A re-evaluation of effector specificity as an organizational principle of cortical movement planning

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Abbreviations

AH	abductor hallucis
BOLD	blood-oxygen-level dependent
CNV	contingent negative variation
CSD	cross-spectral density
dlPFC	dorsolateral prefrontal cortex
EBA	extrastriate body area
EEG	electroencephalography
EOG	electrooculogram
ERD	event-related desynchronization
ERP	event-related potential
FDA	functional data analysis
FDI	first dorsal interosseous
fMRI	functional magnetic resonance imaging
GMP	generalized motor programs
ICA	independent component analysis
ID	index of difficulty
IHI	interhemispheric inhibition
IPS	intraparietal sulcus
LIP	lateral intraparietal region
LRP	lateralized readiness potential
LSP	limb selection potential
M1	primary motor cortex
MEP	motor-evoked potentials
MIP	medial intraparietal region
MT	movement time
MVPA	multi-voxel pattern analysis
NHP	non-human primate
PPC	posterior parietal cortex
RS	repetition suppression
RT	reaction time
SPL	superior parietal lobule
SPOC	superior parietal occipital cortex
TFR	time-frequency representation
TMS	transcranial magnetic stimulation
VE	variable error

Abstract

Pressing a light switch with an elbow or picking up a lost sock with a foot are actions we easily perform. In the past, the cortical control of goal-directed actions with different effectors has been studied by comparing activity preceding eye and hand movements. Posterior parietal cortex (PPC) was found to contribute to movement plans of these effectors. Similar to primary motor cortex, different sub-regions seem to be dedicated to different effectors. A major drawback of this approach, however, is the fact that saccades cannot directly interact with the environment. For instance, we are unable to pick up objects using our eyes. Thus, a comparison of hand and eye movements may be inadequate given the functional differences between the two effector systems. This methodological problem can be overcome by comparing the hand to another limb. A comparison of hand and foot movement planning using fMRI revealed overlapping activity for the two effectors in PPC, shedding doubt on its presumed effector-specific organization. If the same cortical area represents both hand and foot movements, the question arises which other mechanism will ultimately distinguish between the two limbs. Thus, the primary aim of this dissertation project was to re-evaluate the presumed effector-specific organization of PPC by assessing foot, hand, and eye movements while recording the EEG. In the first study (chapter 2), we showed that both hand and foot movements follow Fitts' law. That is, movements with either limb share the same behavioral and motoric principles. In the second study (chapter 3), we identified event-related potentials that code for different parameters of a movement plan. While the CNV encoded the to-be-used effector, a posterior waveform reflected movement difficulty. In

the third study (chapter 4), we found effector-specific modulations of the gamma-band. Here, foot movements were selectively encoded in the range from 60 to 80 Hz at central electrodes. In the final study (chapter 5), we advanced this finding by controlling for potential covert movement plans using a dissociation task. In sum, we show that movements with different effectors are flexibly encoded in the EEG signal.

1 Introduction

The ability to move our body and reach for objects is crucial for everyday behavior. Opening a door, picking up a glass, or shaking someone's hand are effortless movements that we perform without giving much, if any, thought to them. Such goal-directed movements require the identification of the object's location in space, that is, the movement goal, as well as the selection of a body-part that we want to use, that is, the effector. Typically, we perform goal-directed movements with the hands, but we are also able to use other effectors if necessary. For instance, it is quite easy to use an elbow or even a knee to press a light switch when carrying something in our hands. Although these effectors are not the typical choice in our motor behavior, the ability to flexibly use them suggests that the underlying sensorimotor processes are readily computed nonetheless.

A brain region considered to be essential for planning movements with different effectors is the posterior parietal cortex (PPC, see Figure 1.1). It is located between sensory and motor cortices, making it an ideal candidate for sensorimotor processing. It receives inputs from primary visual, auditory, and somatosensory areas and projects to frontal motor areas, transforming sensory information from different modalities into motor commands (Cavada & Goldman-Rakic, 1989b, 1989a; Gillebert et al., 2013; Johnson, Ferraina, Bianchi, & Caminiti, 1996; Pesaran, Nelson, & Andersen, 2008; Siegel, Buschman, & Miller, 2015; Stetson & Andersen, 2014). During this transformation, a decision on which effector to use has to be made. Movement plans for different effectors have typically been investigated by means of a delayed movement paradigm employing eye and hand movements (Snyder, Batista, & Andersen, 1997). In this paradigm, the participant maintains ocular and manual fixation at the beginning of each trial. Either an eye movement, that is, a saccade, or a hand reach towards a visual target is instructed. After a delay period the movement is executed with the instructed effector while the other effector remains at the initial starting position. Neuronal signals emerging throughout the delay period are thought to reflect the movement plan for the instructed effector. Numerous studies have applied this paradigm in non-human primates (NHP) and in humans to investigate effector specificity in movement planning (e.g., Astafiev et al., 2003; Cui & Andersen, 2007; Gallivan, McLean, Smith, & Culham, 2011; Heed, Beurze, Toni, Röder, & Medendorp, 2011; Snyder et al., 1997; van der Werf, Jensen, Fries, & Medendorp, 2010). The rationale to interpret activity as being effector-specific in virtually all of these studies has been to compare activity preceding eye and hand movements. Whereas this approach has proven practicable in the lab, it might in fact be inadequate. Saccades are substantially different from reaches insofar as we cannot manipulate objects with our eyes. Essentially, saccades serve visual perception and are tightly linked to attentional processes both functionally and anatomically (Awh, Armstrong, & Moore, 2006; Deubel & Schneider, 2003; Hoffman & Subramaniam, 1995; Khan, Song, & McPeek, 2011; Kowler, 2011; Kowler, Anderson, Dosher, & Blaser, 1995; Nobre, Gitelman, Dias, & Mesulam, 2000; Schütz, Braun, & Gegenfurtner, 2011). Hence, a comparison of hand and eye movement planning is insufficient to gain insight into the cortical mechanisms controlling movements with different effectors.

One possibility to scrutinize past research on effector specificity is to compare hand movement planning to that of an effector with similar properties, such as the foot. In principle, goal-directed actions we perform with the hands can also be executed with the feet. Indeed, there are numerous anecdotic examples of humans, who were born without arms or lost them later, that show how elaborate skills like painting, playing an instrument, or even riding a non-modified car can be performed with the feet (e.g., McDiarmid, 2011). Hence, the current dissertation project aims at establishing a better understanding of effector specificity by comparing foot movement planning with the planning of hand and eye movements.

In the following paragraph, the cortical organization of eye and hand movement planning in NHP will be described. Subsequently, we will outline what is known about allegedly effector-specific movement planning in humans and why it is essential to take a closer look at different limbs.

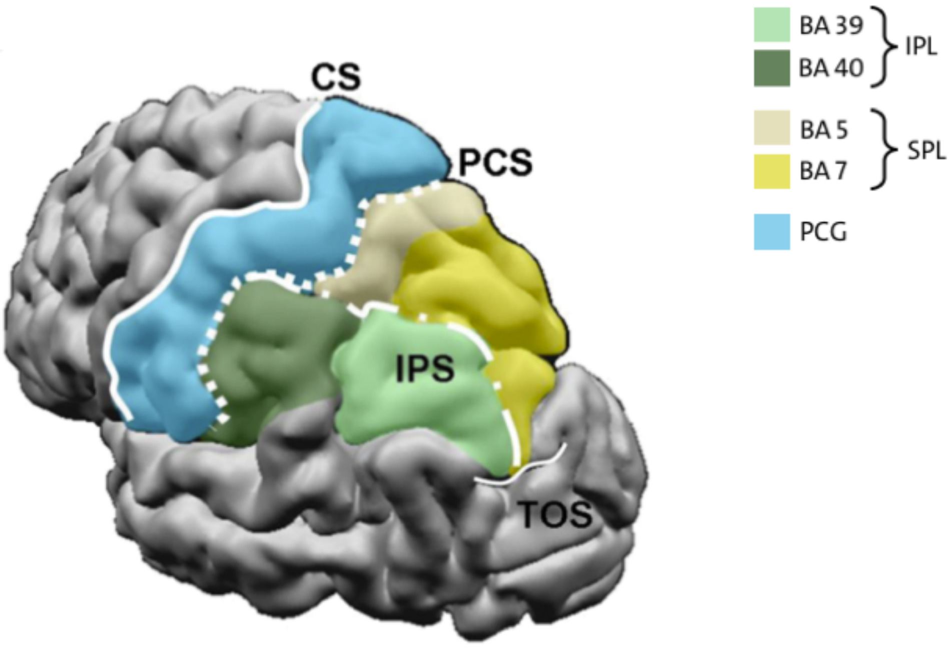

Figure 1.1. Schematic of posterior parietal cortex (PPC). Different colors highlight lateral portions of PPC: inferior parietal lobule (IPL) and superior parietal lobule (SPL). Postcentral gyrus (PCG) divides PPC from frontal cortex. BA = Brodmann area, CS = central sulcus, IPS = inferior parietal sulcus, PCS = postcentral sulcus, TOS = transverse occipital sulcus. Note that precuneus lies on the medial surface of parietal cortex and is not shown here. (Adopted from Culham, Cavina-Pratesi, & Singhal, 2006)

1.1 Movement Planning in Non-Human Primates

Primary motor cortex (M1) plays a key role in movement control in all primates. Electrical stimulation of distinct locations in M1 leads to isolated movements of single effectors on the contralateral body side, such as one hand or even single fingers (Penfield & Boldrey, 1937; Woolsey, 1952). Generally, neighboring stimulation sites are linked to neighboring body regions. In other words, M1 represents an approximate map of the body, the so-called motor homunculus (Donoghue, Leibovic, & Sanes, 1992; Kwan, MacKay, Murphy, & Wong, 1978; Park, Belhaj-Saïf, Gordon, & Cheney, 2001; Sessle & Wiesendanger, 1982; Woolsey, 1952). Thus, M1 is organized in an effector-specific manner.

