively weak, if any, correlation was found between the two tasks. The role of working memory in this correlation is also negligible. Neither component of the visuospatial sketchpad of working memory showed a relationship to postural stability.

The results of this thesis contribute to a better understanding of the interaction between mental rotation and basic motor processes, like postural stability. While working memory does not seem to play a major role in this relationship, the role of embodiment is emphasized, even though study 2 showed no consistent effect of human body part stimuli.

1 Theoretical Background

Formerly, cognitive and motor function were viewed as two separate processes (Georgopoulos, 2000), but it is now common to assume that movements can only occur from interaction with other processes such as action, perception, and cognition (Shumway-Cook & Woollacott, 2007). Also everyday automated motor actions, such as simple upright standing, have been considered independent of cognitive processes. However, these assumptions have been criticized (Rankin et al., 2000), and it has been shown that postural control, the control of the body in space, and cognitive processes can influence each other (Shumway-Cook & Woollacott, 2007). In 1985, a study by Kerr et al. showed first that spatial tasks, but not verbal tasks, interfere with postural control when cognitive and postural tasks are performed simultaneously. They concluded that posture regulation is based on neural mechanisms which are also used for the cognitive processing of spatial tasks. The dual-task methodology they used is a common approach to investigate cognitive-motor interference. In general, dual-task paradigms are experimental procedures in which participants are asked to perform two tasks simultaneously. If a performance decline in one of the tasks compared to the single execution of this task can be shown, it is assumed that both studies compete for similar information processing resources (Künstler et al., 2018). The interference in dual-task designs can be explained in the framework of the "capacity," the "bottleneck," or "crosstalk"-theories (Pashler, 1994). The capacity theory assumes that there is a certain amount of total capacity for processing, and if several tasks must be performed simultaneously, there is less capacity available for each task. The bottleneck theory supposes that some tasks cannot be processed simultaneously because they require a mechanism focusing only on them for a certain amount of time. Consequently, one task is delayed or otherwise impaired. Crosstalk's theories suggest that it depends more on the content of the tasks to be processed. On the one hand, it is assumed that two or more tasks will benefit each other if they use similar or the same process paths, but on the other hand, there is also the view that tasks that are too similar can interfere with each other (Pashler, 1994).

When investigating cognitive-motor interference, upright standing is a frequently used motor task in dual-task designs. It is an essential everyday task, well standardizable and parameterizable. It has already been shown that cognitive tasks performed simultaneously can influence the quiet upright stance. Whether this influence leads to postural stabilization or deterioration is not clear. While in some dual-task studies on this topic, the simultaneous conduction of different cognitive tasks leads to a deterioration of postural stability (Mujdeci et al., 2016; Pellecchia, 2003; Shumway-Cook et al., 1997), other studies show that body sway can be stabilized (Andersson et al., 2002; Dault et al., 2001; M. C. Hunter & Hoffman, 2001; Potvin-Desrochers et al., 2017; Vuillerme et al., 2000). Specific kinds of cognitive tasks, where a relation to motor performance has been extensively discussed, are mental rotation tasks. For example, in quasi-experimental studies, motor experts demonstrate a better mental rotation performance than non-experts (Voyer & Jansen, 2017).

1.1 Mental Rotation

1.1.1 Mental Rotation Ability

Mental rotation is imagining how an object would look if it were rotated from its original position. Back in 1985, Linn and Petersen presented mental rotation as its own category of spatial abilities alongside two others, spatial perception and spatial visualization. In more recent studies, such as from a meta-analysis by Uttal et al. (2013), spatial abilities subdivide into intrinsic, extrinsic, and static and dynamic tasks. This results in a 2 x 2 matrix for classifying spatial abilities. Depending on the type of mental rotation task, mental rotation falls into a different category. Whatever definition it is assigned to, mental rotation is deeply rooted in the concept of spatial abilities. First, Shepard and Metzler (1971) described the ability of mental rotation. It was about imagining the mental representation of objects rotated in mind. They described an experiment in which two cube figures were presented side by side, and the subject had to decide as quickly as possible whether the right cube figure could be transferred to the left figure by rotation. A quasi-linear relationship was found between increasing angular disparity and the required reaction time. Besides this, Zacks et al. (2000) differentiate two types of mental rotation transformations: object-based and egocentric transformations. The task used in the study of Shepard and Metzler (1971) is the classical object-based transformation paradigm. Here, two items are presented on a screen, with the right stimulus rotated and mirrored or non-mirrored versus the left stimulus. The participant must decide whether both stimuli are "the same," i.e., not mirrored, or "different, i.e., mirrored. However, in egocentric mental rotation, a right or left decision must be made. For example, a rotated figure extending the right or left arm is shown. The participant must decide which arm it is. Both types of mental rotation are distinguished by the relationship of the observer to the environment. In object-based mental rotation, the observer's position remains fixed, and the two stimuli are rotated relative to each other. In egocentric mental rotation, the observer's position is assumed to change as the observer imagines rotating himself to solve the task. Compared to object-based rotations in the picture plane, these egocentric or perspective transformations are performed faster and more accurately (Amorim & Stucchi, 1997; Keehner et al., 2006; Wraga et al., 1999; Wraga et al., 2005). Furthermore, the increase of the slope in egocentric mental rotation tasks appears only for angles above 60 or 90 degrees, hence the function of response time on the angle of rotation for egocentric transformations is flatter than for object-based transformations (Keehner et al., 2006; Michelon & Zacks, 2006). One explanation could be that smaller angles in egocentric tasks can be judged by visual matching, whereas larger angles require greater mental effort because of the perspective transformation. The more classical increase of response time with increasing angular disparity is more evident in object-based tasks than in egocentric mental rotation tasks (Jola & Mast, 2005; Michelon & Zacks, 2006).

1.1.2 Mental Rotation Tests

A common distinction in mental rotation testing is categorizing into chronometric, based on Shepard and Metzler (1971), and psychometric, based on Vandenberg and Kuse (1978), mental rotation tests. Chronometric mental rotation tests are computer-based tests in which task reaction time and accuracy can be evaluated. They can be used to test for both, object-based transformations and egocentric transformations. In object-based chronometric mental rotation tasks, the standard setup is that two stimuli are presented next to each other, and a decision must be made whether the right stimulus is the same or a mirrored version of the left stimulus. Since angular disparity is not clearly defined for mirrored stimuli, the usual procedure is to evaluate only non-mirrored stimuli (Jolicœur et al., 1985). Because half of the trials performed are lost this way, there are new approaches that rely on a three-figure design (Jost & Jansen, 2020). Two base figures, mirrored to each other, and a stimulus figure, for which one must decide which of the two figures can be transferred by rotation. Nevertheless, the previous version of the object-based chronometric mental rotation test is still common, and the new design needs further research.

Psychometric mental rotation tests are usually performed as paper and pencil tests. The original psychometric mental rotation test was developed in 1978 by Vandenberg and Kuse based on the test of Shepard and Metzler (1971). In this test, a cube figure is presented on the left, and four variants of this figure are shown on the right. Two of them show the same, but rotated, stimulus and the other two can be mirrored or structurally different versions of the original stimulus. Due to frequent copying of the test material, the quality of the stimulus material continued to deteriorate, so Peters et al. (1995) presented a computer-drawn version of the test. In their frequently used test, 24 items consisting of a target stimulus on the left and four choices (two equal and two unequal stimuli) must be solved. Two subsets of 12 items are presented, which must be solved within three minutes. There is a four-minute break between the subsets. One point is awarded per item for scoring if both possible answers are solved correctly. Compared to the chronometric tests, a major advantage here is that many subjects can be tested quickly. However, since the chronometric mental rotation test provides more detailed information in the analysis, it was used in all experiments presented in this work.

1.1.3 Embodiment in Mental Rotation

A crucial role in mental rotation research plays the influence of the type of stimuli. Using human bodies or body parts as stimuli is the direct consequence of what is known as “embodied cognition” (Lakoff & Johnson, 1999). Embodied cognition means that cognition arises from the need to control the body’s function in the natural environment (Wilson, 2002). Saying this, embodied cognition is based on the assumption that mental and physical processes are related (Glenberg, 2010). Several taxonomies exist within embodied cognition or grounded cognition theories, for example, one of common coding, internal models, or simulation theory, that operate on different levels and interfaces (Jansen, 2022). However, stimuli that provoke a motor response should facilitate cognitive tasks. Kosslyn et al. (1998) investigated the importance of the stimulus material in mental rotation tasks. They demonstrated in a PET study that mental rotation of hand stimuli differs from that of cube stimuli because only the mental rotation of hands activated brain areas associated with low-level motor processes. There is also evidence from other studies that suggest that body-part stimuli, mental rotation, and the body are related. For example, the mental rotation of pictures of body parts correlated with the amount of time needed by the participants to imagine the corresponding process of the body part (Parsons, 1987, 1994). Also, the author demonstrated that participants could more easily imagine a biomechanically comfortable hand rotation than an uncomfortable hand rotation. He came to the conclusion that the subjects used their own hand as point of comparison for the rotated stimulus. Amorim et al. (2006) demonstrated in a series of experiments that the stepwise humanization of a classical cube figure, for instance, by adding a human head to classical cube figures, improves mental rotation performance. The authors explained this by stating that one's body axes are spatially and motorically mapped onto the axes of the rotated stimulus. Voyer and Jansen (2016) used body figures, human-headed cube figures, and classical cube figures, all stimuli taken from Amorim et al. (2006), to investigate whether using embodied stimulus material reduces the typical gender effects in mental rotation tasks. This could not be shown, however, as in Amorim et al. (2006), there was an advantage in mental rotation performance with increasing humanization of the stimulus. Body figures were solved faster than human-headed cube figures, which were faster than classical cube figures. As possible explanations for these results, they suggest, on the one hand, the use of a holistic rotation strategy when solving the task and, on the other hand, the projection of the body coordinate system onto the humanized stimuli.

Furthermore, according to Kessler and Thomson (2010), egocentric mental rotation tasks are embodied differently than object-based mental rotation tasks because interactions between the direction of mental rotation and a person's body posture only take place in egocentric and not in object-based rotation tasks. Regarding mental rotation tasks and the different perspectives, the following link to motor imagery can be constructed, especially with embodied stimuli. Two perspectives of motor imagery can be distinguished: the kinesthetic perspective, in which a person imagines performing the movement himself, and the visual perspective, in which one imagines someone else performing the movement (Stins et al., 2015). Hence, even if it does not exactly fit the definition, an egocentric mental rotation task with embodied stimuli belongs to the kinesthetic perspective, and an object-based mental rotation task is similar to the visual perspective.

1.1.4 Mental Rotation and Working Memory

According to Miyake et al. (2001), working memory plays a role in visual-spatial cognitive abilities and is, therefore, possibly linked to mental rotation. Despite different definitions of working memory (Cowan, 2017), there is a standard and widely used definition by Baddeley and Hitch (1974). They say working memory is a multi-component model (Baddeley et al., 2021). It includes the central executive and the three slave systems, the phonological loop, the episodic buffer and the visuospatial sketchpad (Baddeley, 2000). A mental rotation task includes the following stages: the perceptual stage (perceptual processing, identification and discrimination of stimuli, identification of orientation), stages of the rotation process (mental rotation and judgment of parity) and the decision process. This last process includes the response selection and the execution phase (pressing a key) (Heil & Rolke, 2002). Especially in the stage of the rotation process, participants must keep the object in the working memory until they can complete a parity judgment. For this, information about the object and the spatial arrangement is essential. Smith et al. (1995) investigated spatial memory tasks and object memory tasks via positron emission tomography. They showed that the spatial tasks activated only the right-hemisphere regions and the object tasks activated mainly the left-hemisphere regions. They concluded that different working memory buffers are used for storing spatial and object information. There is already evidence that these two systems may be related to mental rotation. On the one hand, findings suggest the connection between mental rotation and object working memory (Hyun & Luck, 2007). In a dual-task design, they performed mental rotation tasks both during a task involving object working memory and during a task involving spatial working memory. They found a rotation-dependent interference between mental rotation and object working memory but not between mental rotation and spatial working memory. On the other hand, there are indications of a connection between mental rotation and spatial working memory (Kaufman, 2007). He investigated the relationship between working memory capacity and gender differences in mental rotation and spatial visualization. Among other things, he showed a significant correlation between spatial working memory and mental rotation. Cornoldi and Mammarella (2008) showed that subjects with strong spatial abilities, as measured by using mental rotation tasks, perform better on a typical spatial working memory task (Corsi-Block-Task forward and backward) for five blocks or higher than subjects with low spatial abilities. Lehmann et al. (2014) even demonstrated a positive correlation between mental rotation performance and spatial working memory in three- to six-year-old children.

1.1.5 Mental Rotation and Motor Tasks

In general, for the relationship between mental rotation and motor function, it is assumed that motor and mental rotations share common processes (Wohlschläger & Wohlschläger, 1998) and that the mental rotation process can be considered as a covert motor rotation (Wexler et al., 1998). Moreover, motor capabilities seem to be involved in mental rotation processes because motor experts perform better in mental rotation tests than non-motor experts. Steggemann et al. (2011) investigated whether motor expertise provides an advantage in object-based or egocentric mental rotations. They found that motor experts only had an advantage over non-motor experts in egocentric mental body rotations. They explained this by the fact that egocentric mental rotation tasks require a perspective change of one's own body. Pietsch and Jansen (2012) compared sports, music, and education students regarding their mental rotation performance in a psychometric test. They showed that sports and music students had better mental rotation abilities than education science students. Voyer and Jansen (2017) summarized the relationship between motor expertise and performance in spatial tasks in a meta-analysis. They generally found that motor experts perform better in spatial tasks than non-motor experts. They also show several moderators in this relationship, for example, the kind of motor expertise or the type of stimuli in mental rotation tasks. Furthermore, there are also findings that mental rotation ability can be improved by motor training. Jansen et al. (2011) demonstrated that three months of juggling training significantly improved children’s mental rotation ability. Also, Blüchel et al. (2013) and Pietsch et al. (2017) showed that general child-specific motor training could improve children's mental rotation performance in up to 4 weeks. Now that it has been shown that motor tasks, which here were mainly a form of sports activity, are related to mental rotation tasks, the question arises whether this relationship also applies to everyday automated motor tasks, such as standing upright.

1.2 Postural Stability

1.2.1 Definition and Measurement

Stabilizing oneself upright in everyday life is one of the most fundamental movements of human existence. Postural stability, also called balance, is the ability to control the body's center of gravity about the support surface (Shumway-Cook & Woollacott, 2007). To quantify postural stability, usually, the Center of Pressure (CoP) is calculated using a force plate (Rhea et al., 2014). During standing, the CoP represents the weighted average of the sum of the vertical ground reaction forces exerted by both feet onto the force plate (Winter, 1995). The position of the CoP is described two-dimensionally in the anterior-posterior direction and the medio-lateral direction, depending on the stance orientation of the subject. The measurement of the CoP is called posturography, whereby a distinction is made between dynamic and static posturography. Dynamic posturography is defined by the stance measurement while exposed to external perturbations. Measuring the quiet upright stance without any active disturbance, as used in this work, corresponds to static posturography (Duarte & Freitas, 2010). How exactly the stance should be, i.e., whether it is one-legged, two-legged or special stances like the semi-tandem or full-tandem stance, is irrelevant to the measurement itself (Paillard & Noé, 2015). However, when interpreting the results, it should be considered that an increased base of support defined by a polygon bounding the outer edges of the feet, which have ground contact, can lead to more stability (Duarte & Freitas, 2010). The standardization of the foot position in postural stability measurements is therefore a factor that should not be neglected (Chiari et al., 2002). To parameterize the quiet upright stance, the course of the CoP while standing on the force plate is considered. There are numerous possible parameters, which can be classified into global and structural parameters (Baratto et al., 2002). The global parameters deal with the magnitude of the CoP course in the time or frequency domain. There, the CoP course can be considered either as a total or in its two directional components (anterior-posterior and medio-lateral) individually. Typically, lower CoP displacements are referred to as a more stable stance (Palmieri et al., 2002), and this approach is common for many researchers (Rhea et al., 2015). However, since movement variability is a natural phenomenon (Stergiou & Decker, 2011), some variability in the CoP signal can also be considered to be a functional component of stance (Haddad et al., 2013). So, an upright stance with high CoP-displacements over time, evaluated solely based on global parameters, is not necessarily a less stable stance if it does not involve a fall or loss of balance. To examine this variability, there is the second case of classification of CoP parameters, namely the structural parameters. They analyze the temporal organization of the CoP signal, divide the CoP signal into sub-units and try to associate these with the underlying motor processes (Baratto et al., 2002). Which parameters are finally used for analysis is very individual and depends on many factors, such as the experimental design or the postural task to be analyzed. However, a lot of reviews provide an overview of many common parameters and contribute to more transparency and greater comparability between studies through open-source analysis code (Duarte & Freitas, 2010; Hufschmidt et al., 1980; Prieto et al., 1996; Quijoux et al., 2021). Some other factors, such as the stance duration, the sampling frequency and the data filtering, also play a crucial role in the measurement of postural stability. Concerning the sampling duration of the stance, some studies say that a time period of 25 - 40 seconds is sufficient for reliable results (Scoppa et al., 2013). Others say that at least

60 seconds should be recorded (Carpenter et al., 2001; van der Kooij et al., 2011). An important aspect here is the possible non-stationarity of the signal during longer measurements, which means there might be no statistical similarity between successive parts in the CoP data (Duarte & Freitas, 2010; Stergiou, 2016). The longer the stand, the more the signal can "wander." (Collins & Luca, 1994; Fraizer & Mitra, 2008). While some say that in the practical application the influence is not too big (Duarte & Freitas, 2010), others say it is essential to consider (Carroll & Freedman, 1993). In addition, also the strain, because of the difficulty of the task, on the subject must be considered when choosing the sampling duration. Logically, a one-legged stance is more difficult to maintain than a two-legged stance. Another factor that is related to the sampling duration is the sampling frequency, which indicates how precisely the CoP course is recorded. Concerning the Nyquist theorem, measuring with a sampling frequency at least twice as high as the frequency of the fastest expected movement change is recommended. In practice, however, measurements are often made at five to ten times the expected movement frequency. It should be noted that a too-low frequency may not correctly represent the CoP curve, while a too-high frequency may add more measurement noise to the data (Stergiou, 2016). Closely related to the sampling frequency is the filtering of the data. Appropriate filtering can remove noise and artifacts from the data, but it can also alter fundamental structural components of the CoP signal (Rhea et al., 2015; Stergiou, 2016). The measurement of postural stability using the CoP course in dual-task designs is also highly sensitive to interference caused by different types of responding: For example, verbal responses influence body sway (Conrad & Schönle, 1979; Dault et al., 2003; Jeong, 1991; Yardley et al., 1999), and contact with an anchored object, such as operating a laptop, stabilizes body sway (Clapp & Wing, 1999; Jeka & Lackner, 1994).

All these mentioned influencing factors concerning data recording, data processing and response generation must be thoroughly weighed when selecting a method for a dual-task design in postural stability research and considered in the results of a study. To ensure transparency and comparability between studies, it is also recommended to report all details as accurately as possible.

1.2.2 Postural Stability and Working Memory

There are several studies linking different areas of working memory and postural stability. For example, Bhatt et al. (2016) investigated the dual task cost of a working memory task, challenging the phonological loop and a semantic memory task, in healthy young, healthy older and stroke-impaired older adults on body sway. According to their results, the phonological loop task had a greater impact on balance than the semantic memory task. Fujita et al. (2016), for their part, investigated the influence of the central executive on postural control. They determined two groups (low and high WM) using the Reading Span Test and then created a cognitive postural dual-task situation using the Stroop Test. The low WM group had dual-task interference in a demanding postural condition, in contrast to the high WM group. They concluded that general WM capacity might influence dual-task situations with motor tasks. However, concerning mental rotation ability, studies dealing with the connection between the visuospatial sketchpad and postural stability are particularly interesting here. As mentioned earlier, mental rotation ability connects with spatial working memory (Kaufman, 2007) and with object working memory (Hyun & Luck, 2007). Both can be assigned to the visuospatial sketchpad. Concerning the interference of the visuospatial sketchpad and postural stability, Maylor and Wing (1996) investigated age differences in postural stability during the concurrent performance of five different cognitive tasks that address different areas of working memory. They found that the age differences in postural stability are enhanced when a cognitive task involving the visuospatial sketchpad is performed concurrently to a stance task. Similar findings are reported for other locomotor tasks, such as gait (Menant et al., 2014). It was shown that in older adults visuospatial tasks, performed simultaneously, influence gait more than nonspatial tasks. Therefore, they conclude that visuospatial processing shares common networks with locomotor control. Furthermore, relations between patients' balance deficits and visuospatial sketchpad tasks were shown. Brecl et al. (2019) investigated the influence of two working memory tasks, one challenging the phonological loop and one the visuospatial sketchpad, in patients with suspected multiple sclerosis and healthy subjects. They showed that dual-task costs are higher in patients than in healthy subjects and more pronounced in the visuospatial sketchpad task. Smulders et al. (2013) studied the association between Parkinson’s disease and executive dysfunction in 232 non-demented mildly affected Parkinson's patients. This revealed weak relationships between spatial working memory and balance deficits. In contrast to these two studies, Useros Olmo et al. (2020) showed postural stabilizing effects in patients. They investigated the dual-task interaction between working memory and motor tasks in patients with traumatic brain injury and healthy control subjects. Regarding balance, they showed postural stabilization in patients and controls during a spatial working memory task. VanderVelde et al. (2005) took a closer look at the visuospatial working memory – postural stability interference and investigated the influence of two visual working memory systems (object working memory and spatial working memory) on postural stability in healthy young adults. They showed that complex posture tasks significantly deteriorated spatial working memory tasks but did not affect object working memory tasks. They concluded that visual working memory and postural control interact due to the spatial domain. Similar neuronal findings were shown by Chen et al. (2018), who showed with functional near-infrared spectral imaging that postural control has more influence on spatial working memory tasks than on non-spatial working memory tasks. Based on these findings, it seems possible that working memory is involved in the connection between mental rotation and postural stability.

1.2.3 Role of Embodiment in Postural Stability

It has long been known that physical and cognitive states are related (Barsalou, 2008). Since this thesis is concerned with postural stability on the physical side, only the interaction with postural stability will be considered in more detail. Some research branches deal with the interaction of postural stability with emotions (Stins & Beek, 2007) or with the connection to inner attitudes like mindfulness (Rosenstreich et al., 2018). Because embodied stimuli are, as already described, a common approach to elicit an embodiment effect in mental rotation tasks, it is of particular interest how postural stability relates to embodied stimulus material. The basic idea of why these could be related to each other comes, for example, from results of a study by Brass et al. (2001). They showed that movements that are compatible with an observed movement are executed faster. Also, the theory of a mirror neuron system, i.e., that a purely observed action performed by another person causes activation of the motor cortex of the observer provides a theoretical basis (Rizzolatti & Craighero, 2004). Furthermore, there are already neuronal findings showing that mental rotation of hand images shows the same or similar brain activity as during the physical movement of the hand (Lange et al., 2005). Explicitly related to mental rotation, it has already been argued that the two mental rotation tests, object-based and egocentric, could represent a visual perspective or a kinesthetic perspective in terms of perspective-taking. Such a kinesthetic perspective is thought to be more embodied, with postural information being more important (Lorey et al., 2009). Studies, such as those by Rodrigues et al. (2010), that examine these two views of motor imagery in terms of postural stability investigated the imaging of a plantar flexion movement (rising on tiptoes) and found that imaging oneself rising on tiptoes leads to a greater postural sway than imaging someone else rising on tiptoes. They controlled for actual movement during the imagination with measuring the muscle activity at the Musculus gastrocnemius with a surface-EMG and tested in a standardized feet position with both feet together. Stins et al. (2015) investigated the imagination of five different activities (2 lower body movements, two upper body movements and one neutral condition) from a kinesthetic and a visual perspective. They showed that the kinesthetic imagery of lower body movements caused a greater postural sway than that of upper body movements or the neutral condition. For visual imagery, they found no significant differences between the conditions.