It has been suggested that PPC, like M1, comprises distinct sub-regions representing movements with different effectors (for review see Culham et al., 2006). Indeed, a number of functional sub-regions have been identified in PPC of NHPs by means of the delayed movement paradigm adopting eye and hand movements.

In their seminal study on effector specificity, Snyder, Batista, and Andersen (1997) recorded neuronal activity from single cells in intraparietal sulcus (IPS), which is located on the lateral surface of PPC. When NHPs prepared a saccade, the firing rate in the lateral intraparietal region (LIP) increased already early after the effector was cued. In contrast, preparing a hand movement resulted in an increased firing rate in an area located more posteromedially within IPS, corresponding to the medial intraparietal region (MIP) or Brodmann area 5. By training the NHPs to perform simultaneous hand and eye movements to targets in opposite visual hemifields at the same time (the so-called dissociation task), the authors were able to rule out that the signal measured from either hemisphere was contaminated by potential covert movement plans of an uninstructed effector. They found that even more neurons responded selectively for movements with one effector than the other (Snyder et al., 1997). Similarly, saccade planning is accompanied by a relative power increase from 25-90 Hz in LIP (Pesaran, Pezaris, Sahani, Mitra, & Andersen, 2002), while hand movement planning is accompanied by a relative increase from 20-50 Hz in MIP (Scherberger, Jarvis, & Andersen, 2005). Thus, LIP and MIP are truly involved in distinct movement planning processes for eyes and hands, respectively.

It is important to note that the attribution of effector-specific functions to PPC is based on findings of relative as opposed to absolute higher neuronal firing rates for one than the other effector. That is, planning a saccade also results in activation of MIP neurons and planning a reach inversely results in activation of LIP neurons when compared to a baseline (Snyder et al., 1997; Snyder, Batista, & Andersen, 2000). Thus, both areas code for upcoming movements with either effector to some extent.

Parts of MIP together with parts of area V6A, which is located caudally in superior parietal lobule (SPL; Fattori, Gamberini, Kutz, & Galletti, 2001; Galletti, Fattori, Kutz, & Gamberini, 1999), were termed the parietal reach region (PRR; for review see Andersen & Cui, 2009). As most of the neurophysiological studies described here report to have made recordings from MIP, Brodmann area 5, or PRR (which are all located in close proximity in IPS and partially overlap), we will use the term PRR from here on when referring to recordings from these regions.

Additional movement-related areas have been identified within IPS. For instance, activity related to grasping and pointing has been recorded from anterior and ventral

IPS, respectively, while activity in central IPS has been associated with depth perception (for review see Grefkes & Fink, 2005). Thus, IPS seems to contain sub-regions controlling other functions of movement planning in addition to those serving saccades and hand reaching.

Effector-specific activity in IPS was found under various conditions (e.g., Cui & Andersen, 2011; Scherberger & Andersen, 2007). It not only emerges for instructed but also for freely chosen eye and hand movements (Cui & Andersen, 2007). In order to balance the number of effector choices across trials, NHPs were trained to play a game against a computer (the so-called matching pennies paradigm). Here, they were only rewarded when making a choice the algorithm had not predicted. This algorithm encourages choosing both effectors with a similar frequency while avoiding sequential behavior or choices following a specific strategy (Barraclough, Conroy, & Lee, 2004). Just like directly instructed movements, freely chosen eye and hand movements were preceded by activity specific to each type of movement in LIP and PRR, respectively. In another study, activity specifically coding for eye and hand movement planning was shown to be independent from the presence of a visual target. When the NHPs were cued to make either a saccade or a hand reach before the goal of the movement was revealed, a firing pattern similar to the original condition emerged (Calton, Dickinson, & Snyder, 2002; Dickinson, Calton, & Snyder, 2003). Thus, LIP and PRR specifically code for eye and hand movement planning, even when movements are not directly instructed.

Crucially, effector-specific movement plans in PPC seem to be represented independently of the allocation of attention (Quiroga, Snyder, Batista, Cui, & Andersen, 2006). Quiroga and colleagues trained a decoder to predict the locus of attention, that is, the target location, and movement plans for reaches and saccades from activity recorded in PPC. In line with previous findings, reach plans could be decoded optimally from PRR activity while saccade plans could be decoded from LIP activity. This held for single effector as well as dissociation movements. Furthermore, effector plans were a much more reliable predictor of firing rates than target locations, that is, the decoding of targets was suboptimal when attentional effects were considered (Quiroga et al., 2006). However, there is an ongoing debate about the role of LIP in attentional processes. Other studies argue that LIP primarily codes attention, not intention (for reviews see Bisley, Mirpour, Arcizet, & Ong, 2011; Colby & Goldberg, 1999). More recently, Liu, Yttri, and Snyder (2010) were able to reconcile these opposing views by reversibly inactivating two portions of LIP with muscimol, a $GABA_A$-agonist. While the inactivation of the dorsal portion of LIP only affected saccade performance, the inactivation of the ventral portion affected both saccadic and attentional processes. Thus, LIP seems to accommodate two functionally distinct sub-regions, one serving eye movement planning and one serving both attention and eye movement planning.

In contrast to LIP, inactivation of PRR leads to less contradicting results. Reversible PRR inactivation with muscimol reportedly impairs reaching behavior, evident in markedly decreased movement accuracy compared to a control condition without deactivation (Hwang, Hauschild, Wilke, & Andersen, 2012). Specifically, reaches toward the periphery were impaired, a deficit known as optic ataxia (for review see Andersen, Andersen, Hwang, & Hauschild, 2014). Crucially, there was no significant modulation of movement accuracy for saccades, underlining the hand-specificity of PRR (Hwang et al., 2012). Moreover, a functional magnetic resonance imaging (fMRI) study in NHPs confirmed PRR to be specifically involved in hand movement planning, whereas LIP activity was associated with saccade planning (Premereur, Janssen, & Vanduffel, 2015). Hence, findings from multiple methods have established PRR as an area seemingly dedicated to reach movements only.

1.2 Evolution of cortical movement control

Just like NHPs, many other animals, such as birds, insects, and rodents show goal-directed behavior, which is often surprisingly complex (Borgia, 1985; Frisch, 1965; Huntly, Smith, & Ivins, 1986). Across species, the goal of a movement is typically approached by locomotion (Grillner, Wallén, Saitoh, Kozlov, & Robertson, 2008; Takakusaki, 2008). A famous idea states that the motor circuits involved in reaching evolved from those involved in locomotion, as primates evolved from quadrupeds to bipeds (Georgopoulos & Grillner, 1989). Only recently, data supporting this hypothesis were acquired for the first time (Yakovenko & Drew, 2015). Cats were trained to walk on a treadmill and depress a lever. Recordings from motor cortex revealed the neuronal activity in both behaviors to be strikingly similar, suggesting that the same processes may underlie locomotion and reaching. Critically, not only motor cortex but also PPC has been reported to contribute to both locomotion and foot movement planning in the cat (Andujar, Lajoie, & Drew, 2010; Lajoie, Andujar, Pearson, & Drew, 2010; Lajoie, Bloomfield, Nelson, Suh, & Marigold, 2012; Lajoie & Drew, 2007; Marigold & Drew, 2011). Hence, hand and foot share the same evolutionary pathways.

During evolution the brain became increasingly sophisticated (Krubitzer &

Disbrow, 2008). Possibly the most palpable change is the increase in size. The human brain is almost five times larger than a scaled version of the macaque brain (MacLeod, Zilles, Schleicher, Rilling, & Gibson, 2003). The brains of humans and NHPs also differ regarding the proportion and the functional specialization of different areas (Preuss, 2011; Rilling, 2006, 2014). In PPC, for instance, regions associated with tool use and gestures were added to the functionally distinct sub-regions dedicated to reaching, pointing, and grasping, resulting in a relocation of other regions (for review see Kaas & Stepniewska, 2016). These differences render a direct comparison between cortical functions in NHPs and humans problematic. Furthermore, it is unclear how signals obtained with single- or multi-cell recordings in NHPs translate into signals provided by fMRI or electroencephalography (EEG) in humans. The latter offer a much cruder spatial resolution in comparison to intracranial recordings. Nonetheless, some parallels exist between the macaque and human brain (Passingham, 2009) and research in NHPs yields interesting insights into the cortical organization of movement planning.