1.3 Mental Rotation and Postural Stability

For balance ability, significant correlations were shown with rotational performance. Jansen and Heil (2010) showed a significant positive correlation between children's mental rotation performance in a paper-pencil-test and balance ability. Similarly, it was shown for older adults that a single-leg stance correlated with the accuracy rate of the mental rotation tasks (Jansen & Kaltner, 2014). Ganczarek et al. (2015) investigated the influence of viewing pictures with different depths and backgrounds on body sway. Among other results, they found significant positive correlations between body sway and a psychometric mental rotation test, which was measured after the postural task. They suggested that body sway might be mediated by individual differences in mental imagery. These findings on the relationship between mental rotation and balance ability are further supported by the results of a fMRI study by Podzebenko et al. (2002). It demonstrated activation of the cerebellum, which plays a central role in balance ability, during mental rotation tasks. Further, Kawasaki and Higuchi (2013) linked mental rotation, different types of pictures of the body, and postural stability tasks. They found that performing an egocentric mental rotation task with feet as stimuli but not with cars as stimulus material led to less postural sway when sway was measured directly after the mental rotation task. This effect could only be shown for one-legged stance, not for two-legged. In a study of Kawasaki et al. (2014) correlations between the unipedal stance and postural stability parameters were shown. For other investigated body parts (hand stimuli), no significant correlation with body sway could be demonstrated in the single-leg stance. Moreover, the effect of a mental rotation intervention on postural stability, lasting up to 60 minutes in a single-leg stance, was more effective when using foot stimuli than using hand stimuli (Kawasaki & Higuchi, 2016). As a possible explanation they suggest that the feet / ankles play a more important role in postural control than the hands because they are more related to the stance. Therefore, they may interfere more with postural control as hands as stimulus material.

There are only a few studies on dual tasks of mental rotation and postural stability. Dault et al. (2001) examined the effects of different working memory tasks in several postural tasks and the impact of an egocentric mental rotation task with a stick figure on the variability of postural sway in the anterior-posterior and mediolateral directions. Body sway was reduced compared to a control condition (looking at a fixation point) but not to other working memory tasks. A study by Burcal et al. (2014) showed similar results. They investigated the influence of different task instructions on three different working memory tasks (backward counting, random number generation, and mental rotation). It could be seen that instructions on both the balance task and the cognitive task had stabilizing effects over a control condition. In addition, they showed that all cognitive tasks had stabilizing effects over a control condition. They found more stabilizing effects for the mental rotation task versus the backward counting task and concluded that tasks that engage visual-spatial working memory have better effects on postural stability than tasks that engage the phonological loop. Budde et al. (2021) investigated objectbased and egocentric mental rotation with human stimuli while standing in different positions on a force plate. They showed more postural stability in the egocentric mental rotation task than in the objectbased task. To sum up, dual-task paradigms show a stabilizing influence of mental rotation tasks on postural stability (Budde et al., 2021; Burcal et al., 2014; Dault et al., 2001).

2 Summary of the State of Research

How exactly motor and cognitive tasks are related or influence each other has been the research subject for a long time. There are different explanations for why these two supposedly separate processes interact with each other, but also inconclusive results in which way. In the literature, some known associations exist between mental rotation ability and motor tasks of different complexity. It seems that mental rotation is related to both complex motor skills, such as various sports activities, but also to basic motor skills, such as standing quietly upright. Mental rotation means to imagine objects rotated in one’s mind and generally, in mental rotation tasks, it is shown that when a rotation takes place in mind, it lasts longer depending on the degree of rotation and thus is similar in time to a manual rotation of the same object. However, it is not clear how the processes of mental rotation and motor processes are related. Therefore, this thesis addresses how and why mental rotation relates to a basic motor task, standing upright, and attempts to clarify which factors may be essential to understand better the underlying relationship between mental rotation and postural stability.

Study 1 aims to provide the link between mental rotation and postural stability and compares the postural sway during different common mental rotation tests, egocentric and object-based, with different stimulus materials, embodied and non-embodied.

Study 2 focuses on embodied stimulus material and attempts to show whether the type of embodied stimuli and its role in postural control has differential effects on postural stability.

Study 3 deals with another possible explanatory approach and investigates the role of the visuospatial sketchpad of working memory in the relation of mental rotation and postural stability. Because of the many individual studies on these relationships, an overall view of the relationships of the individual processes will be provided and it will be clarified whether the spatial working memory of the visuospatial sketchpad could be a possible explanation for this relationship.

3 First Study: The Relation of Mental Rotation and Postural Stability[1]

3.1 Goal of the Study and Hypotheses

It is the main goal of this study to investigate how different kinds of mental rotation tasks, egocentric tasks with embodied stimuli, object-based tasks with embodied stimuli and object-based tasks with non-embodied stimuli influence a basic motor ability, i. e. postural stability. The results will give insight in the relation of mental rotation and basic motor processes and contribute to the common process theory (Wohlschläger & Wohlschläger, 1998). If mental rotation has an influence on postural stability, one might assume that both tasks share common processes. This might give a hint, that the common process is not a covert motor rotation but a basic motor process.

The following hypotheses will be investigated:

1. First, according to the study of Dault et al. (2001), we assume generally a minor body sway after completing a mental rotation task compared to looking at a fixation cross.
2. Second, the relation of body sway and mental rotation can be investigated due to the nature of the mental rotation task:
   a) More body sway in egocentric tasks than in object-based tasks.
   Because an egocentric mental rotation task is similar to the kinesthetic imagery and an object based mental rotation task is similar to the visual imagery, we hypothesize that solving an egocentric mental rotation task causes a bigger change in body sway than solving an object based mental rotation task because the subject has to imagine rotating his/her own body (Kessler & Rutherford,

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[1] The results presented in this chapter were published in advance in: Hofmann, P., & Jansen, P. (2021). The Relation of Mental Rotation and Postural Stability. Journal of Motor Behavior, 1–15. https://doi.org/10.1080/00222895.2021.1899113

2010). While previous studies have been able to show this relation for lower body movements, we will investigate whole body images, as these correspond to the classical mental rotational stimuli.

b) Less body sway with humanized stimulus material than with cube figures.

In accordance with the results of Kawasaki and Higuchi (2013) we assume that solving mental rotation tasks with human figures causes a stabilization of body sway compared to solving a mental rotation task with cube figures because of the embodiment theory (Wilson, 2002). To control for this we examine the same object-based task and only vary the stimulus-material (cube figures vs human figures).

c) More body sway with increasing angular disparity

As Pellecchia (2003) stated an increasing body sway with an increasing difficulty of the concurrent cognitive task, it will be investigated, if the increasing rotation angles of the stimuli in the mental rotation tasks will cause more body sway.

3.2 Methods

3.2.1 Participants

84 students of the University of Regensburg (64 females and 20 males) participated in this study. With a small to medium effect size f = .15, an alpha-level of p = .05 and a power of 1-ß = .95, a power analysis with G*power (Faul et al., 2007) for the repeated measures ANOVA resulted in N = 84 to detect significant effects for the body sway between the five different types of stimuli. The participants' mean age was 21.1 years (SD = 1.6 years), with a range from 18 – 27 years. The average height of the participants was 171.7 cm (SD = 9.3 cm). None of the participants had a disease or an injury affecting the balance. The experiment was conducted according to the ethical

guidelines of the Helsinki declaration. All participants gave their written informed consent to participate in this study.

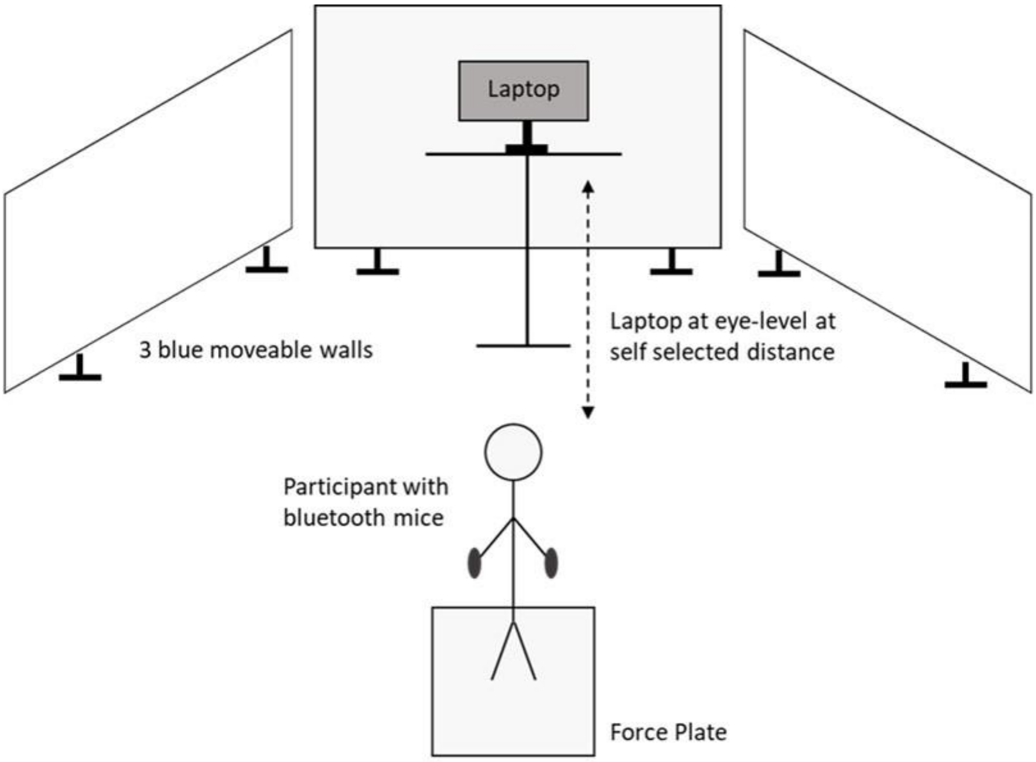
3.2.2 Material

3.2.2.1 Postural Stability Task

To quantify the postural sway of each person, the Center of Pressure (CoP) course over time will be investigated, which is measured with a force platform (Rhea et al., 2014). During bipedal standing the CoP is the point location of a weighted average of the sum of vertical ground reaction forces applied by the feet on the force plate (Winter, 1995). A smaller CoP displacement is referred to as a more stable stance (Palmieri et al., 2002) and this conclusion of a smaller CoP displacement as a more stable stance is common (Rhea et al., 2015). In this study an AMTI force plate (AMTI OR6-7-2000) with a sampling frequency of 1000 Hz was used. The cognitive tasks were run on a laptop (Dell Inspiron 1750, 1600x900) placed on eye-level at a self-selected distance in front of the participant, standing on the force plate. Postural stability in dual task designs is very vulnerable to disturbances caused by different types of response, as for example verbal responses, which have an influence on body sway (Conrad & Schönle, 1979; Dault et al., 2003; Jeong, 1991; Yardley et al., 1999), and also the direct response at the laptop, since any contact with an anchored object stabilizes body sway (Clapp & Wing, 1999; Jeka & Lackner, 1994). Because of this and similar to Huxhold et al. (2006) , the test persons were given one bluetooth mouse in each hand. However only the right mouse was switched on and connected to the laptop for answering. Participants were asked to stand as still as possible in an erected position with their arms at their sides. The palm of the hand faced towards the body without touching the body. The feet were placed in a narrow stance position on either side of a three cm wide tape and with the heels aligned in front of another tape in order to maintain a standardized foot placement (Richer & Lajoie, 2019). The following figure 1 shows a sketch of the test setup.

Figure 1

Exemplary Test Set-Up



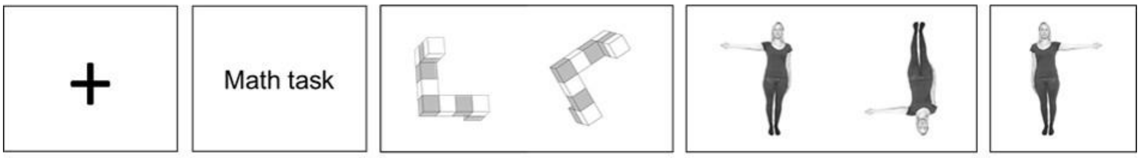
All participants wore ultra-thin try-on socks to maintain the barefoot condition but provide a better hygiene. The head faced the laptop. One trial lasted minimum 70 seconds and consisted out of several tasks of the same condition. The force plate and laptop were aligned so that the line of sight was directed to the wall. In addition, the force plate was located on the open side of a three-part construction with 1,25 m (width) x 1,85 m (height) blue moveable walls to prevent unwanted visual stimuli. To characterize the course of the CoP, the parameters maximum width in anterior-posterior direction, maximum width in medio-lateral direction, mean amplitude and mean sway velocity were calculated (Hufschmidt et al., 1980; Palmieri et al., 2002).

3.2.2.2 Cognitive Tasks

For presenting the stimuli the software “Presentation” (Version 20.1 Build 12.04.17, Neurobehavioral Systems, Inc., Berkeley, CA, www.neurobs.com) was used. Regarding the experimental design there were five different conditions, two control conditions and three mental rotation tasks, see figure 2.

Figure 2

Two Control Conditions and Three Different Mental Rotation Tasks



Note. From left to right: Control condition 1: Looking at fixation cross, Control condition 2: Math task as cognitive-control task, object-based mental rotation task with cube figures, object-based mental rotation task with human figures, egocentric mental rotation task with human figure.

All stimuli were presented on a white screen. In the first control condition participants had to look at a fixation cross without doing something else. In the second control condition they had to solve a math-task with subtractions. For this, they got a randomly chosen number between 200 and 999 as starting number and then a series of numbers between 1 and 9, which they had to subtract from the last interim result. After solving the subtraction in mind, they clicked the right or left mouse button and the next number was presented. When the trial was finished, they informed the experimenter about the final result. The three mental rotation tasks include a) an object based mental rotation task with cube figures, b) an object based mental rotation tasks with embodied stimuli and c) an egocentric mental rotation tasks with embodied stimuli.

Object-based mental rotation task with cube figures: The cube figures consisted of ten alternating black and white cubes and were created with the software R, based on the work of Jost and Jansen (2020). The alternation of colors defines a bottom and a top of the cube figures and makes them therefore more similar to the human figures (Amorim et al., 2006). It was the task of the participants to click either the left mouse button if the two presented stimuli were the same, i.e. the right stimulus was not mirror reversed to the left one, or the right mouse button if the stimuli were different, i.e. the right stimulus was mirror reversed to the left stimulus. The left stimulus always remained the same figure

Object-based mental rotation task with embodied figures: Two pictures of the same female were shown next to each other. The women on the picture raised one arm. Instructions for solving the tasks were the same as in the cube figures condition.

Egocentric mental rotation task with embodied figures: The picture showed only one female human figure, which either raised her right or left arm. Participants had to click the left mouse button if the figure raised the left arm and the right mouse button if the figure raised the right arm. The female figure was the same for both conditions and is the same female figure as used in Kaltner and Jansen (2018).

For all mental rotation tasks, the mental rotation figures had a size of 400 px times 400 px and were only rotated in picture plane clockwise by 60°-steps (0°, 60°, 120°, 180°, 240°, 300°). During the practice session for the mental rotation tasks there was feedback presented for 1500 ms in font size 40 shown in the center of the screen. During the main trial no feedback was given but a fixation cross in the middle of the screen for 1500 ms. The math task revealed the final result during practice but there was no feedback given in the main trial.

3.2.2.3 Cognitive and Physical Effort

As task difficulty or fatigue might be confounding factors the questionnaire ASS ("Effort scale in sport") by Büsch et al. (2015) was used to assess subjective cognitive and physical effort during the experiments. The ASS questionnaire is a German ten-level evaluation questionnaire with additional color coding. Each level is provided with a semantically one-dimensional sentence ("not exerting” to "so exerting that I have to stop"). To evaluate cognitive effort, the tenth level has been replaced by the sentence "so exerting that I cannot solve".

3.2.3 Procedure

The individual test sessions lasted about 45 minutes and took place in a quiet laboratory at the University of Regensburg. All participants were tested separately and there was always the same experimenter. A test session consisted of practice and 10 single trials (each of the five cognitive tasks appeared two times). After this they had to complete a demographic questionnaire. To carry out one trial, one of the five cognitive tasks had to be completed for 70 seconds while the postural stability task on the force plate was being performed simultaneously. A condition could exceed 70 seconds, because the experiment was programmed in a way that the last task of a trial could be solved by the test person, so that the trial was not aborted while solving a task. The cognitive tasks (two control conditions: fixation cross task, math task; three experimental tasks: object-based mental rotation task with cube figures, object-based mental rotation task with human figures, egocentric mental rotation task with human figure) were pseudo-randomized for each participant. This means, the first five trials consisted of the five cognitive tasks in randomized order and so did the second five trials. There was a 90-second break between the trials, during which the subjects sat down and, using the ASS questionnaire, evaluated the previous trial in terms of cognitive and physical effort. At the beginning of each trial, the test person was positioned on the force plate by the experimenter. After this, standardized instructions were given for the respective tasks. Participants were allowed to start the trial themselves by clicking the mouse, which started the trial immediately. Simultaneously with this mouse click, the experimenter started the CoP recording of the force plate. After completion of each trial, the experimenter stopped the CoP recording and asked the test person to step down from the force plate for taking a seat at a table to fill out the ASS questionnaire. Before the 10 trials were completed, there was a round of practice in which all five cognitive tasks were processed for 30 seconds in randomized order while performing the postural stability task. After the practice trials, the test persons were given a sufficient break and the ASS questionnaire was explained to them.

3.2.4 Statistical Analysis

The processing of the CoP data was performed in Matlab. The statistical analysis was performed using SPSS. Only the CoP data of seconds 5 to 65 were evaluated, to avoid movements where the participant anticipated the beginning or end of the trial (M. C. Hunter & Hoffman, 2001) and still have a sufficiently long measurement for getting reliable CoP-data (Carpenter et al., 2001). All irregularities during the trial, such as speaking, coughing, scratching or similar, were noted and the respective trials were excluded from the analysis (Woollacott & Vander Velde, 2008). In a first analysis, a mean value over time was calculated for each parameter per trial and then the course of the CoP was compared between different cognitive tasks using one-way repeated measures analyses of variance.

To investigate the body sway during different mental rotation tasks in more depth (hypothesis 2), the body sway was compared at the different rotation angles of the mental rotation tasks. For this purpose, the force plate data were synchronized with the mental rotation data in Matlab, so that for each period while a stimulus (without fixation cross and pause) was displayed, a value for the sway parameters (maximum width in anterior-posterior direction, maximum width in medio-lateral direction, mean amplitude and mean sway velocity) was given. A two-way repeated measures analysis of variance using the factors "stimulus type" and "rotation angle" was then calculated for each parameter. Additionally, the mean slope of each parameter in the respective measurement unit per 60° angle change. (This results in four mean values for clockwise and anti-clockwise measurements, 0°; 60°/300°; 120°/240°;180°) was calculated for each stimulus type and checked with a one-way repeated measures analysis of variance. Only correct responses to non-mirrored stimuli completed within the 60 seconds were included in the analysis of the individual rotation angles, as angular disparity is not clearly defined for mirrored-reversed stimuli and this is the common way of analysis in mental rotation studies (Jolicœur et al., 1985; Kaltner et al., 2017). The Friedman test was calculated to evaluate the ordinal data of the ASS questionnaire. To correct for violations of sphericity the Greenhouse-Geisser adjustment was used. Post hoc tests were Bonferroni-corrected.

3.3 Results

3.3.1 Mean Sway Parameter Values Per Trial

A mean value was calculated over time for each parameter per trial. Due to the above-mentioned irregularities 4.2% of the data was missing. To handle missing data the mean value of the respective task was inputed for further analysis. To get one value for each condition, the mean value for the two trials of each condition was calculated. Table 1 shows the four different parameters for the five stimuli.

Table 1

Mean CoP-Parameters for the Five Cognitive Tasks

Parameter	Stimulus				
	Fixation cross	Cube figures	Embodied figures	Egocentric Task	Math Task
MA	5.44 (1.28)	3.97 (0.87)	3.94 (0.87)	3.87 (0.83)	4.01 (0.88)
SV	196.95 (32.30)	198.03 (32.36)	197.60 (33.11)	198.12 (31.34)	196.25 (32.72)
Range AP	25.00 (5.54)	19.27 (4.78)	18.83 (4.56)	18.45 (4.02)	19.87 (4.73)
Range ML	19.34 (4.32)	17.15 (3.60)	16.86 (3.48)	17.07 (3.94)	17.14 (3.95)

Note. Mean value (SD) for the two trials of each condition. All values are reported in [mm]. MA = Mean amplitude, SV = Sway Velocity, Range AP = Maximum range of CoP in anterior-posterior direction, Range ML = Maximum range of CoP in medio-lateral direction.

Regarding the mean amplitude of the CoP course the repeated measures ANOVA with “stimulus type” as factor revealed a statistically significant difference of the different stimulus types, ($F(2.84, 235.39) = 107.21$, $p < .001$, partial $\eta^2 = .56$). Bonferroni adjusted post hoc analysis showed that the mean deviation from the arithmetic mean point for the task where participants looked at the fixation cross was significantly higher than in all other tasks (all $p < .001$). All other tasks did not differ significantly from each other.

Regarding the sway velocity of the CoP course the repeated measures ANOVA with “stimulus type” as factor and Greenhouse-Geisser correction (Greenhouse-Geisser = .774) revealed no statistically significant difference between the different stimulus types, ($F(3.10, 256.93) = 1.94$, $p = .122$, partial $\eta^2 = .023$).

Regarding the maximum range of CoP course in anterior-posterior direction the repeated measures ANOVA with “stimulus type” as factor and Greenhouse-Geisser correction revealed a statistically significant difference between the different stimulus types, ($F(3.61, 299.52) = 64.46$, $p < .001$, partial $\eta^2 = .44$). Bonferroni adjusted post hoc analysis showed that during the task where participants looked at the fixation cross the maximum range of CoP course in anterior or posterior direction was significantly higher than in all other tasks (all $p < .001$). Additionally, the maximum range in anterior-posterior direction was statistically significant higher in the math task than in the egocentric mental rotation task ($p < 0.05$). All other tasks showed no statistically significant differences between them.

Regarding the maximum range of CoP course in medio-lateral direction the repeated measures ANOVA with “stimulus type” as factor and Greenhouse-Geisser correction revealed a statistically significant difference between the different stimulus types, ($F(3.11, 258.45) = 13.84$, $p < .001$, partial $\eta^2 = .14$). Bonferroni adjusted post hoc analysis showed that during the task where participants looked at the fixation the maximum range of CoP course in medio-lateral direction was significantly higher than in all other tasks (all $p < .001$). All other tasks did not differ significantly from each other.