1.3 Movement Planning in Humans

1.3.1 Functional organization of PPC

Homologue to the cortical organization of NHPs, a map of the body is represented in human M1 (Lotze et al., 2000; Meier, Aflalo, Kastner, & Graziano, 2008; Penfield & Boldrey, 1937). Likewise, human PPC was suggested to comprise distinct sub-regions dedicated to eye and hand movement planning. By means of fMRI, activity paralleling the findings in NHPs was revealed (Astafiev et al., 2003; Connolly, Andersen, & Goodale, 2003; Fernandez-Ruiz, Goltz, DeSouza, Vilis, & Crawford, 2007; Filimon, Nelson, Huang, & Sereno, 2009; Hinkley, Krubitzer, Padberg, & Disbrow, 2009; Medendorp, Goltz, Crawford, & Vilis, 2005). For instance, an early fMRI study compared goal-directed eye and hand movement planning with attentional processes (Astafiev et al., 2003). Because IPS activity increased in all three tasks, the authors suggested that attentional processes might generalize across different effectors. Compared to saccade planning, hand movement planning additionally activated other regions in parietal cortex, specifically SPL and precuneus. An anatomical comparison of human and macaque cortex revealed considerable spatial correspondence between the location of hand-specific activation in human SPL and non-human PRR (Astafiev et al., 2003). Other studies confirmed this putative human PRR to be located in close proximity of precuneus (Connolly et al., 2003; Fernandez-Ruiz et al., 2007; Filimon et al., 2009). It seems to only be activated when the target location is known (Connolly et al., 2003) and is independent of visual feedback (Filimon et al., 2009). Thus, some studies adopting the classic delayed movement paradigm with eyes and hands suggest an effector-specific organization of PPC.

However, results from other fMRI studies are not as clear-cut, revealing overlapping activity for eye and hand movement plans in PPC (Beurze, Lange, Toni, & Medendorp, 2009; Hagler, Riecke, & Sereno, 2007; Levy, Schluppeck, Heeger, & Glimcher, 2007; Medendorp, Goltz, Vilis, & Crawford, 2003). Although employing very similar paradigms, none of these studies found direct evidence for a human homologue to PRR. A recent study used multi-voxel pattern analysis (MVPA) to achieve a more fine-grained picture of PPC organization (Gallivan et al., 2011). MVPA allows for a higher spatial resolution of fMRI data (for review see Norman, Polyn, Detre, & Haxby, 2006). Whereas Gallivan and colleagues (2011) failed to identify significant differences between eye and hand movement plans with a classic univariate approach, MVPA of the same data revealed that each effector was encoded separately. Consequently, fMRI studies showing no clear distinction between eye and hand movement planning in PPC should be interpreted with caution, as a more elaborate analysis might reveal divergent results.

1.3.2 Disruption of PPC functions

Damage of PPC leads to severe problems with goal-directed reaching, a phenomenon termed optic ataxia (Bálint, 1909; Bálint & Harvey, 1995). The lesions causing optic ataxia are typically located in SPL, IPS, and precuneus (Andersen et al., 2014; Karnath & Perenin, 2005). Patient MH, who was diagnosed with a lesion in and surrounding left IPS, consistently mis-reached when asked to use his contralesional right hand to reach for an object in the right hemifield (for a detailed description of this case, see Cavina-Pratesi, Connolly, & Milner, 2013). It is important to note that M1 and visual areas remained intact (Karnath & Perenin, 2005). Hence, the observed reach errors could not be explained by difficulties to perceive the movement goal or to execute the movement. The visuomotor deficit was specific for hand movements as saccade accuracy was not affected (Trillenberg et al., 2007). Consequently, optic ataxia is often interpreted as evidence for an effector-specific organization of PPC.

By applying disruptive transcranial magnetic stimulation (TMS), reach errors that mirror the behavior in optic ataxia can be provoked in healthy participants. In one study, participants were asked to perform either delayed eye or hand movements while

TMS pulses were applied either to angular gyrus, midposterior IPS, or superior parietal occipital cortex (SPOC; Vesia, Prime, Yan, Sergio, & Crawford, 2010). SPOC is located adjacent to IPS and precuneus and also considered to encode activity specific to hand movement planning (for review see Vesia & Crawford, 2012). TMS stimulation of angular gyrus and midposterior IPS during the planning delay lead to decreased eye and hand movement accuracy. In contrast, stimulation of SPOC exclusively affected hand movements. Hence, this portion of PPC might be specifically involved in hand movement planning, whereas more anterior regions show effector-independent processing (Vesia et al., 2010). Taken together, it seems sensible to conclude that human PPC is organized in an effector-specific manner. However, a comparison of effectors with similar properties, such as the limbs, is essential (see above).

1.3.3 Behavioral principles of hand and foot movements

For instance, hand and foot movements follow the same principles on the behavioral level. One principle proposed to describe motor behavior is Fitts’ law (equation 1.1). Fitts’ law describes the so-called speed-accuracy-tradeoff. In his seminal study, Fitts (1954) asked participants to execute alternating tapping movements between rectangular targets as fast and accurately as possible. The size or width (W) of each target and the distance (D) between them were varied, described by the index of difficulty (ID; equation 1.2). The typical finding is that movement time (MT) increases with increasing ID. In other words, MT is a function of target size and distance.

$$MT = a + b \times ID \qquad (1.1)$$

$$ID = log_2\left(\frac{2D}{W}\right) \qquad (1.2)$$

Even though Fitts' law describes parameters of movement execution, it was shown to manifest already before movement onset. One study utilized early postural adjustments as a measure of movement planning (Bertucco, Cesari, & Latash, 2013). Early postural adjustments can be measured by means of a force platform and represent changes in muscle activation up to one second before movement onset, that is, during preparation. When participants were asked to point to targets of varying IDs, not only MT but also early postural adjustments depended on movement difficulty (Bertucco et al., 2013). Thus, the motoric principles of Fitts' law likely arise already at the level of movement planning rather than during movement execution. Interestingly, Fitts' law was found to transfer to other body-parts, such as the arm, the head, and the foot (Drury, 1975; Hoffmann, 1991; Jagacinski & Monk, 1985; Langolf, Chaffin, & Foulke, 1976). In contrast to limb movements, saccades do not seem to follow Fitts' law (Grosjean, Shiffrar, & Knoblich, 2007; Kourtis, Sebanz, & Knoblich, 2012). This suggests that distinct motor systems exist for eyes as opposed to limbs, rather than specific processes for every single effector type. Thus, a comparison between hand and foot is much more suitable than a comparison of hand and eye to investigate the cortical processes underlying movement plans of different effectors.

1.3.4 Cortical representations of hand and foot movements

Heed, Beurze, Toni, Röder, and Medendorp (2011) were the first to introduce this rationale and compared activity preceding goal-directed eye, hand, and foot movements by means of fMRI. When eye and hand movement planning were compared in a classic univariate approach, higher activation for the latter was evident in anterior SPL, confirming findings from previous studies. When foot movement planning was contrasted against saccade planning, a pattern paralleling the findings for hand movement planning emerged (Heed et al., 2011). In line with other fMRI studies on foot movements (Christensen et al., 2007; for review see Kollias, Alkadhi, Jaermann, Crelier, & Hepp-Reymond, 2001), the activity before upcoming hand and foot movements was statistically indistinguishable in PPC in that study. By means of MVPA, this seemingly effector-independent area was later revealed to preferentially represent one of the effectors while also containing representations of the other two (Leoné, Heed, Toni, & Medendorp, 2014). Thus, the differences between limb representations within PPC appear to be more subtle than the differences between limb and eye representations.

More evidence for a substantial overlap of hand and foot representations in PPC comes from an early case study in a patient with tumor in right parietal cortex. This patient had difficulties to reach towards objects in the left hemifield with the left hand, evident in reaching errors overshooting the target. She showed the same type of errors when trying to touch objects with her left foot (Rondot, de Recondo, & Ribadeau Dumas, 1977). More recently, patient MH, who suffers from optic ataxia, was asked to perform stepping movements onto visual targets. The task was designed to mirror reaching movements with the hand and indeed an identical pattern of errors emerged when MH used his foot (Evans, Milner, Humphreys, & Cavina-Pratesi, 2013). Thus, lesions in PPC affect hand and foot movements alike, suggesting a causal involvement in movement planning for either limb.

Support for this notion comes from studies on action observation. Action observation is thought to recruit the same brain structures as action execution does (Buccino et al., 2001; de Vignemont & Haggard, 2008; Filimon, Nelson, Hagler, & Sereno, 2007; Gazzola & Keysers, 2009). The cortical activation in response to an observed movement is strikingly similar to the activation in response to actual movement execution. Crucially, the cortical activation depends on the observed effector, that is, hand or foot, in M1, but on the type of movement, that is, pushing or dragging, in PPC (Ferri, Rizzolatti, & Orban, 2015; Jastorff, Begliomini, Fabbri-Destro, Rizzolatti, & Orban, 2010). Thus, the type of a movement seems to be represented in PPC, whereas the effector it is performed with is reflected in M1. Yet, this attribution might be flexible, as suggested by an fMRI study with participants who were born without arms (Gazzola et al., 2007). These participants observed movies of day-to-day actions with objects, such as taking a cup, that were performed by either a human or a robotic hand. In a control condition, static pictures of the human hand placed next to an object were shown. In typically developed participants, observing hand actions recruits corresponding motor areas in M1 (Buccino et al., 2001). In contrast, participants without arms showed increased blood-oxygen-level dependent (BOLD) activity in areas related to foot- and mouth-movements relative to baseline. That is, areas corresponding to the effectors that would actually be used to perform the observed action were recruited (Gazzola et al., 2007). This suggests a functional rather than effector-specific processing of the observed movements even in M1. One has to keep in mind that the cortical organization of these participants developed quite differently than in typically developed participants. Still, a TMS study also lends support to the idea that the cortical recruitment operates independently of the observed effector. Here, typically developed participants watched short videos of atypical hand and foot movements, for example, reaching for a pen with the foot or pressing a gas pedal with the hand (Senna, Bolognini, & Maravita, 2014). At the same time, motor-evoked potentials (MEP) were recorded from muscles in the hand (first dorsal interosseous, FDI) and foot (abductor hallucis, AH). MEPs are caused by stimulation of effector-specific areas in M1. Usually, the amplitude of the MEP from a certain muscle is modulated when observing movements that would recruit the same muscle during movement execution (Fadiga, Fogassi, Pavesi, & Rizzolatti, 1995). That is, watching hand movements should affect FDI, whereas watching foot movements should affect AH. Crucially, however, the opposite pattern was found: Watching atypical actions recruited the muscle of the effector that would normally perform the movement rather than the muscle matching the observed effector (Senna et al., 2014). In other words, the goal of the observed movement had a bigger impact on the cortical recruitment than the effector it was performed with.

These findings were recently extended by a TMS study in which videos of hand, mouth, and eyelid movements (opening and closing) were presented (Finisguerra et al., 2015). Here, TMS-evoked hand movements were modulated by observed mouth movements but not by observed eye movements. In other words, observation of an effector that can perform actions analogue to the hand, that is, the mouth, influenced cortical excitability of the hand area in M1. In contrast, observation of an effector that is not able to perform analogue actions, that is, the eyelid, did not (Finisguerra et al., 2015). Taken together, studies on action observation suggest that effectors with similar properties, that is, the limbs, share representations in the motor system. Both PPC and M1 seem to be recruited depending on the desired outcome of an action rather than the observed effector.

1.3.5 Differentiating movement plans of different limbs

How can movement plans of different limbs be distinguished on the cortical level? One approach to differentiate between hand and foot movements is the analysis of event-related potentials (ERP), time-locked to a cue indicating the to-be-used effector. In this paradigm, the late contingent negative variation (CNV) can be observed at central electrodes (Walter, Cooper, Aldridge, McCallum, & Winter, 1964). It is more negative preceding foot movements as compared to hand movements (Brunia & Vingerhoets, 1980, 1981). The CNV most likely originates from primary motor areas (Gómez et al., 2001; Ikeda, Lüders, & Shibasaki, 1996) and is sensitive to the amount of available information during response preparation (MacKay & Bonnet, 1990; Ulrich, Leuthold, & Sommer, 1998; Vidal, Bonnet, & Macar, 1995). In a typical paradigm, a visual cue (S1) provides full, partial, or no information about the upcoming movement, for instance, about the movement direction. After a delay, a second cue (S2) provides the missing information, for instance about the movement force. The movement is executed after the second cue, which serves as a go-signal. As a result, the CNV amplitude increases with the amount of information provided by S1 (MacKay & Bonnet, 1990). When information regarding the effector (in this study, left or right hand) is available early, the movement is prepared, evident in an increased amplitude, even though other parameters, such as movement direction, are still unknown (Leuthold & Jentzsch, 2001). In contrast, when only information regarding the type of movement, such as direction or force, is provided by S1, no increase in the amplitude can be observed, that is, the movement is not being prepared (Leuthold & Jentzsch, 2001). Thus, movements are already prepared when information about the to-be-used effector is available even though other parameters of the movement are not fully specified. This is especially true for hand and foot, but not eye movements (Jentzsch & Leuthold, 2002), again underlining the notion that the limbs differ substantially from the eyes.

Miller (2012) quantified the difference between the CNV preceding hand movements and the more negative CNV preceding foot movements by computing a difference wave that he labeled the limb selection potential (LSP; Miller, 2012). Due to the subtraction, the LSP eliminates target-related influences on the signal. Further, it can be used to assess parameters of the movement plan, such as body side, independently from the to-be-used effector. In a follow-up study, the CNV was found to be modulated by simultaneous movements of hand and foot (Miller & Gerstner, 2013). When contralateral limb movements were combined, for instance, right hand with left foot, the observed CNV closely resembled the sum of the CNVs obtained from single effector movements. However, when ipsilateral limb movements were combined, for instance, right hand with right foot, no such superimposition was found. Instead, the amplitude of the CNV was very similar to that of foot movements alone, indicating an interaction of the two movement plans (Miller & Gerstner, 2013). To sum up, the CNV is a useful tool to measure effector-specific potentials during movement preparation, which are presumably generated in primary motor cortex.

1.3.6 Changes in the power spectrum coding for different effectors

This still leaves us with the question of how movements with different effectors are prepared in PPC. One possibility is the encoding in oscillatory brain signals (for review see Donner & Siegel, 2011). Changes in the EEG that are time-locked, that is, induced, but not phase-locked, that is, evoked) and consequently average out in ERPs can be detected in the power spectrum of oscillations. Typically, oscillations are classified into different frequency-bands that have been associated with different functions, for instance the beta (10-30 Hz) and gamma band (30-80 Hz; Buzsáki & Draguhn, 2004). Both frequency ranges have been reported to show effector-specific modulations. In the beta band, an event-related desynchronization (ERD) has consistently been reported for movement planning, starting as early as 2 s before movement onset (Chatrian, Petersen, & Lazarte, 1959; Jasper & Andrews, 1938; Pfurtscheller, 1977; Pfurtscheller & Aranibar, 1977). This ERD is first located over the contralateral hemisphere and spreads then to ipsilateral hemisphere immediately before movement onset (Pfurtscheller & Lopes da Silva, 1999). The ERD precedes both hand and foot movements in a somatotopic fashion (Pfurtscheller, Neuper, Andrew, & Edlinger, 1997) and is known to be generated in contralateral M1 (Crone et al., 1998; Jasper & Penfield, 1949). In contrast, beta-band ERD preceding eye movements is localized in posterior rather than in central areas (Brignani, Maioli, Rossini, & Miniussi, 2007; Medendorp et al., 2007), suggesting that additional processes, such as visuomotor integration, contribute to this signal. In sum, beta-band ERD preceding movement onset allows to differentiate between eye and limb movement planning.

The gamma-band appears to represent movement plans of different effectors by a power increase in separate frequency bands. In a study by van der Werf and colleagues (2010), participants were asked to perform delayed eye and hand movements to targets presented in either hemifield. Targets were defined as ipsilateral or contralateral with respect to each hemisphere. By subtracting the oscillatory power in the ipsilateral condition from that in the contralateral condition per effector, the target side of the current movement plan was taken into account, reflecting the directional selectivity of the signal. The directional selectivity of upcoming eye movements was characterized by an increase in power from 50-60 Hz. In contrast, the directional selectivity of upcoming hand movements was characterized by an increase in power from 70-90 Hz. Critically, the same frequency bands were selective for eye and hand movement planning, respectively, when participants performed a dissociation task (van der Werf et al., 2010). By means of source analyses, these effector-specific frequency modulations were localized to distinct regions in PPC, matching previous findings obtained with fMRI. Thus, eye and hand movement plans seem to be encoded in distinct gamma-bands in PPC.

Still, the comparison between eye and hand movements remains inadequate, given that only the hands can truly interact with the environment. A comparison between hand and foot movements is thus inevitable to scrutinize the putative effector specificity of PPC, as suggested by the fMRI study of Heed and colleagues (2011). If, indeed, effector specificity is not an essential organizing principle of PPC and hand and foot movements are prepared in the same region, the underlying movements plans might be distinguishable in their oscillatory signature.

1.4 Outline of this thesis

Therefore, my dissertation project aims at a better understanding of movement planning of different effectors in humans. The main objective was to identify a frequency band that specifically dissociates foot from hand movement planning. Finding such a frequency band would provide insight into the neural correlates underlying movements with different limbs. To this end, we developed a suitable paradigm with delayed hand and foot movements by assessing both behavioral and kinematic measures (chapter 2). The aim of this first study was to establish motoric principles that hand and foot have in common, while controlling for potential differences in difficulty between movements with these limbs. In the second study, this paradigm was used to assess both ERPs and oscillatory power during hand and foot movement planning (chapter 3). The aim of this study was to probe ERPs and power modulations that reflect movements with different effectors and different degrees of difficulty. In the third study, eye movements were instructed in addition to hand and foot movements to advance the finding from our previous study (chapter 4). In the fourth study, a dissociation task with all possible combinations of eye, hand, and foot movements was introduced to further strengthen and extend our previous findings (chapter 5).