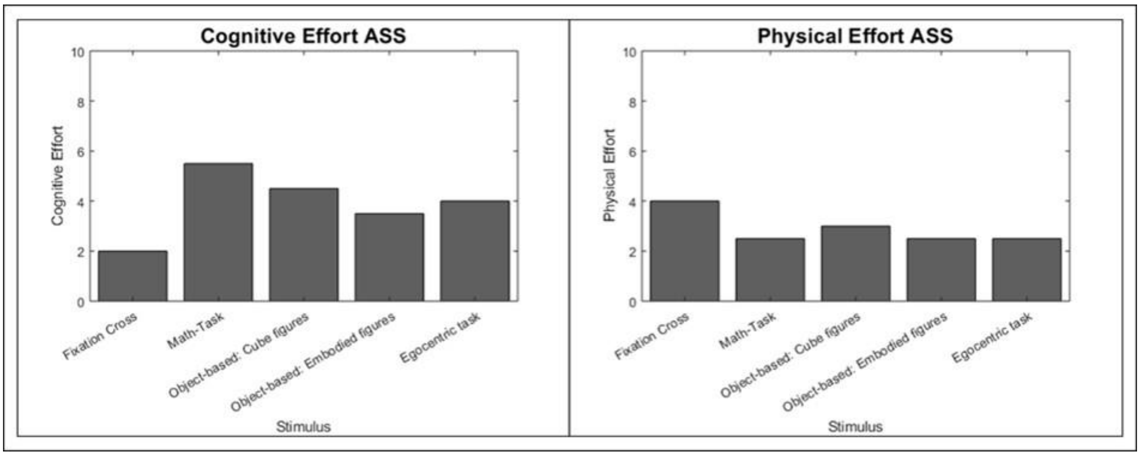
3.3.2 ASS Questionnaire

Figure 3 shows the results for the ASS-questionnaires. The left side of the figure displays the cognitive effort and the right side the physical effort. Since each condition was evaluated twice per person, the median of these two evaluations has been calculated. Regarding the cognitive effort significant differences between the different conditions ($\chi^2(4) = 194.252$, $p < .001$) could be revealed. Post hoc pairwise comparisons between all conditions (Dunn-Bonferroni-tests) showed significant differences between all conditions (all $p < .005$) except for the comparison between object-based mental rotation task with human figures and egocentric mental rotation task ($p = 1.000$). The physical effort also differed significant between the conditions

($\chi^2(4) = 100.056$, $p < .001$). The post-hoc Dunn-Bonferroni-tests showed that only the fixation cross condition differed significantly from all other conditions ($p < .001$).

Figure 3

Results of the ASS Questionnaire



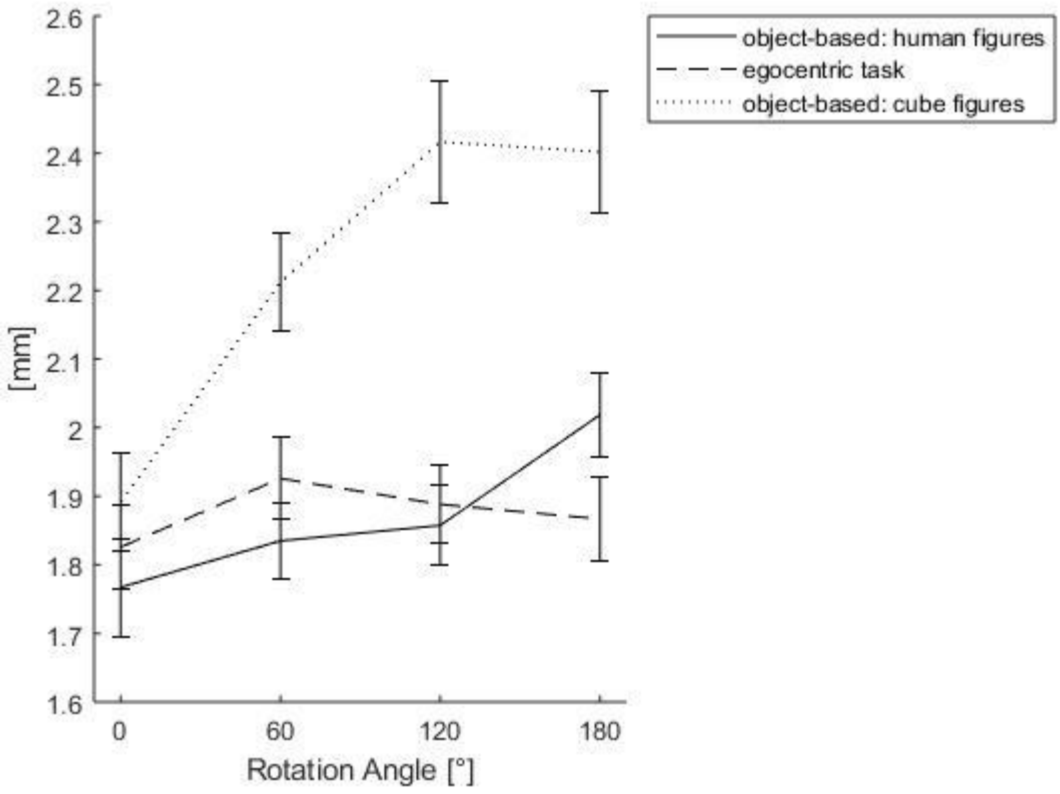
3.3.3 *Influence of Rotation Angles During Postural Stability Task*

Since the stimuli in the mental rotation tasks were displayed on a random basis, it was possible that individual test subjects were not shown certain angular rotations. To deal with these missing data, the mean values per stimulus type and rotation angle were input. A total of 3.8% of the data was missing.

Concerning the mean amplitude, see figure 4, the repeated measures ANOVA showed a significant main effect for the factor “stimulus type” ($F(1.814, 150.566)=52.564$, $p<.001$, partial $\eta^2 = .388$), for the factor “rotation angle”($F(2.737,227.147)=19.522$, $p<.001$, partial $\eta^2 = .190$) and a significant interaction between these two factors ($F(4.488, 372.509)= 7.474$, $p<.001$, partial $\eta^2 = .083$). Additional simple main effect analysis was conducted to detect possible differences of the rotation angles dependent on the type of stimulus. For the object-based task with human figures the mean amplitude of the body sway at the rotation angle 180° differed significantly to 0° ($p = .003$), to 60° ($p = .017$) and to 120° ($p = .049$). For the egocentric mental rotation task, no statistical significant differences could be shown. In the object-based task with cube figures the mean amplitude of the body sway at the rotation angle of 0° differed significantly from all other rotation angles ($p<.001$). The mean amplitude at the rotation angle of 60° differed significant from 120° ($p = .024$). The mean slopes of all three tasks differed significantly from each other ($F(2,166) = 8.898$, $p < .001$, partial $\eta^2 = .097$). Post hoc pairwise comparisons with Bonferroni correction revealed only significant differences between the mean slopes of the egocentric and the object-based task with cube figures ($p < .001$). For a better understanding of the influence of the stimulus type another simple main effect analysis was calculated for each angle. In figure 4 this can be read as vertical difference. For the mean amplitude of the body sway at the rotation angle 0° no significant differences between the tasks could be shown. At an angular disparity of 60° the object-based task with cube figures differed significant from the other two tasks ($p < .001$). For the mean amplitude at the rotation angle of 120° again the object-based task with cube figures differed significant from the two other tasks ($p < .001$). At a rotation angle of the stimuli of 180° the mean amplitude of all three tasks showed significant differences between each other ($p < .05$).

Figure 4

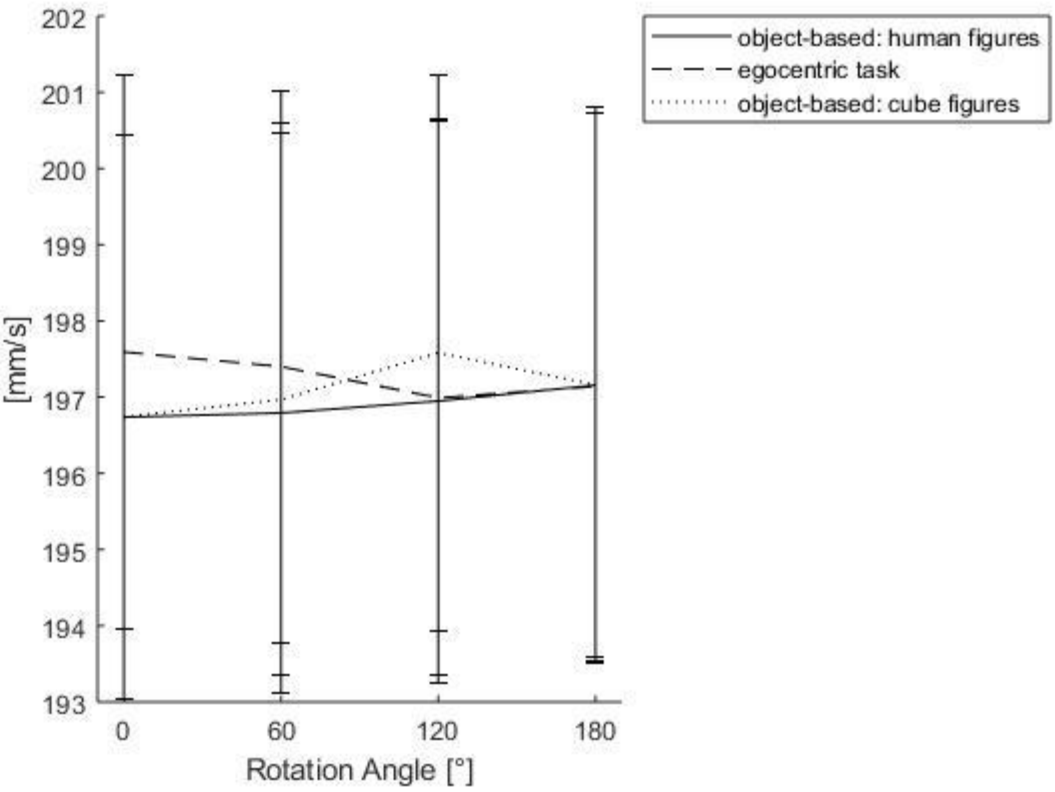
Mean Amplitude of CoP Course per Stimulus Type



Concerning the sway velocity, see figure 5, the analysis of variance showed neither a significant main effect for the factor “stimulus type” (F(1.576, 130.815)=.220, p=.750, partial η² = .003) nor for the factor “rotation angle”(F(1.964,162.980)=.091, p=910, partial η² = .001). Also the interaction between these two factors revealed no statistical significant difference (F(2.530, 209.987)= .588, p=595, partial η² = .007). The mean slopes of all three tasks did not differ significantly from each other (F(1.484,123.190) = .385, p = .619, partial η² = .005)

Figure 5

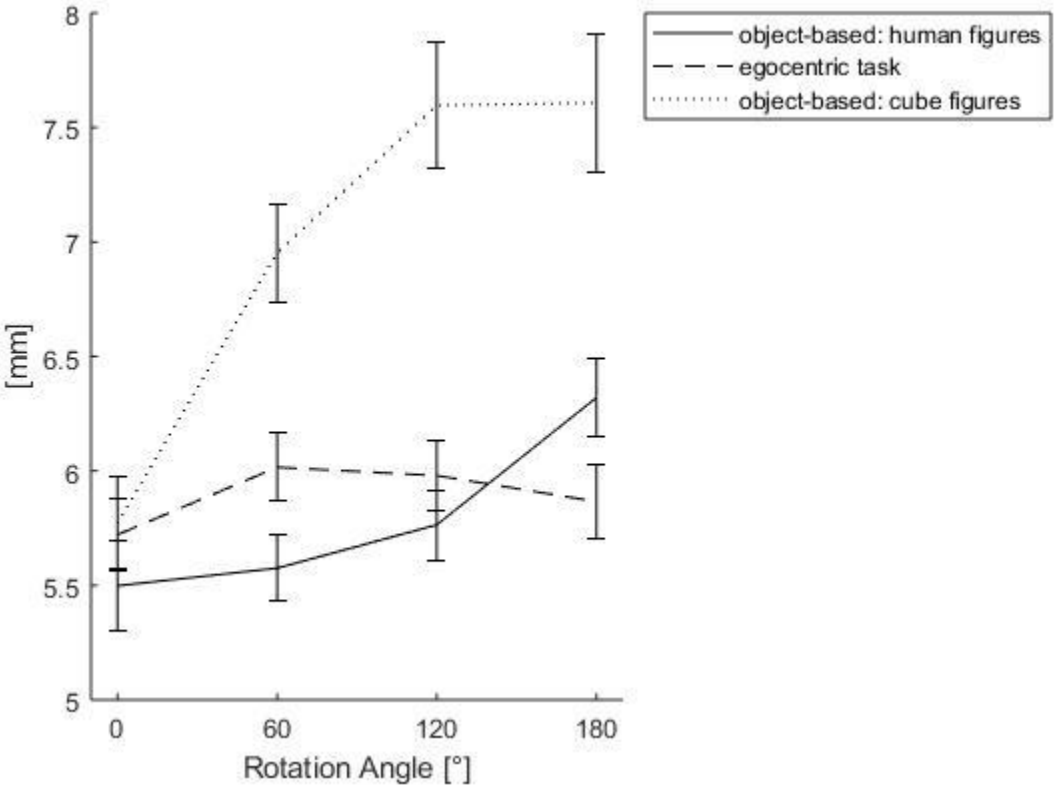
Sway Velocity of CoP Course per Stimulus Type



Concerning the maximum range of motion in anterior-posterior direction, see figure 6, the analysis of variance ruled out a significant main effect for the factor “stimulus type” (F(1.669, 138.548)=42.282, p<.001, partial η² = .337), for the factor “rotation angle”, (F(2.591, 215.056)=24.146, p<.001, partial η² = .225) and a significant interaction between these two factors, (F(4.343, 360.461)= 10.026, p<.001, partial η² = .108). Additional simple main effect analysis was conducted to analyse a possible difference dependent on rotation angle and type of stimulus. It was shown that for the object-based task with human figures the maximum range of motion in anterior-posterior direction at the rotation angle of 180° differed significantly from 0° (p < .001), 60° (p < .001) and 120° (p = .005). For the egocentric mental rotation task no statistical significant differences could be shown. In the object-based task with cube figures the maximum range of motion in anterior-posterior direction at the rotation angle of 0° differed significantly from all other rotation angles ($p<.001$). For the rotation angle of 60° it differed significant from 120° ($p = .035$). The mean slopes of all three tasks differed significantly from each other ($F(2,166) = 12.282$, $p < .001$, partial $\eta^2 = .129$). Post hoc pairwise comparisons with Bonferroni correction revealed significant differences between the mean slopes of the object-based task with human figures and the object-based task with cube figures ($p = .013$) as well as between the egocentric task and the object-based task with cube figures ($p < .001$). For a better understanding of the influence of the stimulus type another simple main effect analysis was calculated for each angle. In figure 6 this can be read as vertical difference. For the maximum range of motion in anterior-posterior direction at the rotation angle of 0° no significant differences between the tasks could be shown. At an angular disparity of 60° the maximum span in anterior-posterior direction differed significant for all tasks ($p < .05$). For 120° the maximum span in anterior-posterior direction during the object-based task with cube figures was significantly higher than in the two other tasks ($p < .001$). At an angle of the stimuli of 180° the maximum span in anterior-posterior direction of all three tasks showed significant differences between each other ($p < .05$).

Figure 6

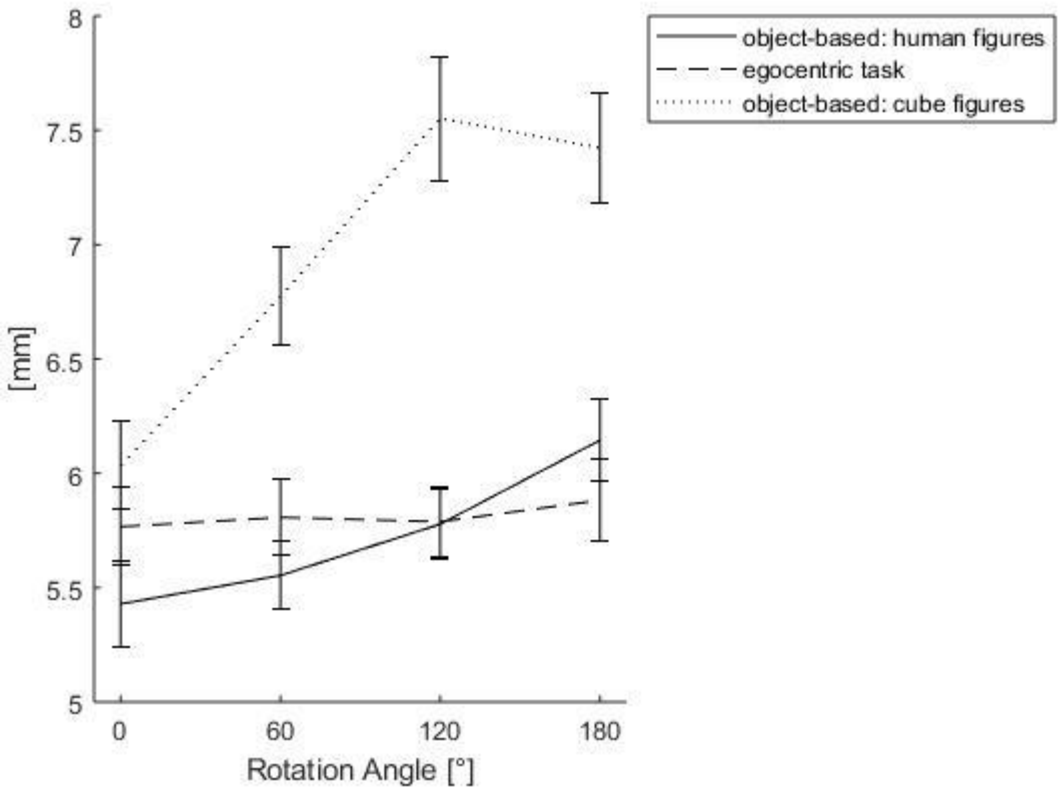
Maximum Range of CoP Course in Anterior-Posterior Direction per Stimulus Type



Concerning the maximum range of motion in medio-lateral direction, see figure 7, the analysis of variance showed a significant main effect for the factor “stimulus type” (F(1.722, 142.886)=65.367, p<.001, partial η² = .441), for the factor “rotation angle”(F(2.580, 214.151)=16.754, p < .001, partial η² = .168) and a significant interaction between these two factors (F(4.877, 404.787)= 6.583, p < .001, partial η² = .073). The simple main effect analysis for the differences of the rotation angles per type of stimulus demonstrated that for the object-based task with human figures the maximum range of motion in medio-lateral direction at the rotation angle of 180° differed significantly from 0° (p = .006) and from 60° (p = .019). For the egocentric mental rotation task, no statistical significant differences could be shown. In the object-based task with cube figures the maximum range of motion in medio-lateral direction at the rotation angle of 0° differed significantly from all other rotation angles ($p< .005$). At the rotation angle of 60° it differed significantly from 120° ($p = .004$). The mean slopes of the three tasks differed significantly from each other ($F(2,166) = 8.853$, $p < .001$, partial $\eta^2 = .096$). Post hoc pairwise comparisons with Bonferroni correction revealed only significant differences between the mean slopes of the egocentric task and the object-based task with cube figures ($p < .001$). For a better understanding of the influence of the stimulus type another simple main effect analysis was calculated for each angle. In figure 8 this can be read as vertical difference. For the rotation angle of 0° a significant higher range of the object-based task with cube figures compared to the object-based task with human figures could be shown ($p = .008$). At an angular disparity of 60° the maximum span in medio-lateral direction during the object-based task with cube figures was significantly higher than in the two other tasks ($p < .001$). Also, for 120° the maximum span in medio-lateral direction during the object-based task with cube figures was significantly higher than in the two other tasks ($p < .001$). At an angle of the stimuli of 180° the same results as for 60° and 120° was shown ($p < .001$), with the maximum range of motion in medio-lateral direction of the object-based task with cube figures significantly higher than the other two tasks

Figure 7

Maximum Range of CoP Course in Medio-Lateral Direction per Stimulus Type



3.4 Discussion

The aim of the study was to investigate the influence of a mental rotation task with different kinds of stimuli on a simultaneously executed motor task, i.e., still upright standing. We showed less body sway, indicating a more stable position, during solving mental rotation tasks than during standing and just looking at a fixation cross (Stabilisation - Hypothesis 1). Taking into account the angular disparities of the mental rotation tasks, our results ruled out a more stable position for egocentric mental rotation tasks than for object based mental rotation tasks with cube figures but not for object-based mental rotation tasks with human figures (Perspective - Hypothesis 2a). Considering the angular disparities, embodied stimuli showed significantly reduced body sway compared to the classical cube figures (Embodiment - Hypothesis 2b).

Additionally, it was shown that within a specific mental rotation task the angular disparity of the stimuli has an influence on body sway only for object-based mental rotation tasks but not for egocentric ones (Angular disparity - Hypothesis 2c).

3.4.1 Stabilization During Mental Rotation

Regarding the influence of a simultaneous executed mental rotation task on body sway, our results are in line with those from Dault et al. (2001). While they showed that an egocentric mental rotation task with a linesman leads to postural stabilization compared to the fixation of a point on the screen, we have extended this finding by focusing on three different kinds of mental rotation tasks (two object-based tasks, one egocentric task). Our results provide evidence that all three tasks differ significantly from a neutral condition, where participants stood still and looked at a fixation cross. All mental rotation tasks stabilized the body sway regarding the mean amplitude, the maximum range of motion in anterior-posterior direction and in medio-lateral direction. It is critical to note that the results of the ASS show that the fixation cross task was perceived as significantly more physically demanding than the other tasks. The extent to which more strain actually occurred or whether this subjective assessment only arose due to a shift in attention can only be objectively controlled with a parallel EMG measurement, which was not performed in this study.

However, our results as well as the one from Dault et al. (2001) are in contrast to many studies regarding dual task designs for balance experiments, where a simultaneous conducted task (but no mental rotation task) often leads to a deterioration of postural stability (Mujdeci et al., 2016; Pellecchia, 2003; Shumway-Cook et al., 1997; Simoneau et al., 1999). Dault et al. (2001) proposed the explanation that their results come from a co-contraction control strategy of postural muscles of the central nervous system, leading to a tighter control of postural sway. Another possible explanation could be that the improved postural stability is the result of a shift of attention to the cognitive task and therefore the automaticity and efficiency of the postural control processes are enhanced (Huxhold et al., 2006; Shumway-Cook & Woollacott, 2007). Richer et al. (2017) investigated whether less body sway during the conduction of cognitive tasks could be due to a stiffening strategy or due to automatic postural control processes. As they found no muscle activity around the ankle joint and concluded enhanced postural stability comes from automatic postural control processes, we also believe that our finding of postural stabilization comes from the shift of attention to the mental rotation or math task. During looking at the fixation cross task, not so much attention is needed and result in a more internal focus of postural control which leads to a deterioration of postural stability (Wulf et al., 2001). Either way, our results show that a simultaneous conducted mental rotation task leads to increased postural stabilization compared to the fixation of a cross, resulting in a smaller CoP displacement. Furthermore, Dault et al. (2001) investigated two other working memory tasks and found no differences in body sway between both tasks and the mental rotation task. We also found no significant difference between a math task and the mental rotation tasks concerning the body sway. This might imply that only the conduction of a secondary task leads to postural stabilization, regardless of the type of the task. Taking into account the results of the ASS questionnaire and those from Pellecchia (2003), who showed that postural sway enlarges with increasing difficulty of the concurrent cognitive task, we would have expected the highest body sway for the math task. As there is no difference in body sway between the math task and the mental rotation tasks this has to be investigated further.

3.4.2 Differences in Postural Stability for Different Types of Mental Rotation Tasks (Perspective Hypothesis)

Furthermore, our results are not in accordance with hypothesis 2a. We assumed that during an egocentric task the subject has to imagine rotating its own body (Kessler & Rutherford, 2010) and because of the closeness of egocentric tasks to kinesthetic imagery tasks (see explanation in the introduction), we expected that solving an egocentric mental rotation task causes more body sway than an object based mental rotation task. But for the angular disparities of 60°, 120° and 180° the mean amplitude of sway, the maximum span in anterior-posterior direction and the maximum span in medio-lateral direction were more stable in the egocentric condition than in the object -based condition with cube figures. For zero degrees, no differences were detectable in these parameters which might be caused by the easiness of the task. Additionally, the mean slopes, i. e. the ratio how much the body sway increases per angle, for the mean amplitude of sway, the maximum span in anterior-posterior direction and the maximum span in medio-lateral direction were significant smaller in the egocentric condition than in the object-based condition with cube figures. Even these results don't support our hypothesis, they are in line with Kawasaki and Higuchi (2013), who were able to show reduced body sway for a previously performed egocentric task with feet stimuli but not for a previously performed object based task with car stimuli. In line with Kessler and Rutherford (2010), one possible explanation , why our hypothesis 2a is not true, is the differently perceived mental rotation task difficulty. For all angular disparities of the mental rotation tasks, which are different from zero, we observed the pattern that the egocentric task leads to a stabilization of the body sway compared to the object-based task with cube figures. However, the latter is also perceived as significantly more difficult than the egocentric task, indicating that in this case the difficulty of the task has an impact on body sway. This might be an explanation because the study of Pellecchia (2003) showed increasing postural sway with increasing difficulty of the concurrent cognitive task. These observations are further confirmed by our finding that the egocentric task and the object-based task with human figures were classified as equally difficult. Between both tasks, there was no difference in body sway, apart from a few exceptions (mean amplitude: 180°; maximum span in anterior-posterior direction: 60° and 180°).

3.4.3 The Relevance of Embodiment (Embodiment Hypothesis)

Another assumption (Hypothesis 2b) was that there is a difference in body sway between mentally rotating cube figures and human figures caused by the effect of embodiment (Wilson, 2002). The already discussed results, with an egocentric task leading to a more stable position then an object-based task with cube figures, provide first evidence for the effect of embodied figures on postural sway. If we take the several angular disparities into account, our results clearly show an impact of embodied stimuli, resulting in less body sway measured with the CoP displacement parameters (Mean amplitude, maximum span in anterior/posterior and medio/lateral direction). This result is consistent with the statements of Kawasaki and Higuchi (2013), even though their actual finding concerning the sway parameter "sway velocity" could not be replicated. They described a decrease in sway velocity, in their words as “stabilization of body sway”, after the egocentric mental rotation of embodied stimuli (images of feet) compared to mental rotation of car images. We did not find any change in sway velocity but a reduction in the already mentioned parameters, indicating a reduction of body sway. It is questionable whether the results are comparable to Kawasaki and Higuchi (2013) because we checked for the differences during object-based mental rotation tasks while they investigated egocentric tasks. Since the use of human figures in mental rotation tasks is a common way to induce embodiment, there is reason to believe that the use of human figures as stimuli leads to a reduction of body sway by triggering a sensorimotor simulation mechanism (Voyer & Jansen, 2016). Furthermore there is evidence that it is more easy for participants to mentally rotate embodied stimuli than abstract shapes, like cube figures (Amorim et al., 2006; Jansen et al., 2012). This confronts us with the issue of different task difficulties which may overshadow an embodiment effect. In the ASS questionnaire the object-based task with cube figures was rated as significantly more difficult than the object-based task with human figures. Therefore it is possible that the higher body sway only appears during the cube figures condition because the task was perceived as subjectively more difficult (Pellecchia, 2003). For future experiments the task difficulty should be determined in a pre-test to guarantee for equal task difficulty. The fact that the results suggest an influence of embodied stimuli, despite the different task difficulty, offers potential for further investigations in this direction. As seen in Kawasaki and Higuchi (2016) a stabilization in body sway can be shown directly after the mental rotation of feet stimuli but not of hand stimuli. As the feet and the ankles are essential parts in the postural control of human upright standing (Gage et al., 2004; Winter et al., 1998; Winter et al., 2003), the authors conclude that the mental rotation of such body parts relates to the ability to stand as still as possible. Our results show that a stabilization also occurs while rotating whole body figures. Now the question arises whether this is due to the fact that whole body figures also include the feet or whether perhaps body parts in general, which are involved in maintaining an upright posture, contribute to postural stabilization. This should be systematically investigated in further studies. First, the stimuli used in Kawasaki (feet and hands) should also be examined during a simultaneous conducted postural task. Further, it would be possible to examine whole body stimuli with covered parts of the body (either covering it piece by piece starting from the feet or starting from the head). This could reveal which body part in a mental rotation task is essential for postural stabilization and therefore which parts of the body are relevant to cause this effect.

3.4.4 Influence of Angular Disparity (Angular Disparity Hypothesis)

The more explorative approach to investigate the influence of angular disparity of the mental rotation stimuli within the mental rotation tasks (Hypothesis 2c) revealed that in egocentric tasks, angular disparity has no influence on postural sway. For the object-based tasks there is a tendency that higher rotation angles lead to more postural sway. Here a parallel to the common behavioral results of mental rotation tasks can be seen, as the classical mental rotation paradigm of Shepard and Metzler (1971) shows a linear increase in reaction time with increasing angular disparity between two presented stimuli. As this means, physically, the mental rotation speed is approximately constant, this could be an explanation for the inconsistency of the CoP velocity and displacement data. In line with the constant mental rotation speed, the sway velocity shows no significant differences. On the other hand, similar to the increasing angular disparity, the body sway data shows higher values for CoP displacement parameters (i.e. spatial disparity) for larger angles in object-based tasks. This explanatory approach is still very speculative but offers great potential for further investigations. The more or less similar increase in body sway during object-based mental rotation task might also be a further hint for the common process theory (Wohlschläger & Wohlschläger, 1998). A further confirmation is that the rather classical increase of response time with increasing angular disparity is usually more pronounced in object-based tasks as compared to egocentric mental rotation tasks (Jola & Mast, 2005; Michelon & Zacks, 2006). Also, this holds true for our findings regarding the body sway as we see no differences in sway between the angles in the egocentric task. This finding is partly comparable with the classical behavioural finding for egocentric mental rotation tasks where reaction times tend to increase for angles above 60° or 90° (Keehner et al., 2006; Michelon & Zacks, 2006). Although the lack of increase contradicts our hypothesis that egocentric tasks lead to more body sway due to the imagination of rotating one’s own body (Kessler & Rutherford, 2010), it still deserves to be examined more precisely in further studies.

3.5 Limitations

There were several limitations in this study. The major limitation is that the difficulty in the tasks were rated as different. In order to make reliable statements, the mental rotation tasks must be perceived as equally difficult in their complexity, to eliminate the effect of cognitive effort on body sway (Pellecchia, 2003). Our sample consisted of healthy sports students who were instructed to stand still on both legs. This task might have been simply too easy for this target group. If one wants to stick to the two-legged stand as a task, since it corresponds very closely to everyday life, then other target groups, such as older people or patients with vestibular diseases, would also be interesting. Due to the many cognitive tasks and the fact of preventing fatigue during the postural task, the mental rotation experiments consisted of very few items compared to classical mental rotation studies. Further studies should concentrate on more specific types of mental rotation tasks with more trials. Additionally there are directions which implicate, that variability in CoP course is functional, task-dependent and cannot be claimed as an unstable stance, as long as it doesn’t cause a loss of balance or a decreased performance of standing (Haddad et al., 2013). For further studies, it could be interesting to consider more ways of measuring postural stability.

3.6 Summary

In summary, this study investigated the relation between mental rotation and postural stability. Our results clearly show that the simultaneous conduction of a mental rotation task stabilizes the postural sway in a both-legged narrow stance. Furthermore, the stabilizing influence of embodied stimuli compared to cube figures was observed. In addition, an effect of the angular disparity of the stimuli on body sway for object-based mental rotation tasks has been discovered. Future studies should investigate the influence of simultaneous mental rotation tasks on body sway for different mental rotation stimuli and in different target groups, as this will give more precise insights in the interaction between mental rotation and postural stability.

4 Second Study: Embodied Mental Rotation – Does It Affect Postural Stability?[2]

Study 1 has shown, among other things, that embodied stimulus material in a dual-task situation leads to stabilization of the body sway compared to non-embodied stimulus material.

4.1 *Goal of the Study*

The overall goal of this study is to investigate the effect of different stimuli of human body parts (whole body, foot, hand) in mental rotation tasks (egocentric and object-based tasks) and a control condition (fixation cross) on a postural stability task that is performed simultaneously. We intended to replicate and extend the results from Study 1 and replicate the results from Kawasaki and Higuchi (2016) in a dual-task situation. Furthermore, the relevance of human body parts stimuli in mental rotation tasks on postural stability must be investigated in more depth (Budde et al., 2021; Kawasaki & Higuchi, 2016; Study 1). As Study 1 couldn’t find a common pattern for egocentric and object-based mental rotation tasks on postural stability, both tasks will be investigated separately.

4.2 *Experiment 1: Egocentric Mental Rotation Tasks*

4.2.1 *Hypotheses*

Hypothesis 1: There will be less body sway during egocentric mental rotation tasks compared to the cognitive control task (fixation cross) (Study 1).

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[2] The results presented in this chapter were published in advance in: Hofmann, P., Jost, L., & Jansen, P. (2022). Embodied Mental Rotation – Does It Affect Postural Stability? *Journal of Motor Behavior*, 1–18. https://doi.org/10.1080/00222895.2022.2151970

Hypothesis 2: Posture-related body parts as stimuli in egocentric mental rotation tasks induce a more substantial decrease of postural sway compared to body parts which are not an essential part of postural control.

a) The postural sway will be reduced in the egocentric mental rotation tasks with foot stimuli compared to egocentric mental rotation tasks with hand stimuli (Kawasaki & Higuchi, 2016).

b) Postural sway for egocentric mental rotation tasks with whole-body stimuli will be less compared to egocentric mental rotation tasks with hand stimuli but not compared to egocentric mental rotation tasks with feet stimuli (Kawasaki & Higuchi, 2016; Study 1).

c) Exploratively, a possible difference between egocentric mental rotation tasks with whole-body stimuli and egocentric mental rotation tasks with feet stimuli will be examined.

d) Furthermore, a possible influence of the factor "rotation angle" will be examined exploratively.

4.2.2 Methods

4.2.2.1 Participants

Based on the results of the first study and a small effect, according to Kawasaki and Higuchi (2016), Cohen's f = 0.422059 was assumed. At an alpha-level of p = .05 and a desired power of 1-beta = .95, a power analysis (G*Power (Faul et al., 2007)) resulted in N = 46. Exclusion criteria were diseases or injuries affecting the balance. In total, there were 47 participants recorded. Due to technical problems, one participant had to be excluded, and another participant was recorded to achieve N = 46 for the data analysis (30 females and 16 males). The resulting sample comprised students from the study subject “Applied Movement Sciences.” The acquisition of the participants took place through a newsletter. The female participants had a mean age of 22.63 (SD = 2.85) and a mean height of 167.83 (SD = 5.92) cm. The male participants had a mean age of 23.75 (SD = 3.00) years and a mean height of 182.69 (SD = 8.62) cm. The Ethical Board of the University of Regensburg approved the study and has been preregistered (https://osf.io/mxyn9). Participants were informed about the study's goal and the privacy policy concerning the data. All participants gave their written informed consent to participate in this study.

4.2.2.2 Material

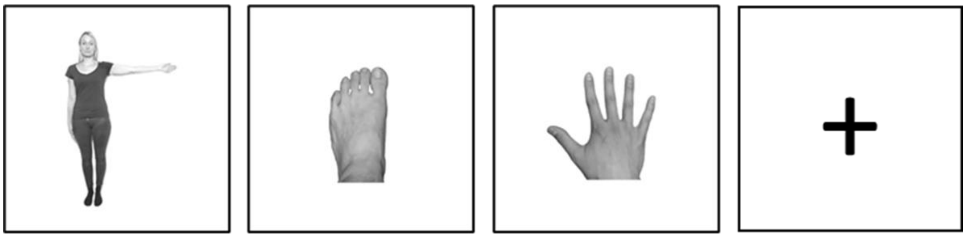
4.2.2.2.1 Cognitive Tasks

The cognitive tasks (three egocentric mental rotation tasks and one fixation cross task) were presented on a laptop (HP Probook 650 G4, 1366x768), using the software OpenSesame (Mathôt et al., 2012). The laptop was placed on a height-adjustable tripod to present the stimuli at the participant’s eye level. The distance to the laptop was allowed to be freely chosen by the participant. Three blue movable screens were placed around the laptop to minimize possible visual distractions. Task instructions were to solve all tasks as fast and as correctly as possible. All stimuli were presented on a white screen. To answer the mental rotation tasks, participants were given one Bluetooth mouse in each hand, of which only the mouse in the right hand was switched on and could be used for answering. During the main experiment, no feedback was given; for the practice trials, there was feedback after each test on whether it was solved correctly. The three mental rotation tasks consisted of 1) a whole-body task, 2) a task with a hand stimulus, and 3) a task with a foot stimulus. In the first task, participants were presented with the front view of a female figure with blonde hair (Kaltner & Jansen, 2018; Study 1) The woman in the picture raised the right or left arm to the side, and the participants must either click the left mouse button when the left arm is raised or the right mouse button when the woman raises the right arm. In the second task, a hand stimulus providing a hand picture in dorsal view was used, the same stimulus as Kawasaki and Higuchi (2016). The task procedure was the same as for the whole-body task.

Participants had to decide whether it was the right or the left hand and press either the right or left mouse button. In the third task, a foot stimulus was used, which was also taken from Kawasaki and Higuchi (2016) and showed a picture of a foot in dorsal view. Again, task instructions were the same, and participants had to decide whether it was the right or left foot. After every presented stimulus, a fixation cross was shown for 1000 ms. Mental rotation stimuli were introduced in the following angular disparities: 0°, 60°/300°, 120°/240° and 180°. The control condition showed a fixation cross in the middle of the screen (see figure 8). Task instructions stated to look at the cross while doing the postural stability task.

Figure 8

Stimuli Experiment 1



4.2.2.2.2 Postural Stability Measurement

For quantification of postural sway, CoP-course over time was measured with a force plate (AMTI OR6-7-2000) and a sampling rate of 1000 Hz. CoP-course was assessed with four parameters: mean amplitude [mm], maximum range in anterior-posterior direction [mm], maximum range in medio-lateral direction [mm] and sway velocity [mm/s] (Hufschmidt et al., 1980; Palmieri et al., 2002). The selection of parameters was based on the results of Prieto et al. (1996) and the methodology used in the first study. All participants stood in a double-legged close stance on the force plate, wearing ultra-thin socks to ensure better hygiene while maintaining the barefoot condition. Before each trial, participants were positioned on the force plate by the experimenter, using a taped "T" of 3 cm wide tape on the force plate, so that the foot position was standardized for each subject (Richer & Lajoie, 2019). The participants were instructed to stand as still and upright as possible during the task. The arms should hang relaxed by their sides and the palms of their hands were to face the body. Only one type of cognitive task was solved per trial. One trial lasted at least 70 sec (Carpenter et al., 2001). To prevent fatigue, there was a 90 sec break between each run where participants sat down while rating perceived cognitive and physical load (see section: Perceived Cognitive and Physical Load).

4.2.2.2.3 Perceived Cognitive and Physical Load

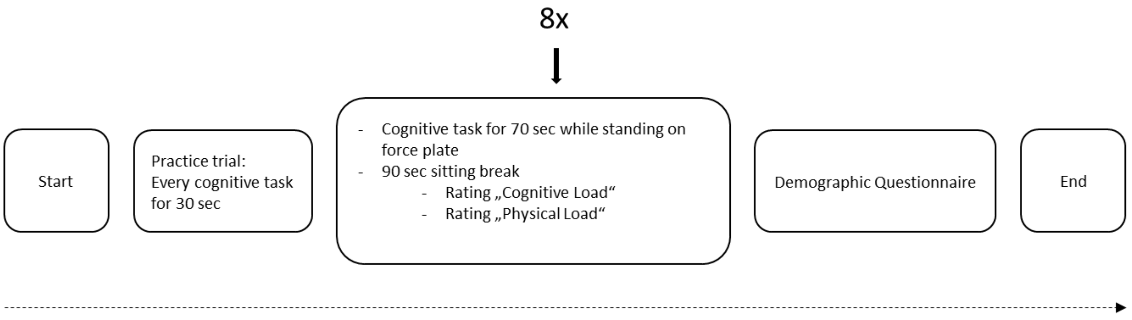
To control for possible confounding factors, as perceived task difficulty or physical fatigue, a modified version of the German scale ASS (“Effort Scale Sport”) was used. The ASS-scale is a ten-level scale with complete level labels with a semantic meaningful sentence, including the adjective “effortful” at each level (Büsch et al., 2021). Additionally, the color-coding as presented in Büsch et al. (2015) was used. Here, colors are used to represent the stages of very light effort in shades of green up to increasingly greater effort, which ends in a strong red. To obtain a meaningful sentence for the tenth level of the scale for cognitive effort, only this level was slightly modified (from “so anstrengend, dass ich abbrechen muss” to “so anstrengend, dass ich nicht lösen kann”). During each 90 seconds break between blocks, the participants assessed the perceived cognitive and physical effort of the last block by saying in each case a number corresponding to the perceived level.

4.2.2.3 Procedure

The study was conducted as within-subject repeated measures dual-task design. All participants completed eight blocks of cognitive tasks while standing as still as possible on a force plate. All tests took place in a laboratory at the University of Regensburg, lasted about 45 minutes and had the same experimenter. During the experiment only the participant and the experimenter were in the laboratory. The experiment consisted out of a practice session and a main session. The trials of the main session were block-randomized with two blocks, each containing the four tasks (three mental rotation tasks and control task) once (every task for 70 seconds). In the practice session, participants were presented all tasks for 30 seconds in random order in their self-selected speed. The exemplary testing procedure is shown in figure 9. Participants were allowed to start the trials themselves, simultaneously the measurement of the body sway started automatically. The mental rotation trials could exceed 70 seconds because the participant was always allowed to solve the last mental rotation task, which started within the 70 seconds.

Figure 9

Procedure of Experiment



4.2.2.4 Data Analysis

The CoP course over time was characterized by the four sway parameters mentioned above. To avoid movements, where the proband may have anticipated the start or ending of a block (M. C. Hunter & Hoffman, 2001), only the CoP-data within the 5s to 65s interval was evaluated. All sway parameters were calculated during the actual execution of the cognitive task. The time between two mental rotation tasks (1000 ms fixation cross) was not analyzed. Only correct responses to non-mirrored stimuli were included in the analysis, as angular disparity is not clearly defined for mirror-reversed stimuli (Jolicœur et al., 1985). All data was first processed in Matlab (R2020b) and then imported in SPSS (IBM SPSS Statistics 26) for statistical analysis. For the comparison between all four cognitive tasks in general (all mental rotation tasks and the neutral condition with the fixation cross) a one-way repeated measures ANOVA was calculated for each sway parameter. To account for the angular disparity of the three different mental rotation tasks, a two-factor repeated measures ANOVA using the factors “stimulus type” (human, foot, hand) and “rotation angle” (0°, 60°/300°, 120°/240°, 180°) was calculated for each sway parameter. The Friedman test was calculated for the ordinal data of the ASS-scale. The alpha-level was set to .05 for all analyses and the respective post-hoc tests. For each hypothesis post-hoc tests were Bonferroni corrected for all comparisons and all parameters, when needed (depending on which main effects or interactions showed significant results). The Bonferroni correction for hypothesis 1 resulted in a corrected alpha value of 0.0028. For hypothesis 2 it resulted in a corrected alpha of 0.0019. For the ordinal data of the ASS-scale, Dunn-Bonferroni tests were used as post-hoc tests. To correct for violations of sphericity the Greenhouse-Geisser adjustment was used.

Additional analyses: After the data analysis as preregistered and described above was finished, a visual inspection of the mental rotation graph (Supplementary Material) showed similar patterns to the CoP-data of the parameters mean amplitude, maximum range of CoP course in anterior-posterior direction and maximum range of CoP course in medio-lateral direction. To test the role of “reaction time”, the following explorative analyses were done successively and only for the parameter mean amplitude, to avoid a flood of analyses.

1. Pearson correlations, independent from the stimulus, between mean amplitude per angle and reaction time per angle.
2. Linear mixed modelling based on an additive model, where “reaction time” was added as fixed effect. (MeanAmplitude ~ StimulusType*Angle + ReactionTime)
3. Linear mixed modelling based on an interaction model (MeanAmplitude ~ StimulusType*Angle*ReactionTime).

Linear mixed models were conducted using lme4 package (version 1.1.26; (Bates et al., 2015)) in R (version 3.6.1, (R Core Team, 2019). Model parameters were estimated by maximum likelihood estimation using bobyqa algorithm wrapped by optimx package (version 2021.10.12; (Nash & Varadhan, 2011)) as optimizer. Model fit was calculated by using likelihood ratio tests to compare models with and without the fixed effect of interest to a significance level of .05. For model building, all models started with a full random effects structure (StimulusType*Angle*ReactionTime) and based on the research of Barr et al. (2013) and Matuschek et al. (2017), the model complexity was reduced by stepwise reducing non-converging models and dropping of non-significant variance components at the significance level of .2. Non-significant fixed effects were further stepwise removed from the model, such that effects, which least decreased model fit were removed first and a model containing only significant fixed effects remained. This model was considered as the final model.

4.2.3 Results

4.2.3.1 Mean Sway Values for the Four Cognitive Tasks

Mean values for each sway parameter over all four angles (0°, 60°/300°, 120°/240°, 180°) per stimulus type were calculated for each participant (see table 2). Prior to analysis, to handle missing data, the respective column mean was imputed for each stimulus type per angle and the fixation cross. None of the single data columns had more than three missing values. In total there were 1.84% of the data missing.

Concerning the mean amplitude of the CoP-course over time a repeated measures ANOVA with the factor “stimulus type” revealed significant differences between the four stimuli (F(1.103, 49.616) = 381.233, $p < .001$, partial $\eta^2 = .894$). Bonferroni adjusted post-hoc tests showed that only in the fixation cross condition the mean amplitude was significantly higher than in the egocentric mental rotation tasks (all $p < .001$). The maximum range of CoP-course in anterior-posterior direction also showed significant differences between conditions (F(1.048, 47.176) = 411.369, $p < .001$, partial $\eta^2 = .901$). Post hoc tests revealed only a higher range in anterior-posterior direction for the fixation cross condition ($p < .001$). Regarding the maximum range of CoP-course in medio-lateral direction also significant differences were found (F(1.064, 47.863) = 395.157, $p < .001$, partial $\eta^2 = .898$). Post hoc analysis revealed those differences only for the fixation cross condition, which had significantly higher values than the mental rotation conditions ($p < .001$). For the parameter sway velocity no significant differences between conditions were found (F(2.047, 92.100) = 0.502, $p = .611$, partial $\eta^2 = .011$).

Table 2

Mean CoP-Parameters during egocentric mental rotation tasks and fixation cross

	Stimulus			
Parameter	Fixation cross	Human figure	Foot figure	Hand figure
MA	5.07 (1.45)	1.15 (0.42)	1.12 (0.44)	1.20 (0.49)
SV	197.00 (55.81)	197.11 (55.78)	197.89 (53.51)	197.63 (54.65)
Range AP	22.18 (6.66)	3.62 (1.21)	3.48 (1.26)	3.71 (1.39)
Range ML	18.00 (5.62)	3.65 (1.21)	3.62 (1.28)	3.84 (1.30)

Note. Mean value (SD) for the two trials of each condition. MA = Mean amplitude [mm], SV = Sway Velocity [mm/s], Range AP = Maximum range of CoP in anterior-posterior direction [mm], Range ML = Maximum range of CoP in medio-lateral direction [mm].