2 Shared behavioral and motoric principles of hand and foot movements

2.1 Introduction

We are able to promptly interact with our environment using different effectors. If necessary, our feet can perform the same type of movements as our hands. However, owing to physical and neuromuscular differences as well as a lack of practice, accurate foot movements are more difficult to perform than accurate hand movements (Paschalis, Nikolaidis, Giakas, Jamurtas, & Koutedakis, 2009). These differences render a direct comparison of hand and foot movements problematic. This problem can be overcome by assessing movements with varying degrees of difficulty within each effector, thus controlling for general physical differences between the effectors. Movements that vary in difficulty can be quantified with Fitts' law, which states that MT is a function of target difficulty (Fitts, 1954). In other words, movements to difficult targets (high ID) are slower than movements to easy targets (low ID), indexing the so-called speed-accuracy tradeoff. Crucially, Fitts' law seems to hold for foot movements (Bertucco & Cesari, 2010; Drury, 1975; Duarte & Latash, 2007; Hoffmann, 1991), allowing for a valid comparison to hand movements. For hand movements, the speed-accuracy tradeoff was shown to emerge already at the stage of movement planning, evident in changes in muscles activation before movement onset (Bertucco et al., 2013). Thus, Fitts' law is not a mere byproduct of movement execution and can be utilized to infer movement plans from motor behavior.

Next to behavioral measures, kinematic measures indicate that hand and foot movements obey Fitts' law. For the hand, a right-skewed velocity profile has been reported for difficult as opposed to easy movements. That is, the deceleration phase (time from peak velocity to end of movement) was extended, while the acceleration phase (time from movement onset to peak velocity) remained unaffected (Bootsma, Marteniuk, MacKenzie, & Zaal, 1994). For both hand foot movements, peak velocity was found to decrease with increasing difficulty (Bertucco & Cesari, 2010; Bootsma et al., 1994). Taken together, these studies suggest that hand and foot share similar planning principles.

However, most of these studies investigated either hand or foot movements, rendering a direct comparison ambiguous. The only study investigating both hand and foot movements has several drawbacks (Hoffmann, 1991): First, hand and foot movements were directed at different targets, which were either placed on a table or on the floor. As a consequence, the viewing distance of the targets was different between the two effector conditions, possibly leading to differences in perceived target sizes. Target size is a critical factor of ID, however. Thus, movement difficulty was likely different between the hand and foot condition in that study.

Second, hand and foot movements were performed with a hand-held probe and a stylus taped to the shoe, respectively. In other words, participants actively used a tool in the hand condition whereas passively moving one in the foot condition. This is problematic because active and passive tool-use are believed to imply different processes (Cardinali et al., 2009; Maravita, Spence, Kennett, & Driver, 2002).

Third, the task was performed with full visual feedback, possibly allowing for corrective movements. In other words, participants might have adjusted movements online. This can be prevented by eliminating visual feedback. Hand movements were shown to also follow Fitts' law when visual feedback is reduced or absent (J. Wu, Yang, & Honda, 2010) but no data are available for foot movements.

Thus, the primary aim of our study was to identify shared mechanisms of hand and foot movements under identical task demands as a measure of planning principles underlying different effectors. To this end, we asked participants to make delayed hand or foot movements toward circular targets, which they touched with the index finger or big toe. We used Fitts' paradigm (Fitts, 1954) to manipulate movement planning within each effector. Though movements are alternated between rectangular targets in the classic task, other studies have confirmed that discrete movements and movements to circular targets also follow Fitts' law (Fitts & Peterson, 1964; Medina, Jax, & Coslett, 2009). The same holds for movements that are executed after a delay (Kourtis, Knoblich, Woźniak, & Sebanz, 2014). Our task will be referred to as the delayed Fitts task from hereon.

We hypothesized that hand and foot movements show analogue differences between easy and difficult targets in both behavioral and kinematic measures. First, in line with previous research, we expected that MT would be longer for difficult than for easy targets for both hand and foot movements (Fitts, 1954; Hoffmann, 1991). Second, we expected higher peak velocities for movements to easy targets than for movements to difficult targets with both effectors (Bertucco & Cesari, 2010; Bootsma et al., 1994). Third, the deceleration phase of movements to difficult targets should be longer than that of movements to easy targets, regardless of the effector (Bootsma et al., 1994). Fourth, the acceleration phase should be unaffected by target difficulty for both effectors (Bootsma et al., 1994). Similarly, reaction time (RT) should not differ between easy and difficult movements with either effector. Finally, we used the variable error (VE) to assess the variability of movement endpoints on the touchscreen as a control for the difficulty manipulation. Accordingly, the VE should be larger for bigger, that is, easy than for smaller, that is, difficult targets.

The secondary aim of this study was to develop a paradigm suitable for EEG (chapter 3 and 4). Here, it is particularly important to avoid perceptual and attentional confounds. These are controlled for by manipulating movement difficulty within each effector. As EEG is highly sensitive to muscular artifacts and eye movements, the setup and design of the study had to be comfortable and feasible for the participants.

2.2 Method

The design of the experiment was optimized twice. Consequently, three different datasets from different participants were acquired. All three designs will be explained in the following but only the results of the final design will be discussed in detail.

2.2.1 Participants

In total, 26 healthy volunteers participated in the study. Nine participants (7 females, mean age = 22.89, range = 20-26 years) completed the first version of the task, seven participants (7 females, mean age = 26.67, range = 21-30 years) completed the second version, and ten participants (8 females, mean age = 22.80, range = 20-28 years) completed the third, and final, version. Motion data were only assessed in the final sample. Owing to technical issues, no motion data were obtained from two participants. One additional participant had to be excluded from the analysis due to poor data quality, which resulted in the loss of all trials in one condition. Hence, the final sample consisted of seven participants (6 females, mean age = 23.43, range = 20-

28 years). All participants had normal or corrected-to-normal vision and reported no neurological, sensory, or motor disorders. They received course credit or monetary compensation (7€/hour). Handedness was assessed with the Edinburgh Handedness Inventory (Oldfield, 1971) and footedness was assessed with the revised Waterloo Footedness Questionnaire - Revised (Elias, Bryden, & Bulman-Fleming, 1998). All but one participant were right-handed (M = 19.67, SD = 3.93), four were right-footed (M = 10.25, SD = 2.22), and three were both-footed (M = 1, SD = 5.2).

2.2.2 Setup

The experimental setup was identical in all three experimental designs, unless stated otherwise. Participants sat in a big armchair that was positioned in a custom-built metal frame. Foam cushions were used to adjust the seat for different body heights and to support a comfortable seating position. In the first design, participants either placed both hands or both feet on flat circular buttons (diameter 6.5 cm) in front of them (Buddy Button, AbleNet, Inc., Roseville, MN, United States). In the second and third design, participants adopted a frog-like posture with each hand and each foot on one button, respectively (Figure 2.1). The buttons were attached to the seat by means of Velcro® tape. The seat was extended to allow for a comfortable positioning of the bare feet. An LED monitor (22 inches; Samsung Electronics GmbH, Schwalbach, Germany) was located in front of the participants. The monitor was occluded by a dark opaque plastic pane to avoid illumination of the workspace. A touch screen (22.5 inches; KEYTEC, Inc., Garland, USA) was attached to the plastic pane such that it covered the area of the monitor behind the pane. The touch screen was used to record movement endpoints. It was calibrated before each session to align its coordinates to the monitor display. A chin-rest (Gerald Kann Kinnstützen und mechanische Vorrichtungen, Magdeburg, Germany) was used to discourage head movements and keep gaze direction stable throughout the experiment. The chin-rest was attached to an adjustable arm, which was mounted to the metal frame to the left side of the seat. By only protruding into the workspace at the height of the participants' head, it allowed for unconstrained movements of the arms and legs. The experiment was controlled by the software Presentation (Neurobehavioral Systems, Inc., Berkeley, CA, United States). Reaching movements were recorded from above with a camera-based motion tracker (Visualeyez II VZ400v, PTI Phoenix Technologies, Burnaby, Canada) at a sampling rate of 100 Hz. Infrared markers were attached to the nail of each index finger and each big toe. Three additional markers were positioned around the touch screen to calibrate the motion tracker with respect to the monitor before each session. The experiment took place in complete darkness to avoid visual feedback of the movements.

In the second and third design, the horizontal component of the electrooculogram (EOG) was displayed online with BrainVision Recorder (Brain Products GmbH, Gilching, Germany). The EOG was monitored by the experimenter throughout the experiment to control for ocular fixation.