4.2.3.2 Sway Values for Different Rotation Angles

4.2.3.2.1 Mean Amplitude

For the parameter mean amplitude (see figure 10 A), the repeated measures ANOVA revealed no significant main effect for the factor “stimulus type”, (F(2, 90) = 2.414, p = .095, partial η^2 = .051) and a significant main effect for the factor “rotation angle” (F(2.196, 98.813) = 27.750, p < .001, partial η^2 = .381). Additionally a significant interaction between both factors could be shown (F(4.564, 205.363) = 4.900, p < .001, partial η^2 = .098). To check for the differences of the rotation angles dependent on stimulus, simple main effects were analyzed. For human stimuli, no significant differences between any rotation angles could be found. For foot stimuli, the mean amplitude at the rotation angle 180° was significantly higher than the other rotation angles (all $p < .001$). For hand stimuli, the mean amplitude was higher at the rotation angles 180° and 120° than at 60° and 0° (all $p < .001$). To check for differences of stimulus types at specific rotation angles, another simple main effect analysis was conducted. No differences between stimuli were significant for any rotation angle.

4.2.3.2.2 Maximum Range of CoP in Anterior-Posterior Direction

Regarding the maximum range of CoP-course in anterior-posterior direction (see figure 10 B), the repeated measures ANOVA showed no significant main effect for the factor “stimulus type” (F(2, 90) = 1.677, $p = .193$, partial $\eta^2 = .036$) but a significant main effect for the factor “rotation angle” (F(2.219, 99.855) = 23.245, $p < .001$, partial $\eta^2 = .341$). The interaction between both factors revealed a significant result (F(3.541, 159.328) = 3.971, $p = .006$, partial $\eta^2 = .081$). To check for the differences of the rotation angles dependent on stimulus, simple main effect analyses were conducted. For human stimuli, no significant differences between all rotation angles were found. For foot stimuli, the maximum range of CoP-course in anterior-posterior direction at the rotation angle 180° was significantly higher than for all other rotation angles (all $p < .001$). The maximum range of CoP-course in anterior-posterior direction at the rotation angle 120° was significantly higher than at 60° ($p < .001$) and at 0° ($p = .0014$). For hand stimuli, the maximum range of CoP-course in anterior-posterior direction was higher at the rotation angle 180° than at 60° ($p < .001$). At the rotation angle 120°, it differed significantly to 60° ($p = .0014$). To check for differences of stimulus types at specific rotation angles, another simple main effect analysis was conducted. At an angular disparity of 0°, no differences between stimuli were significant. At an angular disparity of 60°, foot stimuli had a significantly lower maximum range of CoP-course in anterior-posterior direction than human stimuli ($p < .001$). For 120° and 180°, no significant differences between stimuli were found.

4.2.3.2.3 Maximum Range of CoP in Medio-Lateral Direction

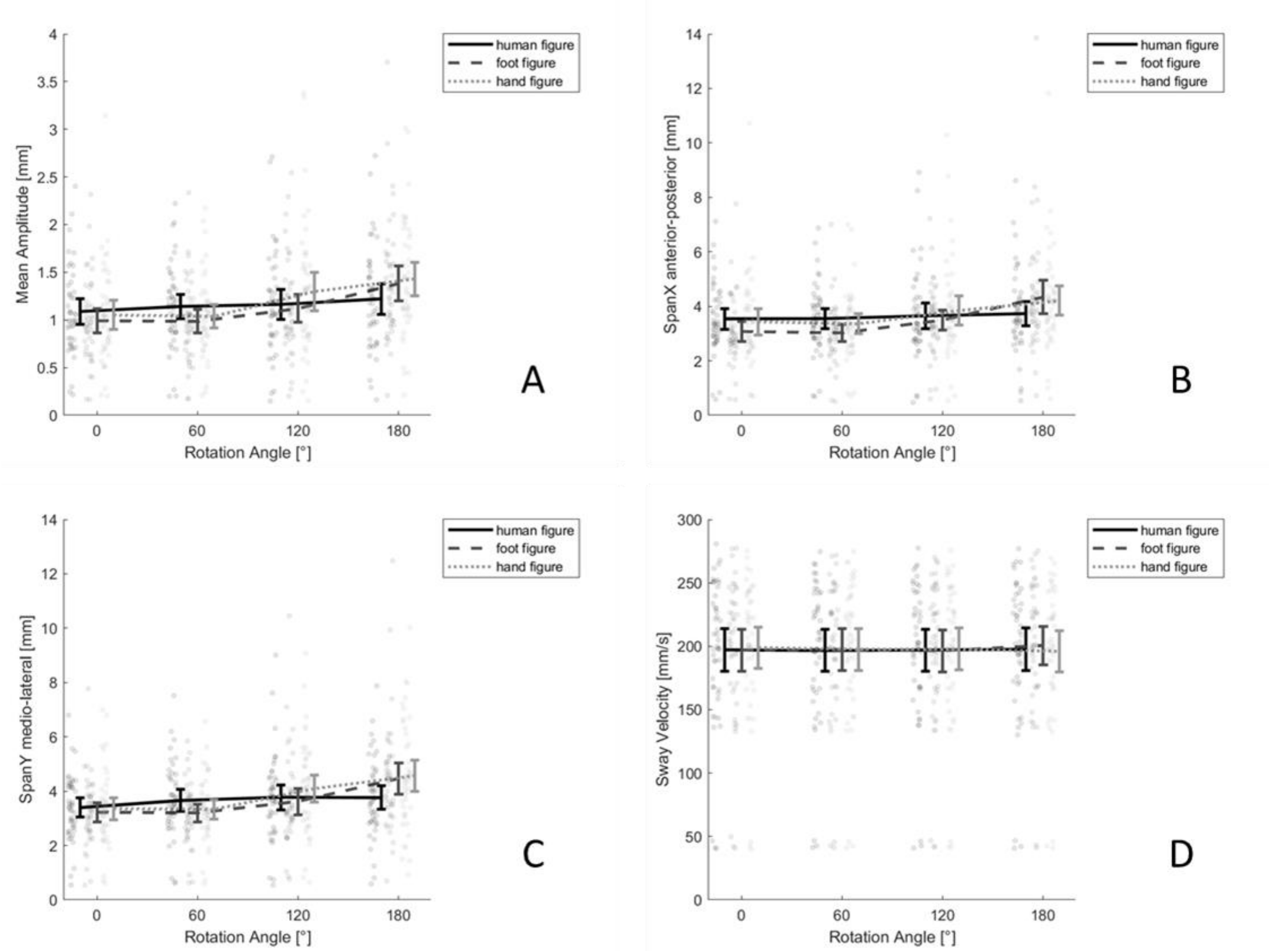
Regarding the maximum range of CoP-course in medio-lateral direction (see figure 10 C) the repeated measures ANOVA showed no significant main effect for the factor “stimulus type” (F(2, 90) = 2.195, p = .117, partial η^2 = .047) but a significant main effect for the factor “rotation angle” (F(2.046, 92.054) = 25.671, p < .001, partial η^2 = .363). The interaction between both factors revealed a significant result (F(4.187, 188.411) = 5.573, p < .001, partial η^2 = .110). To check for the differences of the rotation angles dependent on stimulus, simple main effect analyses were conducted. For human stimuli, no significant differences in the maximum range of CoP-course in medio-lateral direction between all rotation angles were found. For foot stimuli, the maximum range of CoP-course in medio-lateral direction at the rotation angle 180° was significantly higher than at all other rotation angles (p < .001). For hand stimuli, the maximum range of CoP-course in medio-lateral direction was higher at the rotation angles 180° than at 60° and 0° (all p < .001). At the rotation angle 120°, it was significantly higher than at 60° and 0° (all p < .001). To check for differences of stimulus types at specific rotation angles, further simple main effect analyses were conducted. No differences between stimuli were significant for any rotation angle.

4.2.3.2.4 Sway Velocity

Regarding the sway velocity of CoP-course (see figure 10 D) the repeated measures ANOVA showed no significant main effect for the factor “stimulus type” (F(1.643, 73.916) = 0.382, p = .642, partial η^2 = .008), no significant main effect for the factor “rotation angle” (F(1.435, 64.554) = 0.488, p = .554, partial η^2 = .011), and no significant interaction between both factors (F(2.208, 99.373) = 1.433, p = .243, partial η^2 = .031).

Figure 10

Sway Values per Angle for Egocentric Mental Rotation Tasks



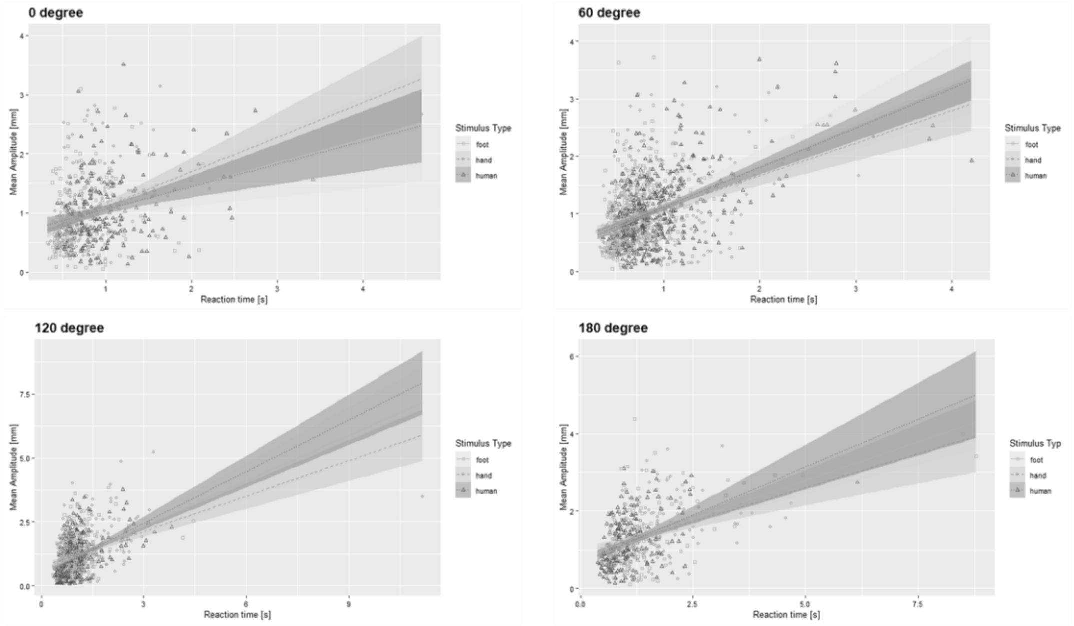
Note. Error-bars are 95% confidence intervals. The individual points are the individual measurements. The points are always on the left side of the corresponding error-bars.

4.2.3.3 Controlling for Reaction Time of MR Tasks in Mean Amplitude

As Pearson correlations (Step 1) between the mean amplitude values and the mental rotation task reaction times at the corresponding equal rotation angles (0° (*r* = .465. *p* = .001), 60° (*r* = .520, *p* < .001), 120° (*r* = .560, *p* < .001), 180° (*r* = .556, *p* < .001)) showed significant results, the additive version (Step 2) of the linear mixed model was fitted with reaction time only as fixed effect (StimulusType*Angle + reaction time). The resulting model identified only reaction time (*p* < .001) as significant influencer of the mean amplitude of the CoP course. To explore other relationships, the linear mixed model with the full three-way interaction structure (StimulusType*Angle*ReactionTime) as fixed effects was fitted (Step 3). The resulting model also revealed only the significant influence of reaction time (*p* < .001). The additional influence of the reaction time is displayed in figure 11.

Figure 11

Mean Amplitude Over Reaction Time for the Four Different Angular Disparities in Egocentric Mental Rotation Tasks



Note. Linear regression fitted graphs with 95% confidence interval (faded band).

4.2.3.4 Subjective Cognitive and Physical Effort

As each subject rated each condition twice, the median of these two ratings was calculated per condition. For the perceived cognitive effort, there was a significant difference between conditions ($\chi^2(3) = 32.476$, *p* < .001). Post-hoc tests showed a lower rating for the condition “fixation cross” than for all other conditions (*p* < .05). The stimulus “hand” was rated higher than human or foot stimuli (*p* < .05). The perceived physical effort also showed significant differences ($\chi^2(3) = 45.721$, *p* < .001). Post-hoc tests revealed a significantly higher rating for the “fixation cross” task (*p* < .001).

4.2.4 Summary of Experiment 1

Experiment 1 aimed to further work out the effects of human body parts in egocentric mental rotation tasks. The first hypothesis that mental rotation tasks reduce the extent of postural sway and in dual-task designs was confirmed. This is in line with the first study. Neither without nor with the inclusion of rotation angle consistent effects for the influence of the stimulus material on body sway can be seen for hypotheses 2 a - c. Only descriptively, slight tendencies for a reduced body sway can be found for solving tasks with foot stimuli compared to solving tasks with hand stimuli. Furthermore, it can only be partially identified descriptively that the body sway during solving human figures is higher than the body sway during foot stimuli and below the body sway during hand stimuli. Higher body sway values for higher rotation angles in egocentric mental rotation tasks occurred only for foot and hand stimuli (Hypothesis 2 d). The additional analysis of the role of reaction time in egocentric mental rotation tasks identified it as a significant predictor for postural stability.

4.3 Experiment 2: Object-Based Mental Rotation Tasks

Since different rotation processes seem to be ongoing in egocentric and object-based mental rotation (Zacks & Michelon, 2005) and Study 1 also did not find a consistent pattern of effects on postural stability for both types of tasks, the task types were analyzed separately in this study. The presentation of the order of the experiments in this study does not represent a temporal order of the experiments.

4.3.1 Hypotheses

Hypothesis 1: There will be less body sway during the object-based mental rotation tasks compared to the cognitive control task (fixation cross) Study 1.

Hypothesis 2: Posture-related body parts, as stimuli in object-based mental rotation tasks, induce a more substantial decrease of postural sway, depending on the angle, compared to body parts which are not an essential part of postural control.

a) Postural sway will be smaller in object-based mental rotation tasks with foot stimuli compared with object-based mental rotation tasks with hand stimuli. (Kawasaki & Higuchi, 2016)

b) Postural sway for object-based mental rotation tasks with whole-body stimuli will be less than object-based mental rotation tasks with hand stimuli but not object-based mental rotation tasks with foot stimuli. (Study 1; Kawasaki & Higuchi, 2016)

c) Exploratively, a possible difference between object-based mental rotation tasks with whole-body stimuli and object-based mental rotation tasks with feet stimuli will be examined.

4.3.2 Methods

4.3.2.1 Participants

Based on the first study, Cohen's f = 0.2695805 was assumed. At an alpha level of p = .05 and the desired power of 1-beta = .95, a power analysis with G*Power (Faul et al., 2007) resulted in N = 109. Exclusion criteria were diseases or injuries affecting the balance. Due to technical problems, four participants had to be excluded. After a check of the demographic questionnaire, six more participants had to be excluded as some information about current injuries met the exclusion criteria. For these ten excluded participants, another ten participants were recorded to achieve N = 109 for the data analysis (63 females and 46 males). The resulting sample comprised participants from the study subject “Applied Movement Sciences.” The acquisition of the participants took place through a newsletter. None of the participants had participated in Experiment 1 (see Section 2.2.1: Participants, Experiment 1). The female participants had a mean age of 21.97 (SD = 1.89) and a mean height of 167.97 (SD = 7.23) cm. The male participants had a mean age of 22.13 (SD = 1.92) and a mean size of 182.54 (SD = 7.02) cm. The Ethical Board of the University of Regensburg approved the study, and it has been preregistered (https://osf.io/mxyn9). Participants were informed about the study's goal and the privacy policy concerning the data. All participants gave their written informed consent to participate in this study.

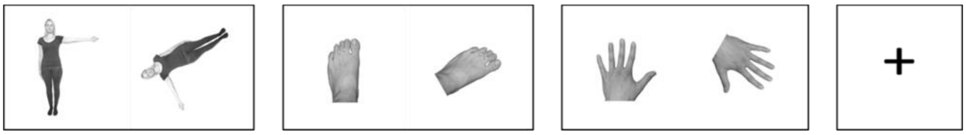
4.3.2.2 Material

4.3.2.2.1 Cognitive Tasks

The stimulus material, hardware, and software were the same as in Experiment 1. In contrast to Experiment 1, only object-based mental rotation tasks were examined (see figure 12). Therefore, two stimuli were presented at the same time. Participants had to either click the left mouse button when the two stimuli were the same, meaning the right stimulus was rotated compared with the left stimulus, or the right mouse button when the stimuli were different, representing the right stimulus was mirror-reversed to the left stimulus. The left stimulus always remained in the same position.

Figure 12

Stimuli Experiment 2



4.3.2.2.2 Postural Stability Measurement

The measurement was the same as in Experiment 1.

4.3.2.2.3 Perceived Cognitive and Physical Load

Perceived cognitive and physical load was measured the same way as in Experiment 1.

4.3.2.3 Procedure

The procedure was the same as in Experiment 1 (see figure 9).

4.3.2.4 Data Analysis

The preregistered data analyses and the additional exploratory analyses were the same as in Experiment 1. The Bonferroni correction for both hypotheses 1 and 2 resulted in a corrected alpha value of 0.0021.

4.3.3 Results

4.3.3.1 Mean Sway Values for the Four Cognitive Tasks

Mean values for each sway parameter over all four angles (0°, 60°/300°, 120°/240°, 180°) per stimulus type were calculated for each participant (see table 3). Before analysis, the respective column mean was imputed for each stimulus type per angle and the fixation cross to handle missing data. None of the single data columns had more than five missing values. In total there were 0.71% of the data was missing.

Concerning the mean amplitude of the CoP-course over time, a repeated measures ANOVA with the factor “stimulus type” revealed significant differences between the four stimuli (F(1.072, 115.799) = 944.212, $p < .001$, partial $\eta^2 = .897$). Bonferroni adjusted post hoc tests showed that the mean amplitude was higher in the fixation cross condition than in the object-based mental rotation tasks ($p < .001$). The maximum range of CoP-course in anterior-posterior direction also showed significant differences between conditions (F(1.041, 112.411) = 1335.345, $p < .001$, partial $\eta^2 = .925$). Post hoc tests revealed only a higher range in the anterior-posterior direction for the fixation cross condition (*p* < .001). Regarding the maximum range of CoP-course in mediolateral direction also significant differences were found, (F(1.087, 117.346) = 1404.104, *p* < .001, partial η^2 = .929). Post hoc analysis revealed those differences only for the fixation cross condition, which had significantly higher values than the mental rotation conditions (*p* < .001). The parameter sway velocity revealed significant differences between conditions, (F(2.193, 236.871) = 5.937, *p* = .002, partial η^2 = .052). Post hoc tests showed a lower sway velocity for hand stimuli than for the fixation cross condition (*p* < .001).

Table 3

Mean CoP-Parameters during object-based mental rotation tasks and fixation cross

	Stimulus			
Parameter	Fixation cross	Human figure	Foot figure	Hand figure
MA	5.44 (1.45)	1.29 (0.35)	1.33 (0.36)	1.29 (0.32)
SV	200.58 (38.00)	200.10 (37.74)	200.35 (37.77)	199.53 (37.19)
Range AP	23.45 (5.73)	3.94 (0.96)	4.10 (0.98)	3.97 (0.89)
Range ML	18.63 (4.30)	3.95 (1.02)	4.08 (1.02)	4.00 (0.87)

Note. Mean value (SD) for the two trials of each condition. MA = Mean amplitude [mm], SV = Sway Velocity [mm/s], Range AP = Maximum range of CoP in anterior-posterior direction [mm], Range ML = Maximum range of CoP in medio-lateral direction [mm].

4.3.3.2 Sway Values for Different Rotation Angles

4.3.3.2.1 Mean Amplitude

For the parameter mean amplitude (see figure 13 A), the repeated measures ANOVA revealed no significant main effect for the factor “stimulus type” (F(2, 216) = 2.142, $p = .120$, partial $\eta^2 = .019$) but a significant main effect for the factor “rotation angle” (F(2.604, 281.253) = 126.581, $p < .001$, partial $\eta^2 = .540$). No significant interaction between both factors could be shown (F(4.870, 525.925) = 1.015, $p = .407$, partial $\eta^2 = .009$). Post hoc analysis revealed significant differences in the parameter mean amplitude between all angular disparities (all $p < .001$).

4.3.3.2.2 Maximum Range of CoP in Anterior-Posterior Direction

Regarding the maximum range of CoP-course in anterior-posterior direction (see figure 13 B), the repeated measures ANOVA showed a significant main effect for both the factor “stimulus type” (F(2,216) = 3.051, $p = .049$, partial $\eta^2 = .027$) and the factor “rotation angle” (F(2.311, 249.592) = 135.263, $p < .001$, partial $\eta^2 = .556$). The interaction between both factors did not reveal a significant result (F(4.683, 505.799) = 1.230, $p = .295$, partial $\eta^2 = .011$). Post hoc analysis revealed no differences between stimuli but there were significant differences for the maximum range of CoP-course in the anterior-posterior direction between all angular disparities (all $p < .001$).

4.3.3.2.3 Maximum Range of CoP in Medio-Lateral Direction

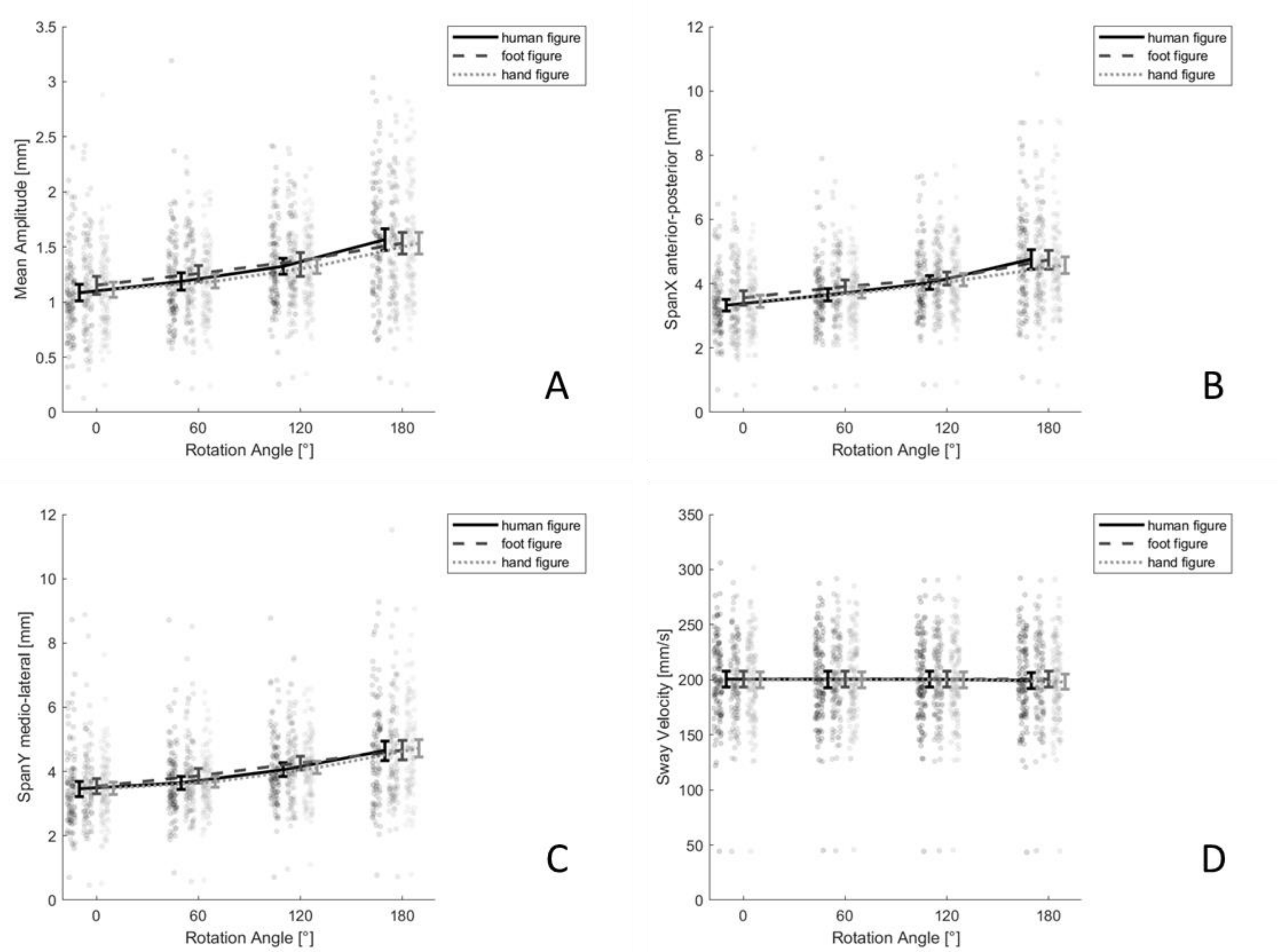
Regarding the maximum range of CoP-course in mediolateral direction (see figure 13 C) the repeated measures ANOVA showed no significant main effect for the factor “stimulus type” (F(2,216) = 1.854, $p = .159$, partial $\eta^2 = .017$) and a significant main effect for the factor “rotation angle” (F(2.558, 276.257) = 113.240, $p < .001$, partial $\eta^2 = .512$). The interaction between both factors did not reveal a significant result (F(4.887, 527.795) = 0.605, $p = .692$, partial $\eta^2 = .006$). Post hoc analysis revealed significant differences in the parameter maximum range of CoP-course in the mediolateral direction between all angular disparities (all $p < .001$).

4.3.3.2.4 Sway Velocity

Regarding the sway velocity of CoP-course (see figure 13 D) the repeated measures ANOVA showed a significant main effect for the factor “stimulus type” (F(1.880, 203.081) = 4.858, $p = .010$, partial $\eta^2 = .043$) and no significant main effect for the factor “rotation angle” (F(1.535, 165.814) = 3.003, $p = .066$, partial $\eta^2 = .027$). The interaction between both factors did not reveal a significant result (F(3.541, 382.393) = 2.079, $p = .091$, partial $\eta^2 = .019$).Post hoc analysis revealed no significant differences between stimuli.

Figure 13

Sway Values per Angle for Object-Based Mental Rotation Tasks



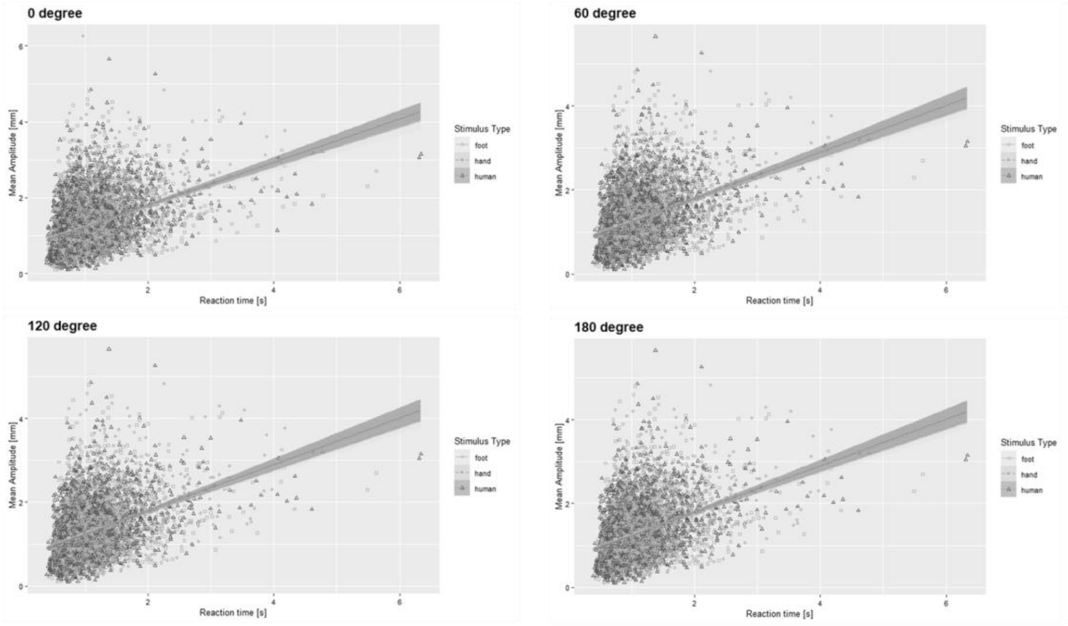
Note. Error-bars are 95% confidence intervals. The individual points are the individual measurements. The points are always on the left side of the corresponding error-bars.

4.3.3.3 Controlling for Reaction Time of MR Tasks in Mean Amplitude

As Pearson correlations (Step 1) between the mean amplitude values and the mental rotation task reaction times at the corresponding equal rotation angles (0° (r = .290, p = .002), 60° (r = .431, p < .001), 120° (r = .483, p < .001), 180° (r = .470, p < .001)) showed significant results, the additive version (Step 2) of the linear mixed model was fitted with reaction time only as fixed effect (StimulusType*Angle + reaction time). The resulting model showed a significant influence of reaction time (p < .001) and rotation angle (*p* = .014). To explore further relationships, the linear mixed model with the full three-way interaction structure (StimulusType*Angle*ReactionTime) as fixed effects was fitted (Step 3). The resulting model significantly influenced the interaction rotation angle and reaction time (p < .001). The additional influence of the reaction time is displayed in figure 14.

Figure 14

Mean Amplitude Over Reaction Time for the Four Different Angular Disparities in Object-Based Mental Rotation Tasks



Note. Linear regression fitted graphs with a 95% confidence interval (faded band).

4.3.3.4 Subjective Cognitive and Physical Effort

As each subject rated each condition twice, the median of these two ratings was calculated per condition. For the perceived cognitive effort, there was a significant difference between conditions ($\chi^2(3) = 74.294$, *p* < .001). Post-hoc tests showed a lower rating for the condition “fixation cross” than for all other conditions (*p* < .001). The stimulus “foot” was rated higher than human stimuli (*p* < .05). The perceived physical effort also showed significant differences ($\chi^2(3) = 74.859$, $p < .001$). Post-hoc tests revealed a significantly higher rating for the “fixation cross” task ($p < .001$).

4.3.4 Summary of Experiment 2

Experiment 2 aimed to investigate further the effect of human body parts in object-based mental rotation tasks on postural stability. As in experiment 1, the already known result of the first study, that mental rotation tasks cause a reduction of postural sway was confirmed (Hypothesis 1). Contrary to hypothesis 2 a), it could not be shown that foot stimuli have lower body sway values than hand stimuli. Also, whole-body stimuli were not shown to have lower body sway values than hand stimuli (Hypothesis 2 b). Also, for hypothesis 2 c), no difference could be demonstrated in body sway during solving mental rotation tasks with whole-body stimuli and with foot stimuli. There were slight tendencies that foot stimuli had the highest body sway. In the mentioned exploratory analyses, reaction time in object-based mental rotation tasks was identified as a significant predictor.

4.4 Discussion

This study examined the effect of human body part stimuli on postural stability in the two standard versions of mental rotation tests, egocentric and object-based mental rotation tests.

4.4.1 Mental Rotation Effects on Postural Stabilization

In both experiments, mental rotation tasks were shown to reduce body sway relative to a neutral condition in which a fixation cross was viewed. This confirms, on the one hand, the results of Dault et al. (2001), who showed postural sway reduction for egocentric mental rotation tasks with stick figures, and on the other hand, the results of the first study, which demonstrated a postural sway reduction effect for both egocentric and object-based mental rotation tasks against the same neutral condition (fixation cross). In the broad field of dual-task studies, several explanations exist for a more stable stance during the simultaneous execution of a cognitive task. One explanation could be an attentional shift towards simultaneously solving the cognitive task, leading to more automated processing of the postural task (Donker et al., 2007). However, postural control is generally a very automatic process (Massion, 1992). Simple standing with a focus on the quiet upright stance is thereby somewhat artificial (Wulf et al., 2001) and thus may hinder the automated process. An alternative explanatory approach could be a co-contraction control strategy of postural muscles of the central nervous system, which may lead to tighter control of body sway (Dault et al., 2001). However, the authors postulate that the co-contraction control strategy is independent of task difficulty.

Since the mental rotation tasks in this study differ in their difficulty, we cannot confirm this postulation. The results of our study indicate that task difficulty does matter, as our study tends to find higher body sway values at higher angles. In mental rotation tasks, higher reaction times and higher error rates are usually found for larger rotation angles, suggesting that these are more difficult. More difficult cognitive tasks require more cognitive resources, increasing dual-task costs and worsening postural stability (Pellecchia, 2003). However, the fact that the ASS scale for the fixation cross condition shows the lowest cognitive effort but the largest body sway values contradicts this. We think it is difficult to compare this condition with the mental rotation tasks because, as we discussed, it may be that the simultaneous processing of a cognitive task (in this study: mental rotation tasks) creates a shift of attention to the cognitive task, meaning an external focus, which leads to a minor variability in CoP-course (Donker et al., 2007). This shift of attention might not take place in the fixation cross condition.

Moreover, the perceived physical effort in the fixation cross condition is significantly higher than the perceived effort in the mental rotation tasks in both experiments. This would also support the theory that the focus in the fixation cross condition is on the physical activity instead of the deflected attention for the cognitive tasks. It is conceivable that the higher perceived physical effort and focus on the physical task is accompanied by more muscle activity, which could mean that no automatized control occurred here, and thus more sway is measured. However, this is purely speculative since we did not measure focus or any muscle activity. Future studies should thus either employ such measurements or different control conditions, which are expected to produce comparable attentional shifts as the experimental conditions.

Furthermore, this study exploratively examined the influence of rotation angle in egocentric mental rotation tasks, as Study 1 did not observe an increase in postural sway values at higher angles for egocentric mental rotation tasks with a whole-body figure. This effect is replicated in this experiment for the same whole-body figure from Study 1. However, it does not carry over to egocentric tasks in general, as in this experiment foot and hand stimuli also had occasionally higher body sway values at higher rotation angles in egocentric mental rotation tasks. This study showed evidence for a higher body sway at higher rotation angles, independent of the stimulus for object-based mental rotation tasks. This also confirms the results of the first study. It found higher body sway at the angular rotation of 180° compared to the other angles in an object-based mental rotation task with the same whole-body stimulus as in this study. Budde et al. (2021), who also tested whole-body stimuli in egocentric and object-based mental rotation tasks, found, on the one hand, evidence for higher body sway for the angle 135° compared to 45°, but on the other hand, also for lower body sway for 180° compared to 135°. So, there is no consistent pattern for body sway for increasing angle.

It should be noted that their results were shown for both mental rotation tasks together, and in their study, the whole-body stimulus was shown from the back. Thus, there was one axis of mental rotation less (the longitudinal axis) than in this study. Therefore, both studies are not entirely comparable.

In line with the results of the first study, this study also shows that mainly the parameters measuring the range (mean amplitude, the maximum range of CoP-course in the anterior-posterior direction, and maximum range of CoP-course in medio-lateral direction) are affected by the simultaneous solving of the mental rotation tasks. The sway velocity, however, seems to be unaffected. Study 1 offered a speculative approach, that this might relate to the constant mental rotation speed (Shepard & Metzler, 1971). DiDomenico and Nussbaum (2005) showed that with increasing mental demands, the Root mean square-distance of CoP-course decreased, but the sway velocity remained the same. Compared to the results in this study, this is either in line or contrary to our results: When we consider mental rotation tasks as increasing mental demands, compared to the fixation cross condition, the results of this study show the same pattern. However, our results show the contrary pattern when considering higher rotation angles within the mental rotation tasks as increasing mental demands. But differences in sway velocity between rotation angles with simultaneous mental rotation are found in Budde et al. (2021).

4.4.2 Embodiment Effects on CoP-Course

Mainly, the hypotheses of this study were based on the results of a study by Kawasaki and Higuchi (2016). They showed up to 60 min lasting postural sway reduction for unipedal standing after the egocentric mental rotation of foot stimuli. Based on the embodiment effect (Wilson, 2002), it is assumed that the mental rotation of body parts causes cognitive processes, which are used for motor imagery and motor execution of the specific body part (Parsons, 1994; Schwoebel et al., 2001) and therefore might interfere with actual motor tasks. As the foot plays an essential role in maintaining postural stability (Gage et al., 2004), we hypothesized that the findings from Kawasaki and Higuchi (2016) might result from the fact that only those body parts interfere with postural stability, which are directly involved in postural control. So, the aim was to transfer the postural stabilizing effects, after the egocentric mental rotation of foot stimuli, to a dual-task paradigm to determine the effects of simultaneous mental rotation (egocentric and object-based) of body parts on postural stability. The descriptive analysis of the CoP-courses of the parameters Mean Amplitude, Maximum Range of CoP-course in the anterior-posterior direction, and Maximum Range of CoP-course in the medio-lateral direction per angle suggests that an effect might exist in egocentric mental rotation. Although the graphs show a similar curve for foot and hand stimuli, the values of the foot stimuli are mostly slightly lower. However, the results of the ANOVA don’t show any differences.

Since the results of Kawasaki and Higuchi (2016) are only shown in the single-leg stance, which causes greater sway values than the double-leg stance, it is possible that the calculated power, according to the results of Kawasaki and Higuchi (2016), of our study was too small. It is therefore critical to note that the attempt to directly apply the results of Kawasaki and Higuchi (2016) to a double-leg dual-task design, may have been too ambitious. Thus, repeating our experiments in a single-leg stance would be interesting. However, the results suggest that the interaction Kawasaki and Higuchi (2016) found does not necessarily transfer in the same way to other balance tasks, even when the same mechanism of embodiment should apply.

Whole-body stimuli were also thought to be more involved in postural control, or at least to show more body parts involved, than hand stimuli. This assumption could not be confirmed: It is conceivable that this pattern would also be more evident in the single-leg stance, as this is a more difficult postural task (Remaud et al., 2012).

In the egocentric tasks, the maximum range of CoP-course in the anterior-posterior direction at 60° shows a significant smaller postural sway during the foot stimuli compared to the whole-body stimuli. Because of the many non-significant results, we would not overestimate this result, but it may indicate what the descriptive results suggest.

4.4.3 Influence of Reaction Time

For both experiments, we found positive correlations between the reaction time in mental rotation tasks and the body sway values of the parameter mean amplitude, so reaction time was exploratively included in the analysis. In both experiments, both versions of the linear mixed models identified reaction time as a significant influencing predictor. It was even the only explanatory predictor in the egocentric mental rotation tasks. The graphical illustrations and the significant correlations show that, between-subject, with higher reaction times in the egocentric and object-based mental rotation tasks also higher values for the mean amplitude, meaning worse postural stability, are measured. One possibility could be that in trials, that take a longer time to be solved, is simply more time to sway. However, this idea should be discarded, since range and velocity parameters should be nearly time-independent measures. Nevertheless, to control for different reaction times future dual-task experiments (especially: reaction time tasks vs postural stability tasks) might think about analyzing only equal periods of time from the CoP-course. It would be task specific how large these sections should be and at which point they should be cut out. In the case of mental rotation tasks, the problem arises that the exact temporal structure of the mental rotation phases is not clear (Heil & Rolke, 2002).

Another possible explanation for the significant influence of reaction time is that a more difficult cognitive task, in the context of mental rotation: higher rotation angles, leads to more postural sway because of higher attentional demands (Pellecchia, 2003). However, Kawasaki et al. (2014) found lower body sway values, in single-leg stance, significantly correlated with faster reaction times in following mental rotation tasks with foot stimuli. Since the mental rotation tasks were conducted after the postural stability measurements, it is excluded that these two tasks influence each other like in a dual-task paradigm. These findings suggest that it is not exclusively the actual amount of time performing the postural stability task but rather a person's specific mental rotation ability. S. W. Hunter et al. (2020) identified executive functions, with the Trail-Making-Test, as mediator between visual acuity and postural stability. One aspect of executive functions is working memory, which plays a role in visual-spatial cognitive abilities (Miyake et al., 2001) and, therefore, also in mental rotation (Linn & Petersen, 1985). The impact of executive functions on postural stability is not clear yet, but it would be interesting if mental rotation training could improve postural control. First evidence might have come from Kawasaki and Higuchi (2016), who have already shown evidence for positive short-term effects (up to 60 minutes) of mental rotation on postural stability but concluded this was due to embodiment effects. Future studies could investigate the role of mental rotation training, besides training of executive functions in general, for improving postural control. Further insights could make mental rotation an interesting rehabilitation tool for people with impaired postural control.

4.5 Limitations

A limitation of the study is that only healthy young sports students who presumably have higher motor expertise than the general population are examined. Since a relation is known between mental rotation ability and motor expertise (Voyer & Jansen, 2017), this might influence the results. Furthermore, the bipedal stance as a motor task might be too easy to detect a clearer interference with mental rotation tasks, especially for this sample. In general, more extended measurements are needed for reliable postural stability measurements (Carpenter et al., 2001; Le Clair & Riach, 1996; van der Kooij et al., 2011). Therefore, it is a limitation that we only analyze concise time periods. More fundamental structures in the body sway can probably not be detected in this way. Also, the influence of reaction time may overshadow possible embodiment effects, as these might be much smaller. Ideally, future studies would identify stimuli with the same angle–reaction time relation to control for reaction time and test them for differences.

4.6 Conclusion

This study shows the effects of two types of mental rotation tasks (egocentric vs. object-based) with human body part stimuli on postural stabilization. In general, human body part stimuli led to more postural stability than neutral conditions in both mental rotation tasks. We conclude that mental rotation tasks, in general, affect postural stability in dual tasks. However, the different types of human body part stimuli had no consistent effects on postural stability between the mental rotation tasks. Additionally, reaction time in mental rotation tasks was shown to be a significant predictor of postural stability. For a better understanding of the influence of embodiment in mental rotation tasks on postural stability, this requires further research and maybe more difficult motor tasks to enlarge dual-task costs. Once the interaction between mental rotation and postural stability is better understood, mental rotation may offer an interesting approach for rehabilitating patients with impaired postural control.

5 Third Study: The Role of Working Memory in the Relation Between Mental Rotation and Postural Stability

While Study 2 focused on the embodiment aspect, Study 3 will address the role of working memory. Study 2 explicitly showed that reaction time in the mental rotation tasks correlated with the mean amplitude parameter of body sway and even was a significant predictor, when both tasks were performed simultaneously. The question arises if there is a common mechanism between mental rotation and postural stability? One possible common mechanism might be working memory.

5.1 Goal of the Study and Hypotheses

It is assumed that the visuospatial sketchpad of working memory and its two components, spatial working memory and object working memory, play a role in the relation between mental rotation and postural stability. As already mentioned, studies show associations between mental rotation and spatial working memory (Kaufman, 2007) and between mental rotation and object working memory (Hyun & Luck, 2007). In contrast, only the link between spatial working memory and postural stability is known (VanderVelde et al., 2005). This study aims to investigate all these concepts together by using standardized procedures and provide an overview of how mental rotation, postural stability and the two components of visual-spatial working memory, object and spatial working memory, are related in healthy young adults. Therefore, the following hypotheses are examined:

1. Mental rotation ability correlates positive with postural stability (Budde et al., 2021; Burcal et al., 2014; Dault et al., 2001; Kawasaki et al., 2014; Study 1; Study 2)
2. The spatial working memory is related to mental rotation ability (Kaufman, 2007) and postural stability (VanderVelde et al., 2005).
3. The object working memory is only related to mental rotation ability (Hyun & Luck, 2007) but not to postural stability (VanderVelde et al., 2005)

4. Spatial working memory is the best predictor of postural stability among mental rotation ability, spatial working memory and object working memory.

5.2 Methods

5.2.1 Participants

The needed sample size for detecting an effect of $f^2 = 0.0989$ of the regression coefficient of spatial working memory in a linear multiple regression model to predict postural stability with the three predictors: mental rotation ability, spatial working memory ability and object working memory ability, was calculated. An a-priori G*Power analysis with an alpha-level of $p = .05$ and a desired power of 1-beta = .9 resulted in a total sample size of $N = 89$. Participants had to be at least 18 years old and received course credit for participation. Exclusion criteria were diseases or injuries affecting the balance. The study was performed in line with the principles of the Declaration of Helsinki. Participants were informed about the goal of the study and the privacy policy concerning the data. All participants had to give their written informed consent before participating in this study. The study was approved by the Ethical Board of the University of Regensburg and was preregistered (https://osf.io/2kn8p). A total of 91 subjects were sampled, because two subjects had to interrupt the experiment early due to technical problems. In addition, two further subjects had to be excluded because their performance in the mental rotation test was below chance level. Therefore, the resulting sample size consists of 87 healthy students from the study-subject "Applied Movement Science" of the University of Regensburg. The 42 female students had a mean age of 21.6 years (*SD*: 1.9 years) and a mean height of 168.5 cm (*SD*: 6.9 cm). The 45 male students had a mean age of 23.2 years (*SD*: 2.8 years) and a mean height of 181.7 cm (*SD*: 6.8 cm). All participants had normal or to normal corrected vision. None of the participants could read Chinese characters.

5.2.2 Postural Stability Measurement

Each participant was tested three times in a one-legged stance task with the preferred leg on a force plate (AMTI OR6-7-2000; 1000 Hz). Each trial was performed for 70 seconds. To avoid fatigue, a sitting break (minimum 90 seconds) was taken between trials. The subject was positioned in a standardized position on the force plate by the experimenter using a taped “T” on the force plate. The instruction was to stand upright and as still as possible, with the arms hanging relaxed at the sides of the body and the non-standing foot free in the air. The head faced straight ahead to a fixation cross shown on a laptop at eye-level. To maintain barefoot condition, but to guarantee better hygiene, all participants had to wear disposable socks.

5.2.3 Mental Rotation Task

Mental rotation tasks were presented on a laptop, using the software OpenSesame (Mathôt et al., 2012). Two cube figures, which are either the same or mirrored, were presented rotated relative to each other, see figure 15. The figure on the left side was always in the non-rotated state (0°). The subject had to decide whether the right stimulus was the same or a mirrored version of the left stimulus. If both stimuli were the same, the subject had to press the left mouse button, if both stimuli were mirrored to each other, the subject had to press the right mouse button. A total of three different cube figures (Jost & Jansen, 2020) were displayed rotated in 60° steps (0°, 60°, 120°, 180°, 240°, 300°) in the image plane. Each angle of each figure was displayed 3 times in non-mirrored and 3 times in mirrored form, resulting in a total of 108 trials (3x6x2x3). Before the main trials, practice runs were performed. There was feedback given in the form of a green check mark for correct answers or a red cross for incorrect answers. During the main trials there was no feedback given but a fixation cross was shown between the single trials.