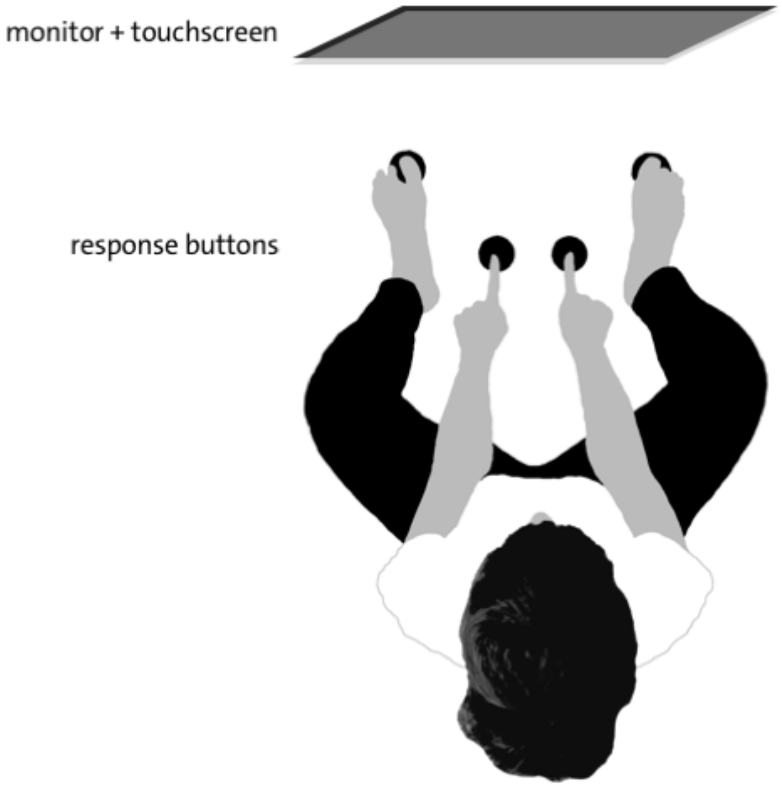

Figure 2.1. Schematic of the experimental setup. Participants were seated in front of a monitor with a touchscreen and placed each effector on a button. The head rested on a chin rest (not displayed here).

2.2.3 Stimuli and Design

2.2.3.1 First Design

Figure 2.2 shows an example trial of the first design. The target display consisted of a gray fixation point and a row of four circular target stimuli on a black background. All stimuli were presented in the lower half of the screen (90 mm below the center) with the fixation point in the center and two target stimuli in each hemifield. Each possible target was made up of one yellow dot (7 mm) surrounded by eight red dots (7 mm each; diameter of resulting circle = 56 mm), resembling an LED arrangement. The yellow dots were horizontally aligned to the fixation point. The distance of the yellow dots was 93 and 186 mm from fixation in each hemifield. The conditions effector (“hand” vs. “foot”) and difficulty (“easy” vs. “difficult”) varied randomly per block and were instructed at the beginning of each block. In case of the “hand” condition, participants were allowed to rest their legs wherever comfortable. In the “foot” condition, participants typically rested their hands on the armrest. In the “easy” condition, the movement had to end within the circle of red dots (ID = 6). In the “difficult” condition, the movement had to end as close to the yellow dot as possible (ID = 3). Body side (“left” vs. “right”), target side (“left” vs. “right”), and distance of the target from fixation (“near” vs. “far”) varied randomly per trial to avoid stereotypical movements. In total, eight blocks of 24 trials were completed.

At the beginning of each trial the target display appeared and the fixation point was added after 250 ms. After a variable delay of 1000 – 2000 ms (square distribution), the body side was indicated for 2000 – 3000 ms (square distribution) by centrally displaying a word (“left” or “right”). As a reminder, the current effector condition was depicted as a symbol (hand or foot) surrounded by a box colored like the current difficulty condition (yellow for difficult or red for easy) below the body side instruction. After 1000 ms one of the yellow dots briefly flashed twice for a total duration of 384 ms, signaling the movement goal. After a variable delay between 3000 and 4000 ms (square distribution) all targets disappeared, serving as the go-signal. Participants had to reach towards and touch the remembered target location with the instructed effector as fast and accurately as possible (in accordance with the current accuracy condition). The trial ended 3000 ms after the go-signal.

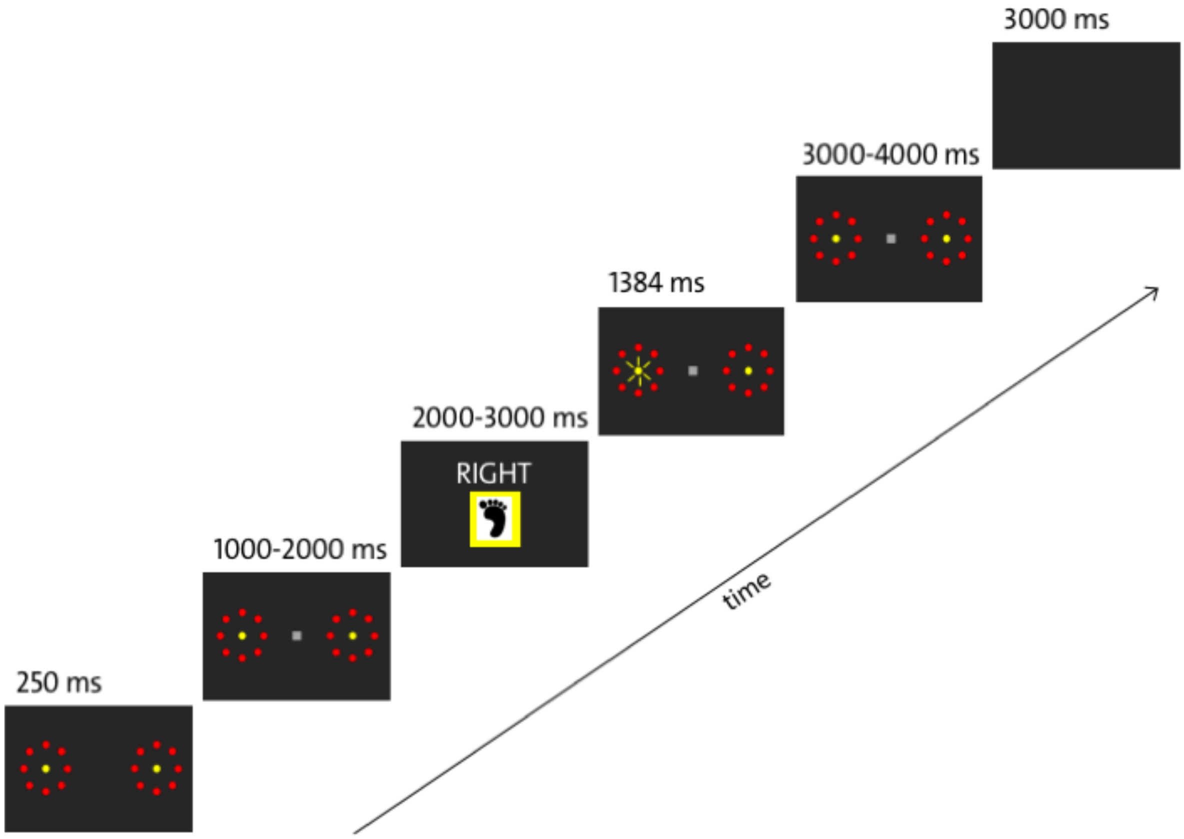

Figure 2.2. Example trial of the first design. The fixation point was added to the display after 250 ms. After a first delay, body side was cued. A reminder was shown for effector (symbol) and accuracy (color). Next, the target flashed. After a second delay, all stimuli disappeared and the movement was executed.

An explorative analysis of the behavioral data revealed no differences between MT to easy and difficult targets for either effector, that is, Fitts' law was not evident in our dataset. One reason for this lack of a speed-accuracy tradeoff might have been the blocked design of the difficulty condition, as it could have led to expectancy or short-term training effects.

In light of the prospective EEG study, this design had another flaw: Flashing stimuli would likely result in a very pronounced visual response that could possibly interfere with the subtler planning processes we were interested in. In addition, the duration of one trial was relatively long regarding the high trial numbers required for EEG analyses.

2.2.3.2 Second Design

The drawbacks of the first design were accounted for by changing the type of stimuli, the timing of the trials, and the block design. Now, effector and difficulty were instructed on a trial-by-trial basis. As a consequence, participants had to remain seated with each effector on one button throughout the experiment. An example trial is depicted in Figure 2.3. Each trial began with the appearance of a white fixation cross on a black background in the lower half (90 mm below the center) for a random duration of 300 – 400 ms (square distribution). Next, two gray symbols indicating the to-be-used effector type (hands or feet, both left and right) were presented in place of the fixation cross for 250 – 350 ms (square distribution), followed again by the fixation cross (1000 ms; effector plan phase). After this first delay, the effector-symbols reappeared along with a green target circle for 450 – 550 ms (square distribution). The target circle could be presented in the left or right hemifield and had a diameter of either 20 mm (“difficult”, ID = 5) or 70 mm (“easy”, ID = 3). Opposite to the target, an isoluminant (0.4 cd/m^2) gray circle was shown as visual counterbalance. The distance of the circles from the fixation cross in both hemifields was varied (70.6 or 127 mm) to avoid stereotypical movements. To specify the body side, only one of the two effector-symbols was now colored green (left or right). The target presentation was again followed by the fixation cross (1000 ms; target plan phase). After this second delay, the fixation cross disappeared, serving as the go-signal. The movement had to be initiated within 250 – 750 ms after the go-signal and was allowed to last up to 2000 ms. The touch screen response terminated the trial. The inter-trial interval was jittered from 1900 – 2100 ms (square distribution). Only the instructed effector was allowed to move, that is, only one button was to be released and the eyes had to fixate centrally. When participants released an incorrect button or reached towards the incorrect target side, the trial was repeated at the end of the current block. The experiment consisted of 6 blocks with 32 trials each (i.e., 192 in total). The trials were made up of each possible combination: 2 effectors (hand vs. foot) x 2 body sides (left vs. right) x 2 difficulties (easy vs. difficult) x 2 hemifield (left vs. right) x 2 distances (near vs. far). This resulted in 48 trials per condition of interest (effector x difficulty).

Before the experimental session, participants performed at least one and up to three practice blocks with visual feedback, depending on their performance. After each trial, an emoticon indicated whether the correct button had been released within the allowed time window (happy=correct, sad=incorrect, neutral=too early/late). Next, the target re-appeared and the position the participant had touched was displayed as a colored dot. The color of the dot indicated whether the endpoint of the movement had hit (green) or missed (red) the target.

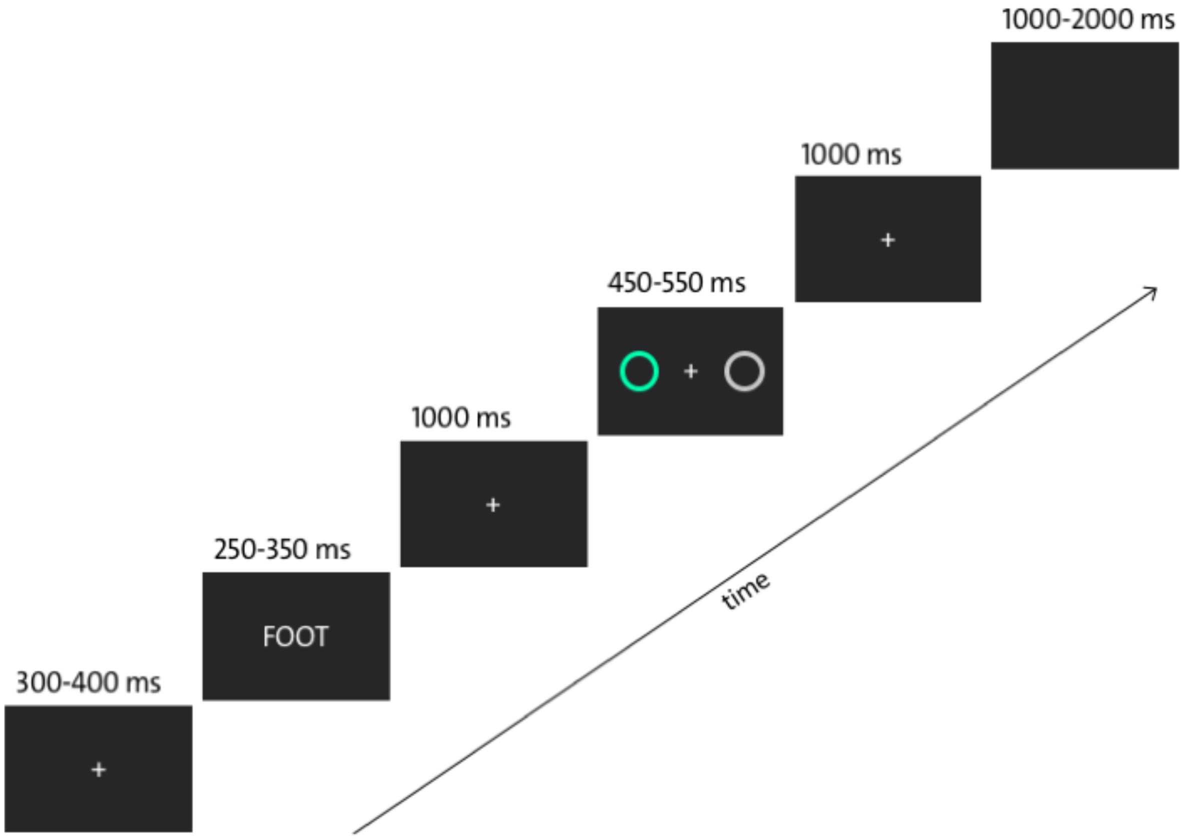

Figure 2.3. Example trial of the second design. After a variable delay, the effector was cued with the word “hand” or “foot”. After a first planning delay, the target (green circle) appeared. The size of the circle determined the difficulty of the movement. After a planning second delay, the fixation cross disappeared and the movement was executed.

The average MT of all participants is shown in Figure 2.4. An exploratory analysis revealed no difference between easy and difficult hand movements (M_{easy} = 410.56 ms, SD = 135.96 ms; $M_{difficult}$ = 410.38 ms, SD = 134.17 ms). In contrast, MT was slightly higher for difficult than for easy foot movements (M_{easy} = 593.09 ms, SD = 224.82 ms; $M_{difficult}$ = 621.49 ms, SD 233.92 ms). A repeated-measures analysis of variance (ANOVA) revealed significant main effects of both effector, F(1,5) = 12.54, *p* = 0.017, and difficulty, F(1,5) = 24.13, *p* = 0.004. Even though the data suggest that only foot movements were affected by difficulty, the interaction of effector and difficulty failed to reach significance, F(1,5) = 3.13, *p* = 0.137, likely owing to the small number of participants. Hence, the major drawback of the second design was the size of the stimuli. In addition, participants often reported that movements had to be initiated too quickly, resulting in a loss of accuracy. Taken together, these results likely reflected a floor effect.

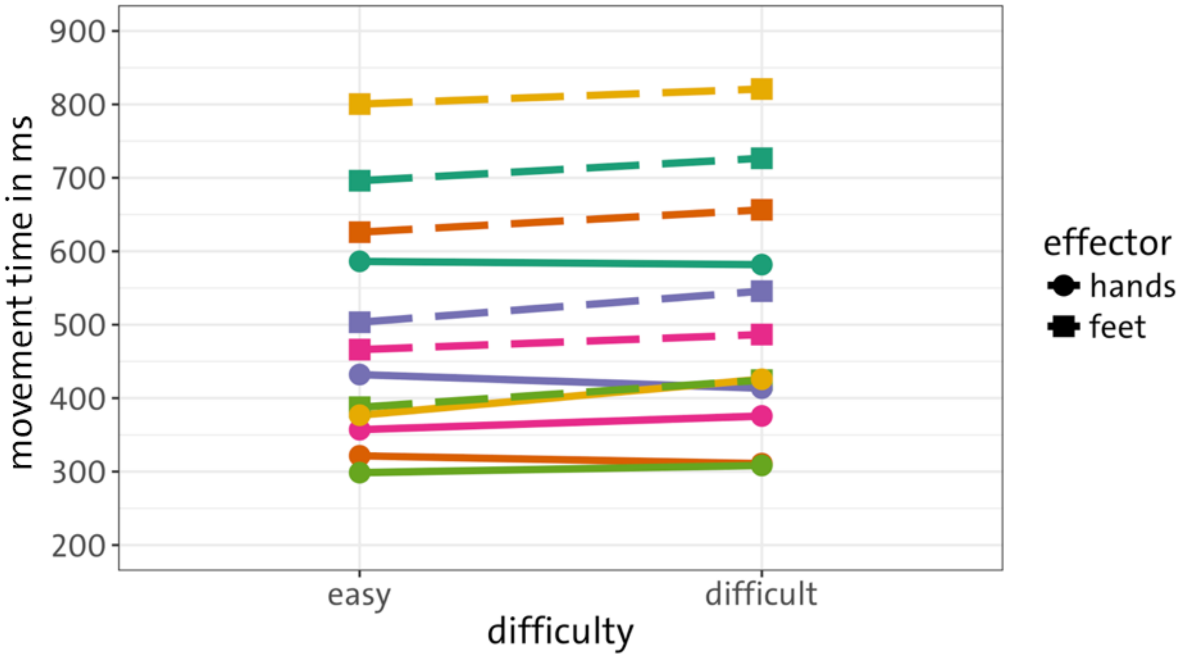

Figure 2.4. Average movement time in the second design. Different colors represent different participants. Foot movements (dashed lines) were slower for difficult than easy target for all participants. Hand movements (solid lines) were not affected by target difficulty.