5.2.4 Spatial Working Memory Task

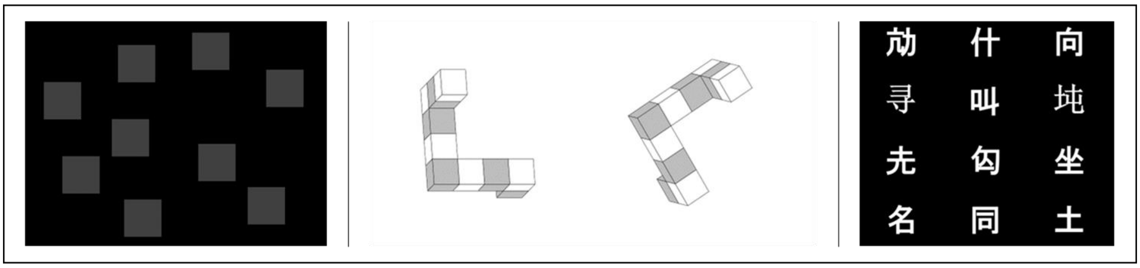
The Corsi block tapping test was performed on a laptop using the software Psychology Experiment Building Language (PEBL) (Mueller & Piper, 2014). In this computer variant, 9 unevenly distributed blue squares were shown, see figure 15. It started with a block sequence of two blocks lighting up yellow sequentially, which the subject had to reconstruct by clicking on the blocks using the computer's mouse. Two trials were given per block sequence of the same length and at least one of them had to be solved correctly for proceeding to the next increased block sequence. This was repeated until the subject was wrong two times at the same block sequence level or the maximum of nine blocks has been solved. In total, the Corsi block tapping test was repeated three times. The first trial used the original block sequences (Kessels et al., 2000) and the sequences for the further two trials were created using a random number generator.

5.2.5 Object Working Memory Task

The task was performed on a laptop, using the software OpenSesame (Mathôt et al., 2012) and was based on a cognitive test used in Klauer and Zhao (2004). For 18 trials six white chinese characters were presented in sequence, each for 500 ms (interstimulus interval 500 ms) on a black background. This was followed by a 500 ms white mask, where the whole screen turned white. Subsequently, the six presented characters and six distractors, also chinese characters, were shown in a 3x4 field, see figure 15. The task was to correctly recognize as many characters as possible. Six characters had to be selected for each answer. The task was not time-based. In the run-up to the study all Chinese characters were selected by the experimenter. Each subject was shown the same characters in each trial.

Figure 15

Cognitive Tasks



Note. From left to right: Exemplary images of the Spatial Working Memory Task, Mental Rotation Task and Object Working Memory Task.

5.2.6 Procedure

The experimental sessions lasted about one hour and all sessions were done in the same laboratory. Each subject received all four tests in counterbalanced order and additionally a short demographic questionnaire at the end of the measurement.

5.2.7 Data Processing

All data was processed in Matlab (version: R2021b).

Postural stability was interpreted via CoP course over time. First, raw CoP-data was low-pass filtered by a 4th order Butterworth filter and a 10 Hz cutoff frequency. Then, the following linear parameters were used to describe body sway: Mean Amplitude (MA) [mm] (Prieto et al., 1996), Sway Velocity (SV) [mm/s], which is the total sway path length divided by whole-trial time, and the 80% frequency in anterior-posterior (80Freq_AP) and medio-lateral direction (80Freq_ML) (Baratto et al., 2002). Here, Power Spectral Density was calculated by using Welch’s method implemented by the default parameters of the pwelch-Matlab function (The MathWorks Inc., 2023) and for obtaining the 80% frequency the trapezidoal rule is used (Duarte & Freitas, 2010). A lower value in Mean Amplitude or in Sway Velocity is interpreted as higher postural stability. The values of the two frequency parameters provide information about which postural control strategy was used preferentially. Higher values indicate that faster, high frequent, changes are used as a postural control strategy (Paillard & Noé, 2015). Furthermore, the structural parameter sample entropy (Ramdani et al., 2009) was calculated (Martínez-Cagigal, 2018) for the CoP course in anterior-posterior (SampEn_AP) and medio-lateral (SampEn_ML) direction. Sample entropy is a measure of regularity in time series data, where a higher sample entropy indicates more irregularity. The original data were downsampled to 100 Hz (Koltermann et al., 2018; Rhea et al., 2011). The input parameters m and r were chosen to be $m = 3$ and $r = 0.2$ times the standard deviation of the CoP data (Rhea et al., 2011). A higher value of sample entropy is associated with a more effective strategy of postural control (Borg & Laxåback, 2010; Kędziorek & Błażkiewicz, 2020).

To analyze the mental rotation tasks, the reaction time [s] was measured. Only non-mirrored tasks that were answered correctly were evaluated (Jolicœur et al., 1985). Within a person, all values of a specific angular disparity that were above or below three standard deviations of the mean value of the respective angle were considered as outliers and excluded. An average was taken across all means per angle, with a lower value associated with better mental rotation ability. In addition to the preregistered parameters, the accuracy [%] parameter was also calculated. This indicates the percentage of tasks that were solved correctly. A higher value indicates a better mental rotation ability.

For analyzing the Corsi block tapping test, the Corsi Span, which is the number of blocks in the last correctly repeated block sequence, was calculated (Kessels et al., 2000). Since there were three trials, a mean value was calculated over all trials for Corsi Span. A higher mean Corsi span is interpreted as better spatial working memory ability.

For analyzing the object working memory task, the total number of correctly remembered Chinese characters was counted. A higher value is interpreted as better object working memory ability.

5.2.8 Statistical Analysis

Statistical analyses were performed using the software SPSS (IBM SPSS Statistics; version: 28.0.0.0) and the software JASP (JASP Team, 2023). The analyses were extended compared to the preregistered analyses by adding Bayesian correlations with 95% Credible Interval to answer hypotheses 1-3. Bayesian analyses have the advantage over classical frequentist approaches of avoiding the usual binary acceptance and rejection of the null hypothesis and instead provide information on whether the collected data rather speak for the null hypothesis or the alternative hypothesis. To test hypotheses 1-3, a bidirectional noninformative prior was used because it is a conservative measure when the exact magnitude of the association cannot be estimated (Nuzzo, 2017; Wagenmakers et al., 2018). When having assumptions about the direction of the association, a one directional noninformative prior was used. To state at what point the data become sufficiently more supportive of a hypothesis, the bounds of 1/3 and 3 were used, which say that a Bayes factor between 1/3 and 3 is considered indecisive (Dienes, 2019). However, even with indecisive results, the Bayes factor can be interpreted as the data the amount of Bayes factor more likely under one hypothesis than under the other. Thus, trends can also be shown and quantified. For answering hypothesis 1- 3, the parameter accuracy was added to the preregistered parameters, to measure mental rotation ability as well. For the prediction of postural stability by the mental rotation task and the two working memory tasks, hierarchical linear multiple regressions with the predictors mental rotation ability (parameter: Reaction Time), spatial working memory ability (parameter: Corsi Span) and object working memory ability were performed for each postural sway parameter. Two regression models are presented for each postural sway parameter.

First, Model 1, a linear multiple regression with all three predictors. Next, Model 2, where the spatial working memory ability component was removed and the change in R^2 is considered. The significance level for detecting a change in R^2 in the hierarchical regressions was Bonferroni-corrected for the six dependent postural sway parameters and therefore set to alpha = .0083.

5.3 Results

5.3.1 Relationships Between the Different Tasks

To give a comprehensive overview of the relationship between the concepts, various correlation tables are presented. Table 4 shows the correlations between the different cognitive tasks. For the relationship between OWM and SWM, no Bayes factor is reported because no hypothesis was formulated about this relationship.

Table 4

Bayesian Pearson's Correlations Between Cognitive Tasks

Variables	n	Pearson's r	BF_{01}	Lower 95 % CI	Upper 95 % CI
MR (Reaction Time) - OWM	87	-.189	1.644	-.379	.023
MR (Accuracy) - OWM	87	.026	7.252	-.182	.232
MR (Reaction Time) - SWM	87	-.061	6.383	-.264	.149
MR (Accuracy) - SWM	87	.283	0.230	.075	.460
OWM - SWM	87	.092			

Note. MR = Mental Rotation, SWM = Spatial Working Memory, OWM = Object Working Memory. The Bayes factor indicates how much more likely the data are under the null hypothesis compared to the alternative hypothesis.

Table 5 provides information on the correlations between the individual cognitive task parameters and the postural sway parameters.

Table 5

Bayesian Pearson's Correlations Between Cognitive Measurements and Postural Sway Parameters

Cognitive Parameter	Postural Sway Parameter	Pearson's r	BF_{01}	Lower 95 % CI	Upper 95 % CI
MR: Reaction Time	Mean Amplitude	.153	1.520	.015	.350
	Sway Velocity	.193	0.796	.025	.384
	80% Frequency AP	.0004	7.464	-.207	.208
	80% Frequency ML	.162	2.459	-.049	.355
	Sample Entropy AP	.073	11.832	-.193	-.002
	Sample Entropy ML	-.186	0.899	-.378	-.023
MR: Accuracy	Mean Amplitude	.166	18.131	-.150	-.001
	Sway Velocity	.075	11.919	-.192	-.002
	80% Frequency AP	.099	4.947	-.112	.299
	80% Frequency ML	-.118	4.183	-.315	.094
	Sample Entropy AP	-.055	10.685	.002	.203
	Sample Entropy ML	-.071	11.649	.002	.194
SWM	Mean Amplitude	.051	6.706	-.159	.254
	Sway Velocity	.082	5.652	-.129	.283
	80% Frequency AP	.116	4.262	-.096	.314
	80% Frequency ML	-.039	7.006	-.244	.170
	Sample Entropy AP	-.085	5.509	-.286	.126
	Sample Entropy ML	.096	5.094	-.116	.296
OWM	Mean Amplitude	-.078	5.794	-.279	.133
	Sway Velocity	-.097	5.021	-.297	.114
	80% Frequency AP	-.018	7.362	-.224	.190
	80% Frequency ML	.125	3.888	-.087	.322
	Sample Entropy AP	-.026	7.260	-.231	.183
	Sample Entropy ML	.170	2.217	-.042	.362

Note. MR = Mental Rotation, SWM = Spatial Working Memory, OWM = Object Working Memory. The Bayes factor indicates how much more likely the data are under the null hypothesis compared to the alternative hypothesis.

The following table 6 shows the correlations of the postural stability parameters with each other. Since it is only intended to be a help for interpretation of the results, due to the use of linear and non-linear parameters, only the Pearson's correlation value is given. Since there were no hypotheses here, no inferential statistics or Bayesian values are presented. The Pearson's correlation values between the parameters should indicate in which direction the parameter should be interpreted when we talk about better postural control or more stability.

Table 6

Pearson's Correlations Between Postural Sway Parameters

Variable	MA	SV	80_Freq_AP	80_Freq_ML	SampEn_AP	SampEn_ML
MA	-					
SV	0.258	-				
80_Freq_AP	0.280	0.381	-			
80_Freq_ML	0.081	0.400	0.166	-		
SampEn_AP	-0.617	0.419	-0.082	0.157	-	
SampEn_ML	-0.649	0.115	-0.088	0.111	0.485	-

Note. MA = Mean Amplitude, SV = Sway Velocity, 80_Freq_AP = 80% Frequency anterior-posterior direction, 80_Freq_ML = 80% Frequency medio-lateral direction, SampEn_AP = Sample Entropy anterior-posterior direction, SampEn_ML = Sample Entropy medio-lateral direction.

5.3.2 Prediction of Postural Sway Parameters

For each postural stability parameter, a linear hierarchical multiple regression with two steps was calculated. Model 1 used the three independent variables MR = "mental rotation (reaction time)", SWM = "spatial working memory (corsi span)" and OWM = "object working memory". In Model 2, only the variable SWM was removed to see how much relevance it had for each dependent variable.

Mean Amplitude could not be predicted by either Model 1, $F(3,83) = 0.857$, $p = .467$, or Model 2, $F(2,84) = 1.116$, $p = .333$. Model 1 explained 3% of the variance in the Mean Amplitude and Model 2 explained slightly less at 2.6%. It is assumed that neither model predicts the parameter Mean Amplitude better than the other, due to a non-significant change in the R^2 value between the two models, $R^2 = -0.004$, $F_{change}(1,83) = 0.356$, $p = .552$. In both models, none of the predictors significantly predicted the parameter Mean Amplitude. The exact values of the individual variables in each model are shown in table 7.

Table 7

Two Step Regression Results for the Parameter "Mean Amplitude"

Variable	B	95% CI for B		SE B	β	R2	ΔR2
		LL	UL				
Step 1						.030	.030
Constant	6.407	3.190	9.624	1.618			
MR	0.155	-0.077	0.388	0.117	.146		
OWM	-0.008	-0.041	0.024	0.016	-.056		
SWM	0.076	-0.177	0.329	0.127	.065		
Step 2						.026	-.004
Constant	6.855	4.017	9.693	1.427			
MR	0.152	-0.079	0.383	0.116	.143		
OWM	-0.008	-0.040	0.025	0.016	-.051		

Sway velocity was not predicted by either Model 1, *F*(3,83) = 1.488, *p* = .224, or Model 2, *F*(2,84) = 1.806, *p* = .171. The models explained 5.1% (model 1) and 4.1% (model 2) of the variance in sway velocity, respectively, and were not significantly different from each other, R^2 = -0.010, F_{change}(1,83) = 0.859, *p* = .357. None of the predictors significantly predicted SV, see table 8.

Table 8

Two Step Regression Results for the Parameter "Sway Velocity"

Variable	B	95% CI for B		SE B	β	R2	ΔR2
		LL	UL				
Step 1						.051	.051
Constant	28.521	6.871	50.170	10.885			
MR	1.343	-0.223	2.908	0.787	.186		
OWM	-0.072	-0.291	0.147	0.110	-.071		
SWM	0.793	-0.909	2.494	0.855	.100		
Step 2						.041	-.010
Constant	33.201	14.042	52.359	9.634			
MR	1.310	-0.252	2.872	0.785	.181		
OWM	-0.064	-0.282	0.154	0.110	-.063		

The parameter 80Freq_AP was not predicted by either model. Model 1, $F(3,83) = 0.399$, $p = .754$, explained 1.4% of the variance and Model 2, $F(2,84) = 0.014$, $p = .986$, explained 0% of the variance. Both models were not significantly different, $R^2 = -0.014$, $F_{\text{change}}(1,83) = 1.170$, $p = .283$, and also showed no significant predictor. The exact values can be found in table 9.

Table 9

Two Step Regression Results for the Parameter "80% frequency in anterior-posterior direction"

Variable	B	95% CI for B		SE B	β	R2	ΔR2
		LL	UL				
Step 1						.014	.014
Constant	.117	0.078	0.155	0.019			
MR	$2.912*e^{-5}$	-0.003	0.003	0.001	.002		
OWM	$-5.029*e^{-5}$	0.000	0.000	0.000	-.029		
SWM	0.002	-0.001	0.005	0.002	.118		
Step 2						.000	-.014
Constant	0.126	0.092	0.160	0.017			
MR	$-3.907*e^{-5}$	-0.003	0.003	0.001	-.003		
OWM	$-3.296*e^{-5}$	0.000	0.000	0.000	-.019		

The further frequency parameter 80Freq_ML was not predicted by any variable constellation. Model 1, $F(3,83) = 1.555$, $p = .206$, resolved 5.3% of the variance. Model 2, $F(2,84) = 2.278$, $p = .109$, with 5.1% descriptively slightly less. However, the two models were not statistically significantly different from each other, $R^2 = -0.002$, $F_{\text{change}}(1,83) = 0.156$, $p = .694$. No significant predictor was found in either model, see table 10.

Table 10

Two Step Regression Results for the Parameter “80% frequency in medio-lateral direction”

Variable	B	95% CI for B		SE B	β	R2	ΔR2
		LL	UL				
Step 1						.053	.053
Constant	-0.226	-1.344	0.893	0.562			
MR	0.071	-0.010	0.152	0.041	.191		
OWM	0.009	-0.003	0.020	0.006	.165		
SWM	-0.017	-0.105	0.070	0.044	-.042		
Step 2						.051	-.002
Constant	-0.329	-1.314	0.657	0.496			
MR	0.072	-0.008	0.152	0.040	.193		
OWM	0.008	-0.003	0.020	0.006	.161		

The sample entropy of the CoP data in the anterior-posterior direction could not be predicted by either model. While model 1, $F(3,83) = 0.336$, $p = .800$, resolved 1.2% of the variance, model 2, $F(2,84) = 0.234$, $p = .792$, resolved slightly less variance at 0.6%. Both models did not differ, $R^2 = -0.006$, $F_{\text{change}}(1,83) = 0.541$, $p = .464$. Table 11 shows that none of the predictors significantly predicted SampEn_AP.

Table 11

Two Step Regression Results for the Parameter “Sample Entropy in anterior-posterior direction”

Variable	B	95% CI for B		SE B	β	R2	ΔR2
		LL	UL				
Step 1						.012	.012
Constant	0.021	-0.004	0.046	0.013			
MR	0.001	-0.001	0.002	0.001	.067		
OWM	$-6.531*e^{-6}$	0.000	0.000	0.000	-.006		
SWM	-0.001	-0.003	0.001	0.001	-.081		
Step 2						.006	-.006
Constant	0.017	-0.005	0.039	0.011			
MR	0.001	-0.001	0.002	0.001	.071		
OWM	$-1.425*e^{-5}$	0.000	0.000	0.000	-.012		

Similary, for the parameter SampEn_ML neither model 1, $F(3,83) = 1.730$, $p = .167$, nor model 2, $F(2,84) = 2.372$, $p = .100$, significantly predicted SampEn_ML. The two models did not differ, $R^2 = -0.005$, $F_{\text{change}}(1,83) = 0.476$, $p = .492$. Model 1 resolved 5.9% of the variance of SampEn_ML and model 2 resolved 5.3%. None of the predictors in either model showed a significant result, see table 12.

Table 12

Two Step Regression Results for the Parameter “Sample Entropy in medio-lateral direction”

Variable	B	95% CI for B		SE B	β	R2	ΔR2
		LL	UL				
Step 1						.059	.059
Constant	0.016	-0.027	0.060	0.022			
MR	-0.002	-0.005	0.001	0.002	-.157		
OWM	0.000	0.000	0.001	0.000	.133		
SWM	0.001	-0.002	0.005	0.002	.074		
Step 2						.053	-.005
Constant	0.023	-0.015	0.061	0.019			
MR	-0.002	-0.005	0.001	0.002	-.160		
OWM	0.000	0.000	0.001	0.000	.139		

5.4 Discussion

The study aimed to investigate the role of the two visuospatial sketchpad components "spatial working memory" and "object working memory" in the relationship between mental rotation and postural stability. Additionally, this study aimed to present an overview between these individual processes, measured with standardized methods. Four of six postural stability parameters are descriptively weakly positively related to mental rotation ability (hypothesis 1), but with Bayes factors in a range considered indecisive. Spatial working memory is related to mental rotation but not to postural stability. Thus, hypothesis 2 was partially confirmed. Object working memory is descriptively weakly positively related to mental rotation ability, but the Bayes factor is in an indecisive range. As expected, object working memory is not related to postural stability (hypothesis 3). The assumption that spatial working memory is the best predictor of postural stability must also be rejected (hypothesis 4).

In searching for the answer to the question of why there is a connection between mental rotation and postural stability, one possible explanation might be working memory. Executive functions, in which working memory plays a role, have been shown to mediate between visual acuity and postural stability (S. W. Hunter et al., 2020). Additionally, results exist that mental rotation is related to the visuospatial sketchpad of working memory. Here, findings vary whether mental rotation is related to object working memory (Hyun & Luck, 2007) or to spatial working memory (Cornoldi & Mammarella, 2008; Kaufman, 2007). Regarding postural stability, there are already some findings showing that postural stability is related to spatial working memory (Chen et al., 2018; Smulders et al., 2013; VanderVelde et al., 2005) but not to object working memory (VanderVelde et al., 2005). Therefore, this study's main goal was to investigate all relations in one study. No relationship was found between the classical chronometric mental rotation measure reaction time and the two components of the visuospatial sketchpad. For spatial working memory, the Bayes factor is six times more in favor of no relationship to mental rotation than in favor of one. Given the moderate to strong correlation in Kaufman (2007) and the correlations in Cornoldi and Mammarella (2008), this is initially surprising. However, both studies demonstrated this relationship in a paper and pencil test. In these tests, reaction time cannot be measured, but an overall score is formed by how many individual items one solves correctly. In a chronometric test, this corresponds to the parameter accuracy (Voyer et al., 2006). Considering this, our data, showing a positive correlation of the accuracy in mental rotation tasks with spatial working memory, aligns with the previous findings from both studies (Cornoldi & Mammarella, 2008; Kaufman, 2007). Regarding the relationship between object working memory and mental rotation, the correlation with reaction time indicates a weak to moderate correlation (Cohen, 1988), with the Bayes Factor ranging in an indecisive area. With accuracy, no correlation was shown. Because previous findings on this relationship come from only one dual-task-interference study with a small number of participants (Hyun & Luck, 2007), the point estimate of the correlation with reaction time provides an interesting reference point, which could be used for power analyses for further research on this relationship. Although it was not explicitly investigated descriptively, no correlation was shown between object working memory and spatial working memory, supporting the differentiation of an object and a spatial working memory buffer (Smith et al., 1995).

Different results are shown in this study regarding the relation of reaction time in mental rotation tasks and postural stability. For parameters describing postural sway in the anterior-posterior direction, there are no correlations with mental rotation parameters. For the remaining parameters, the Bayes factor moves in a range considered indecisive. Descriptively, weak to moderate correlations were found there. However, one might ask why no stronger or clearer correlations were found since the association has already been shown frequently in dual-task studies (Budde et al., 2021; Burcal et al., 2014; Dault et al., 2001; Study 1; Study 2) and explicitly in a correlation study for egocentric mental rotation of body parts by Kawasaki et al. (2014). It is possible that the findings from dual-task designs resulted because of attentional capacity limits rather than specific processes that are stimulated during mental rotation (Pellecchia, 2003; Woollacott & Shumway-Cook, 2002). The results from Dault et al. (2001) and Study 1 of this thesis support this explanation, as both studies showed no difference in sway between different cognitive tasks. However, to clarify this definitively for mental rotation, more dual-task studies that control systematically for different cognitive tasks and collect more than global sway parameters would need to be conducted. Even if mental rotation and postural stability use similar or even the same process pathways, then the interference of these two does not need to mean that they must be highly correlated when considered individually. To truly demonstrate a relationship between mental rotation ability and postural stability, this needs to be examined in an intervention study where the effect of mental rotation on postural stability could be clarified. Kawasaki et al. (2014) found moderate to near-strong correlations for the relationship between embodied egocentric mental rotation and postural stability, which differs from our results. However, their study only examined egocentric mental rotation, and significant correlations were only shown between postural stability and foot stimuli. Since the study presented here looked at non-embodied stimulus material with cube figures in an object-based mental rotation task, the results of this study are most comparable to the correlation between single-leg stance and egocentric mental rotation of car stimuli of Kawasaki et al. (2014). Descriptively, this study shows even a higher correlation compared to Kawasaki et al. (2014). Despite significant results, it must be critically noted that only 24 subjects were examined by Kawasaki et al. (2014), which may limit the validity of their results (Brysbaert, 2019). In general, it should be reconsidered what correlations could be expected with an object-based mental rotation task with cube figures. Possibly, the expectation for the correlation was too high. However, even if correlations of up to 0.2 do not represent large correlations, descriptively, the tendency could very well be seen that especially the postural sway parameters in the medio-lateral direction correlate more with mental rotation than those in the anterior-posterior direction. From a biomechanical point of view, it is reasonable to assume that in this study, the body sway in the medio-lateral direction is more prominent since the base of support is smaller in this direction due to the single-leg stance (Duarte & Freitas, 2010). However, if mental rotation would not be related to postural stability, there should also be no difference between the two possible sway directions. So, this could be an indication that the connection between mental rotation ability and postural stability exists. However, due to the correlations with the Bayes factor in the indecisive range, this is purely speculative and requires further research.

The correlation between visuospatial sketchpad and postural stability must be rejected based on the results from this study. Regarding spatial working memory, none of the correlations suggests a relationship to postural stability. Also, when comparing the two regression models, there is no significant difference from zero for either model nor is there a difference between the models when the spatial working memory parameter is removed in model 2. Previous associations between spatial working memory and postural stability relate in healthy participants behaviorally to interference paradigms (VanderVelde et al., 2005) or to neural findings (Chen et al., 2018). Results from pure correlation designs can only be found in patient studies (Brecl et al., 2019; Smulders et al., 2013). Therefore, it is interesting to see that this correlation does not exist in healthy young participants. This does not necessarily mean that it is not present at all, but it is possibly overshadowed by other processes. As expected, no correlations with postural stability were found regarding the object working memory (VanderVelde et al., 2005). Only a correlation with the parameter sample entropy in the medio-lateral direction is within an indecisive range but is clearly more in favor of the null hypothesis. Overall, the regression models never showed more than a 6% explanation of the total variance of the respective postural stability parameter. This underlines the small part the chosen cognitive variables have in postural stability. To examine this in more detail, it could be helpful to explicitly clarify the role of spatial working memory in postural stability in an intervention study.

In future studies that collect various postural sway parameters, a correlation table, such as table 6, should also be provided. Usually, with each postural stability measure, there is some indication of associated postural stability or postural control. Thus, for global postural stability parameters, one assumes that a lower value implies better postural stability (Palmieri et al., 2002) and, for example, for sample entropy, one implies better postural control for a larger value, even if this mathematically means more chaotic data (Borg & Laxåback, 2010; Kędziorek & Błażkiewicz, 2020). When looking at table 6, it is noticeable that the parameter sway velocity is descriptively positively correlated with both parameters of sample entropy. Possibly this is an indication that, at least in this study, a higher sway velocity relates to better postural control or a higher sample entropy for more stability. Findings like this may be interesting for the interpretation of a study. For example, results by Budde et al. (2021) have shown that during egocentric mental rotation, the range of CoP values but also the sway velocity of CoP values is reduced compared to object-based mental rotation. They interpret this, as is typical, as postural stabilization. Possibly, however, the decreased sway velocity (see table 6) may also be interpreted as lower postural control. Both Budde et al. (2021) and Study 1 of this work compared the process of egocentric mental rotation to the kinesthetic perspective of motor imagery. Both studies assumed that egocentric mental rotation could elicit more body sway because of the assumption that here the participant has to imagine a rotation of his own body to solve the task (Kessler & Rutherford, 2010). Both studies did not prove that, but it may be conceivable that the reduction of the sway velocity in Budde et al. (2021) could also be interpreted as reduced control due to the mental rotation of the own body. However, this is purely speculative but may provide an interesting hint for further research.

5.5 Limitations

There are a few limitations to note in this study. The sample with healthy young sports students represents a very special sample for studies on motor control and mental rotation, as it is already known that there are relationships (Pietsch & Jansen, 2012; Voyer & Jansen, 2017). However, the motor task was made more difficult for this purpose by conducting the single-leg stance, which created more challenging motor conditions. Additionally, the choice of cognitive tests can be questioned. Although the Corsi block tapping test is the gold standard to measure the spatial working memory component (Baddeley, 2003), it is originally designed more for everyday clinical use. However, this should be fine since it has also been used in many non-clinical studies.

For testing the object working memory, the adaption, according to Klauer and Zhao (2004), was conclusive, but the test is not an established object working memory test. Further, some Bayes factors are in an indecisive range for the correlations. Even this might be better than simply reporting non-significant p-values, especially with Bayes factors, a so-called adaptive sampling can be used, in which the data is collected until conclusive Bayes factors are reached. But due to a preregistered power analysis and for reasons of economy, the sample size was maintained.

5.6 Conclusion

The study aimed to show the relationships between mental rotation, the two components of the visuospatial sketchpad of working memory, spatial working memory and object working memory, and postural stability. Additionally, it was aimed to verify whether spatial working memory is the actual predictor of postural stability. As spatial working memory could not be shown to be an essential predictor for postural stability, it is not assumed that spatial working memory explains the relationship between mental rotation and postural stability. The correlation tables in this study provide interesting insights into the relationships between all measured concepts and will provide realistic estimators for effect sizes for future research. Even if the correlation between postural stability and mental rotation was smaller than expected, it is still worth further investigation as it is interesting why the results differ from those of dual-task design studies. So, future studies should clarify whether the relationship in dual-task studies is only due to increased dual-task costs or due to true relationships between mental rotation and postural stability. Once the relationship between mental rotation and postural stability becomes clearer, mental rotation may offer an interesting starting point in the rehabilitation of individuals with impaired postural control.

6 General Discussion

6.1 Summary

This thesis attempted to clarify the relationship between postural stability and mental rotation. Several aspects that could provide information about this relationship were considered.

The first study investigated the relationship between different types of mental rotation tasks (objectbased vs. egocentric) and postural stability. The simultaneous solution of mental rotation tasks has led to postural stabilization compared to a neutral fixation cross condition. Regarding the amount of postural sway, egocentric mental rotation tasks with human body figures did not differ from object-based mental rotation tasks in general but only from object-based mental rotation tasks with cube figures. Generally, a more stable stance was observed during the solution of embodied stimuli than during cube figures. Furthermore, the tendency was shown that higher rotation angles in object-based mental rotation tasks lead to more postural sway.

The second study followed up on the result regarding the effects of the embodied stimuli. Two separate dual-task experiments investigated the effect of different human body part stimuli in egocentric (experiment 1) and object-based (experiment 2) mental rotation tasks on postural stability. Both experiments showed a stabilizing effect during mental rotation tasks compared to a neutral fixation cross condition. Additionally, for both mental rotation tasks, higher body sway was shown for higher rotation angles. But while egocentric mental rotation showed a trend for hand and foot stimuli to lead to more body sway than solving whole-body stimuli, object-based mental rotation tasks showed no difference between stimuli. Exploratively, both experiments revealed the reaction time in mental rotation tasks as a good indicator of postural stability.

The third study investigated whether the visuospatial sketchpad of working memory could explain the relationship between mental rotation and postural stability. In contrast, to studies 1 and 2, all different tasks were performed in a single-task design and the different correlational relationships between the variables were presented. The results suggested that the relationship between mental rotation and postural stability cannot be explained by the visuospatial sketchpad. However, various interesting correlation measures were presented, and it was shown that the correlative relationship between mental rotation and postural stability is very weak, if present at all.

6.2 Relationship Between Mental Rotation and Postural Stability

That there is some form of relationship between mental rotation and postural stability is already known. Several dual-task studies have shown interference between the two tasks (Budde et al., 2021; Burcal et al., 2014; Dault et al., 2001). Kawasaki et al. (2014) showed a correlational relationship land further studies even an influence of mental rotation on subsequent postural stability tasks (Kawasaki & Higuchi, 2013, 2016). Both Study 1 and Study 2 demonstrated that mental rotation tasks contributed to postural stabilization in dual-task experiments compared to a neutral control condition, looking at a fixation cross. This replicates the results from Dault et al. (2001) and Burcal et al. (2014), showing that egocentric mental rotation with a stick figure leads to postural stabilization over a control condition. However, more importantly, Study 1 and Study 2 also extend the results by showing that an object-based mental rotation task also leads to more postural stability. Whether this is truly due to mental rotation or simply because performing a cognitive task while standing tends to shift attention toward the cognitive task and thus, postural stability benefits from more automated postural control (Donker et al., 2007; Huxhold et al., 2006; Shumway-Cook & Woollacott, 2007), cannot be definitively determined. Indeed, the results from Study 1, the results from Dault et al. (2001), and the results from Budde et al. (2021) each find no difference between occurring body sway during mental rotation tasks and body sway during other cognitive tasks. However, Burcal et al. (2014) showed that in cognitive tasks involving different areas of working memory, the task involving the visual-spatial component of working memory, the egocentric mental rotation task, induced more postural stabilization than the task involving the phonological loop.

In addition to the interference results, Study 3 attempted to establish a correlational relationship between the classical object-based mental rotation paradigm and postural stability. While in the study of Kawasaki et al. (2014), moderate to almost strong correlations occurred between egocentric mental rotation with foot stimuli and postural stability, only very small correlations are shown in Study 3. The associated Bayes factors indicate that it is unclear whether the data speak for or against a correlation between mental rotation and postural stability. However, since it is descriptively evident that the correlation is more pronounced in the medio-lateral direction than in the anterior-posterior direction, which is biomechanically conclusive due to the base of support (Duarte & Freitas, 2010), it can be assumed that a correlation may exist, since otherwise, the direction of the body sway would not be relevant. Especially with the correlative result of Study 3, it is clear that the relationship between mental rotation and postural stability cannot be simply generalized.

6.3 Influencing Factors on the Relationship Between Mental Rotation and Postural Stability

Various factors can contribute to the relationship. For example, demographic characteristics such as age or gender are possible influencing factors. When solving mental rotation tasks or, in general, tasks involving spatial abilities, it is known that older people perform worse than younger people (Berg et al., 1982; Techentin et al., 2014), and it is also known that individuals have poorer postural stability in old age (Gill et al., 2001). According to Maylor and Wing (1996), age differences in postural stability are even more pronounced when solving cognitive tasks that demand the visuospatial sketchpad of working memory. In addition, besides the well-known gender effects in mental rotation (Voyer et al., 1995) showing that women tend to perform worse than men, there is a similar relationship in postural stability. Here, women are shown to be more likely to have poorer postural stability than men (Błaszczyk et al., 2014; Kim et al., 2012). However, the factors of age and gender are not considered critical to the results of this work, as all three studies examined healthy young adult individuals in a more or less balanced gender ratio per study. However, other possible factors for the relationship between mental rotation and postural stability could be the known relationships of both concepts to working memory or the extent of embodiment of the mental rotation tasks. Therefore, this thesis checked for these two possible factors in more detail.

6.3.1 Role of Working Memory

In a study by Kawasaki et al. (2014), correlations were shown between postural stability and embodied egocentric mental rotation. Study 2 found reaction time in both embodied egocentric and embodied object-based mental rotation tasks to be a predictor of postural stability. Since it is known that working memory plays a role in visuospatial cognitive abilities (Miyake et al., 2001) and consequently in mental rotation (Linn & Petersen, 1985), Study 3 attempted to represent the relationship between mental rotation and postural stability in general by correlating the classic object-based cube paradigm of Shepard and Metzler (1971) as mental rotation test with postural stability. Based on known associations between the visuospatial sketchpad component of working memory and, respectively, mental rotation (Hyun & Luck, 2007; Kaufman, 2007) and postural stability (Chen et al., 2018; VanderVelde et al., 2005), there was the assumption that mental rotation and postural stability are linked via this common component. But, the correlations between mental rotation and postural stability in Study 3 were lower than expected. However, compared with the results for non-embodied stimulus material, pictures of cars, from Kawasaki et al. (2014) descriptively, even larger correlations in Study 3 are seen. Surprisingly, the expected correlation of postural stability to spatial working memory could not be shown. The correlation may be overshadowed by other processes in healthy individuals. However, as expected (VanderVelde et al., 2005), no correlation was shown to object working memory. Currently, based on these findings, it is rather assumed that the visuospatial sketchpad does not play an essential role in the relationship between mental rotation and postural stability.

6.3.2 Role of Embodiment

A possible common factor in the relationship between mental rotation and postural stability is the amount of embodiment. Typically, mental rotation tasks use humanized stimulus material to induce embodiment and it is demonstrated that embodied stimulus material facilitates mental rotation (Amorim et al., 2006; Voyer & Jansen, 2016). Regarding the effect of embodiment on postural stability, it is already known that, for example, imagining the movement of a body part triggers a sensorimotor response of the actual body part (Lange et al., 2005; Schwoebel et al., 2001). A possible explanation for this could be the existence of the mirror neuron system (Rizzolatti & Craighero, 2004). Findings that mental rotation of embodied stimulus material may also be related to postural stability come from Kawasaki et al. (2014). They were able to show correlations between postural parameters in single-leg stance and egocentric mental rotation of foot stimuli. They found no correlations with other stimuli, such as pictures of hands or cars. Further studies even showed a subsequent postural stabilizing effect of egocentric mental rotation with foot stimuli but not with hand and car stimuli (Kawasaki & Higuchi, 2013, 2016). In these three studies, only egocentric embodied mental rotation was investigated; thus, the results from Study 1 extend this to the finding that using embodied stimulus material also produces postural stabilizing effects for object-based mental rotation tasks. In the studies mentioned above (Kawasaki et al., 2014; Kawasaki & Higuchi, 2013, 2016), the results are explained in terms of the foot having a more important function in stance than, for example, the hand and, therefore, foot stimuli interfere more with postural control. Study 2 investigated this systematically in egocentric and object-based mental rotation and could not confirm this interpretation. Only slight descriptive tendencies were shown. However, it must be mentioned that due to the dual-task situation in Study 2, the postural task was a bipedal stance and thus, the triggered processes by mental rotation of foot stimuli may just not have been strong enough to change anything in the more stable bipedal stance.

Kessler and Thomson (2010) described that egocentric mental rotations and object-based mental rotations are embodied differently. Thus, in egocentric mental rotation, the observer's position in relation to the environment is assumed to change to solve the task, and in object-based mental rotation, this observer-environment relation remains fixed and only the two stimuli are rotated in relation to each other (Kessler & Rutherford, 2010). Because these two views are similar to the kinesthetic and visual perspectives in the context of motor imagery, Study 1 and Budde et al. (2021) explicitly investigated the differences in postural stability between an object-based and an egocentric mental rotation. Study 1 showed that a more stable stance was measured during an egocentric mental rotation task with a human figure than during an object-based task with cube figures. However, this could possibly be explained by the easier mental rotation of embodied stimulus material (Amorim et al., 2006; Voyer & Jansen, 2016) and that more demanding cognitive tasks lead to more body sway (Pellecchia, 2003). In line with this interpretation, the comparison of egocentric mental rotation and object-based mental rotation with the same human figure, both tasks were found to be equally difficult, showed no differences in Study 1. However, Budde et al. (2021) showed a posture-stabilizing effect of an egocentric task compared to an object-based task with the same human figure. They explain this by the easier task of egocentric mental rotation, which for them is reflected in lower reaction times and fewer incorrect responses compared to the object-based task. Study 1 and Budde et al. (2021) differ in the viewing direction of the human figure. In Study 1, the participant sees it from the front and in Budde et al. (2021) from the back. This may be a starting point for further research since the view from the front would theoretically require another imagined rotation around the longitudinal axis (Ebersbach & Krüger, 2017).

6.4 Limitations

In addition to the individual limitations of each study, there were also a few general limitations. In principle, it should be noted that in the course of this work, there was an apparent gain in knowledge regarding the analysis of postural stability or the statistical evaluation of data. For example, the first study would have benefited if structural parameters had been considered in addition to global parameters. Since each analysis of study 2 only considers fragments of the overall course of the postural task, it can be assumed that the structure of the CoP course is destroyed by this anyway and there would have been no benefit in analyzing structural parameters in study 2. Also, using linear mixed models or Bayesian statistics would have helped the first study. The same applies to open science tools such as creating preregistrations and making data available, which should become a common practice. In addition, the differential task difficulty of different mental rotation tasks or control conditions is an influential factor, especially in cognitive-motor interference tasks (Pellecchia, 2003). This problem can best be addressed with well-designed studies that clarify a priori the different perceived difficulties. Apart from that, the population in all three studies with sports science students is above average in athleticism. Since relationships between sports and mental rotation have already been demonstrated (Pietsch & Jansen, 2012; Voyer & Jansen, 2017) and sport involves more complex motor processes, it is conceivable that studying the relationship between mental rotation and more complex motor tasks, not just basic motor tasks such as upright standing, would also reveal more evident relationships. For example, it would be interesting to complicate the postural stability task by external influences, such as standing on a wobbly surface or to use a generally more complex basic motor task, such as walking.

6.5 Outlook

During this thesis, some interesting questions arose, but it was not possible to answer all of them. Thus, there are various opportunities for further research. First, some questions would be interesting but also very nonspecific, as they are interesting for many cognitive-motor interference contexts. Since there are findings that mental rotational performance differs across the lifespan (Iachini et al., 2019) as well as findings that age has an impact on postural stability (Gill et al., 2001), it would be of particular interest to investigate how this relates to each other in the corresponding life stages. There are already findings that generally show that this cognitive-motor interference is more pronounced in old age (Maylor & Wing, 1996). A possible connection could be interesting for the creation of cognitive training for older people, which could slow down the reduction of postural control in aging. In addition, the gender effect, which has already been mentioned, but is negligible in this thesis, might also be worth considering.

More specifically and based on this work's results, embodiment effects stand out as the most likely possible explanation for the relationship between mental rotation and postural stability. However, the previous studies could not fully clarify the role of embodiment in this relationship. Therefore, further studies should be conducted in this direction. Regarding the role of embodiment, it would certainly be of interest to design a study in which the limitation concerning different difficulties of the mental rotation tasks do not occur again. Since cognitive-motor dual-task studies are sensitive to different difficulties in the cognitive tasks (Pellecchia, 2003), the actual effect for embodied stimulus material may be best studied if there is an equally difficult non-embodied mental rotation task, for example with the classical cube figures. Task difficulty could be well measured with subjective surveys, such as questionnaires (see

Study 1 and Study 2), or objective methods, such as pupil diameter (Bauer et al., 2022), recorded with eye tracking methods. Now when the embodied task and the non-embodied task are equally difficult, differences in postural stability in dual-task designs could be interpreted much more meaningfully. However, not only in the context of embodiment, controlling the difficulty of cognitive tasks would provide more benefit. In general, it would be interesting to investigate different types of equally difficult cognitive tasks (similar in principle to Study 1) with global and structural CoP parameters. Here, the influence of mental rotation on postural stability could be better distinguished from the influence of cognitive tasks in general. Another interesting point is the measurable extent of embodiment via body sway in egocentric and object-based mental rotation tasks. It is assumed that in an object-based mental rotation task, the observer has a fixed point of view and rotates the two stimuli to each other. In an egocentric mental rotation task, it is assumed that the observer's position changes mentally to solve the task (Kessler & Rutherford, 2010). While previous studies either failed to show that these two tasks differed in body sway (Study 1) or when they did differ (Budde et al., 2021), the problem of different task difficulties emerged (Pellecchia, 2003), it might be interesting to investigate this question in more detail. To do so, a broader base of various global and structural postural stability parameters would need to be collected so that no facet of stance is overseen. In addition, to trigger embodiment effects more intensively, the mental rotation task would need to be systematically modified, which would include, for example, rotation of the stimulus material around different body axes (Ebersbach & Krüger, 2017), size of the stimulus material (Kaltner et al., 2017), and matching of the stimulus material to the self (Kaltner et al., 2014). Furthermore, to better understand the contribution of mental rotation to postural stability and the role of embodiment, it could be investigated, following Krüger et al. (2014), how embodied stimulus material in impossible body positions affects postural stability. Krüger et al. (2014) showed that cube figures that were given humanized parts in the form of head, hands, and feet were more difficult to solve when the body parts were placed in anatomically impossible positions than when they were in anatomically possible positions. They suggested that body parts automatically trigger embodiment during mental rotation, but that this can also be a handicap in cases where it does not match the anatomical body. It would be interesting to investigate in dual-task designs whether the effect of the mental rotations tasks on postural stability differs for mental rotation with cube figures with embodied parts in anatomically possible locations, with embodied parts in anatomically impossible locations and additionally cube figures of the same difficulty but without embodied parts. It would be assumed that between cube figures with body parts in anatomically possible positions and equally difficult stimuli without embodied parts, more effect on the postural stability in the embodied condition occurs. For the comparison between cube figures with body parts in anatomically impossible positions and equally difficult figures without embodied parts, it would be interesting to observe whether, in this case, seeing body parts alone triggers a sensorimotor response and influences postural stability or whether the impossible anatomical positions of the body parts inhibit embodiment and both tasks would have the same effect on body sway. Additionally, it would be interesting to investigate whether patients in whom the ability of embodiment is impaired, such as in autism (Conson et al., 2015), schizophrenia (Stanghellini, 2009), or anorexia (Fuchs, 2022), show fewer effects of embodied mental rotation on postural stability than healthy subjects. If so, this would be a strong indicator that embodiment can explain the relationship between mental rotation and postural stability.

Another interesting point to investigate is the use of mental rotation training to enhance motor skills. There is already research on the effects of complex athletic training on mental rotation performance in adults (Jansen et al., 2009) and children (Jansen et al., 2011; Pietsch et al., 2017). The other way around, there is first evidence of subsequent effects of mental rotation on postural stability (Kawasaki & Higuchi, 2013, 2016) and small correlational results in Study 3. Therefore, it is conceivable that mental rotation training alone could improve physical skills. In the context of motor imagery training in general, there are already results showing that mental imagery as a training method improves postural stability (Hamel & Lajoie, 2005). Should this also be shown for typical mental rotation tasks, this could add interesting value to physical rehab through cognitive tasks and would additionally contribute to the common process theory of Wohlschläger and Wohlschläger (1998). To investigate this, an intervention study that examines body sway before and after mental rotation training would have to be conducted. Based on the previous findings, it would make sense to start with embodied stimulus material since greater effects are expected here.

6.6 Implications and Conclusions

This thesis dealt with the question of how mental rotation and postural stability are related. Specifically, the factors of embodiment and working memory that could explain this relationship were investigated. In the first study, previous findings that egocentric mental rotation is related to postural stability were extended and it was shown that both egocentric and object-based mental rotation tasks have a stabilizing effect on postural stability when performed simultaneously. In addition, embodied stimulus material was also shown to have a more stabilizing effect than non-embodied stimulus material in mental rotation tasks. This follows the findings of previous studies (Kawasaki et al., 2014; Kawasaki & Higuchi, 2013, 2016) and may be explained by triggering a sensorimotor response due to the processing of an embodied stimulus. Study 2 explored this relationship in more detail, as it was hypothesized that the function of the shown stimulus in postural control might have an influence. However, this could not be confirmed yet. Since correlative relationships between mental rotation and postural stability were shown (Kawasaki et al., 2014; Study 2), and since there are known relationships between the visuospatial sketchpad of working memory with mental rotation ability but also with postural stability, this connection was examined in more detail in Study 3. It was shown that working memory cannot explain the relationship between mental rotation and postural stability. At this stage, it can be assumed that the association between mental rotation and postural stability in healthy young adults is most likely explained by embodiment effects. However, further studies are needed to investigate this in more detail. A better understanding of the relationship between mental rotation and postural stability could provide interesting approaches in the future for the treatment of patients with impaired postural control.

7 Declarations

7.1 Ethical Standards

All three studies were performed in line with the principles of the Declaration of Helsinki. Participants were informed about the goal of the study and the privacy policy concerning the data. All participants had to give their written informed consent before participating in this study

7.2 Informed Consent to Participate and to Publish

In all studies participants gave their written informed consent for participating and for publishing anonymous results before participating.

7.3 Open Research Practices

There were preregistrations of Study 2 (https://osf.io/mxyn9) and Study 3 (https://osf.io/2kn8p). The data supporting the findings of Study 2 is available at https://osf.io/m2u5e/files. The data for Study 3 will also be made available after publication of the study.

7.4 Acknowledgements

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7.5 Conflict of Interests

There were no conflicts of interests in all presented studies.

7.6 Funding

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