2.2.3.3 Third Design

The drawbacks of the second design were accounted for by changing the size of the stimuli and the trial timing (Figure 2.5). The overall procedure remained the same. “Easy” targets now had a diameter of 80 mm (ID = 3.5) and “difficult” targets had a diameter of 40 mm (ID = 2.5). Participants were allowed to initiate the movement from 200 up to 1500 ms after the go-signal. The effector and target plan phases lasted 750 ms and 1000 ms, respectively.

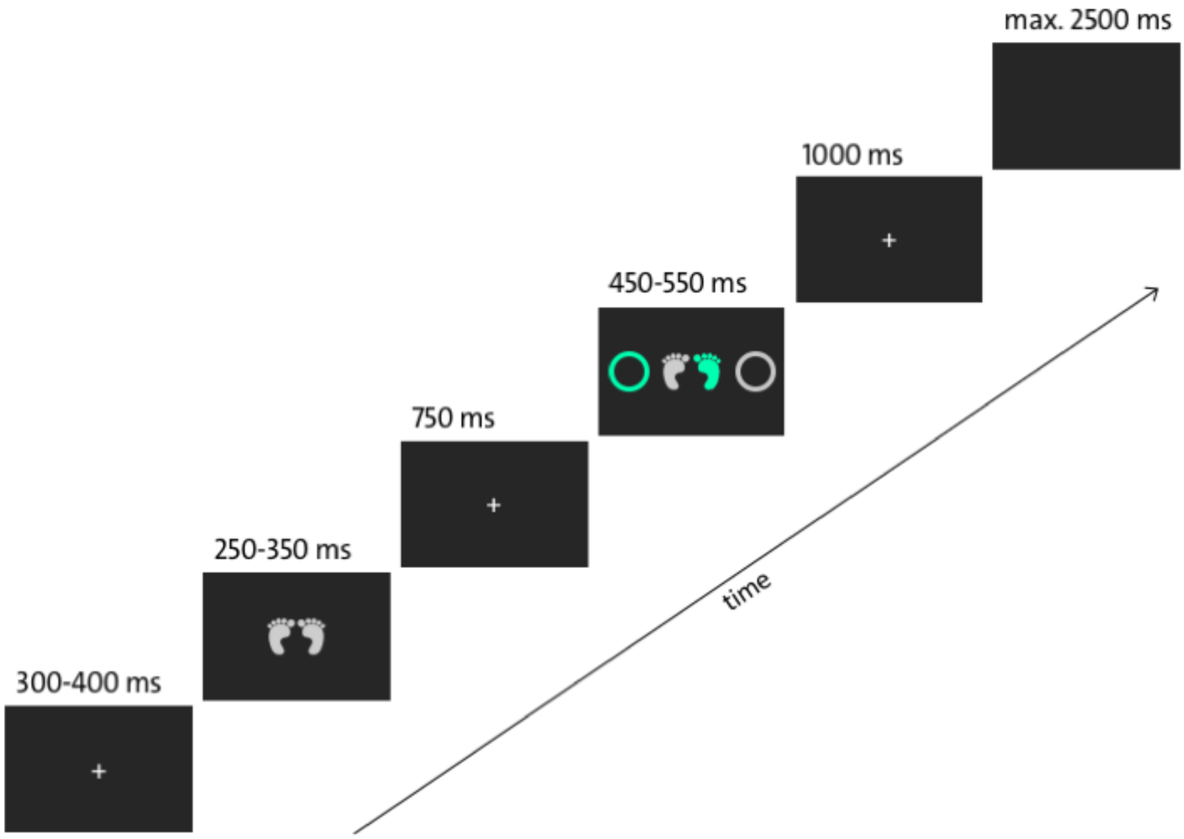

Figure 2.5. Example of the final trial design in the delayed Fitts task. After a variable delay, gray symbols indicated the effector. After a first planning delay, the target (green circle) appeared and the body side was cued (green effector symbol). After a second planning delay, the fixation cross disappeared and the movement was executed.

2.2.4 Analysis

All data were preprocessed in MATLAB (R2014a, The Mathworks, Natick, MA, USA). We pooled across body sides for each effector type after confirming that there were no differences between the two. Similarly, we collapsed across target locations within the “easy“ and “difficult“ condition. Trials with false responses (incorrect effector or target side), misses, and premature responses (< 200 ms) were excluded from the analysis. After preprocessing, all dependent measures were exported to the statistical software R, Version 3.3.3 (R Core Team, 2013).

2.2.4.1 Behavior

MT was defined as the time from button release until the touch screen response. RT was defined as the time from the go-signal until button release. The VE was obtained as follows: All movement endpoint coordinates, which were measured with the touchscreen, were normalized by subtracting the x- and y-coordinates of the current target position. The corrected endpoints were used to compute the VE by taking the square root of the summed squared difference between each single endpoint (χ_i) and the mean endpoint ($\bar{\chi}$) divided by the total number of recorded endpoints (n). The obtained VE for the x- and y-direction of the touch screen were combined by taking the square root of the sum of the squared variable error of each direction.

2.2.4.2 *Kinematics*

Given that participants performed movements towards targets in front of them, the y-dimension of the three-dimensional reach trajectory was analyzed (i.e., depth dimension). Because trajectories were recorded throughout the entire trial, the first time point of interest was defined by the button release and all preceding data points (which represent the starting position) were discarded. Many trajectories had missing data points at the beginning of the reaching movement, often caused by the upper body occluding the limbs. These were replaced by the first valid data point, simulating a straight reach up until this point in time. Since the first data point was next subtracted from all other data points in order to align the reach to 0 mm, this “straight reach” was marked by no change in the y-dimension at movement onset. All trajectories were extended with their last sampling point to match the duration of the participant’s slowest reach. Trials with extreme values (> 30 mm between two consecutive sampling points) and bad data quality were rejected. On average, 136.71 (SD = 29.48) trials per participant were included in the analysis.

Individual reach trajectories were subjected to a functional data analysis (FDA) and fitted with a spline function (Ramsay & Silverman, 2005). Spline functions smoothly interpolate discrete data points, resulting in a continuous, mathematical representation of the movement trajectory. FDA is commonly used to approximate motion data (e.g., Brandes & Heed, 2015; Gallivan & Chapman, 2014). To ensure accurate spline fitting at the beginning and the end of each trajectory, it was artificially extended by repeatedly adding the first data point (600 times). These extensions were cut off again after fitting the trajectories. FDA was implemented using the MATLAB toolbox “FDAfuns” (Ramsay, Hooker, & Graves, 2009). The fitting criterion lambda, which trades off data-fit against trajectory smoothness, was determined based on the degrees of freedom of the spline fit by accounting for 25% of data points of each trajectory (Hastie & Tibshirani, 1990).

The following parameters were extracted from each single trial and averaged per participant and condition: peak velocity (i.e., maximum of the first derivative of the trajectory), duration of the acceleration phase (i.e., time from button release to peak velocity), and duration of the deceleration phase (i.e., time from peak velocity to end of movement). Trials with values exceeding the mean by ±3 SD (per participant and condition) were discarded as outliers.

2.2.4.3 Inferential Statistics

All dependent variables (except for VE) were subjected to linear mixed-effects analyses using the R package lme4 (Bates, Mächler, Bolker, & Walker, 2015). The behavioral (MT, RT) and kinematic (peak velocity, acceleration, deceleration) measures were each analyzed with a model comprising fixed effects for the factors “effector” (hand vs. foot) and “difficulty” (easy vs. difficult). Factors were specified with contrast coding (effector: hand -1, foot 1; difficulty: easy -1, difficult 1). For fixed effects, main effects and interactions were modeled. Because the model including the full random effects structure, that is, all main effects and their interaction, failed to converge, we reduced the random-effects structure to only include random intercepts per participant (Barr, Levy, Scheepers, & Tily, 2013; Schielzeth & Forstmeier, 2009).

The significance of fixed effects was assessed with a model comparison using the package afex (Singmann, 2015). Here, reduced models are created by removing single effects from the full model. These reduced models are compared to the full model in a step-by-step approach to calculate *p*-values. Parametric bootstrapping was employed to approximate the sampling distribution (Singmann, 2015). Fixed effects were considered significant at $p < 0.05$. To comply with the assumptions of normality and homoscedasticity, dependent measures were box-cox transformed when necessary before setting up the model (Box & Cox, 1964).

2.3 Results

2.3.1 Behavior

2.3.1.1 Movement Time

Average MT is depicted in Figure 2.6. There were main effects of effector ($\chi^2(1)$ = 263.7, *p* = 0.001) and difficulty ($\chi^2(1)$ = 6.67, *p* = 0.009). As expected, interaction between effector and difficulty did not reach significance ($\chi^2(1)$ = 0.89, *p* = 0.34). Movements with the feet were generally slower than movements with the hands. With both effectors, movements to difficult targets (M_{hands} = 384.87 ms, SE = 27.69 ms; M_{feet} = 511.19 ms, SE = 57.97 ms) were slower than movements to easy targets (M_{hands} = 377.46 ms, SE = 28 ms; M_{feet} = 482.26 ms, SE = 48.64 ms). Thus, movements with hands as well as feet followed Fitts' law (Fitts, 1954).

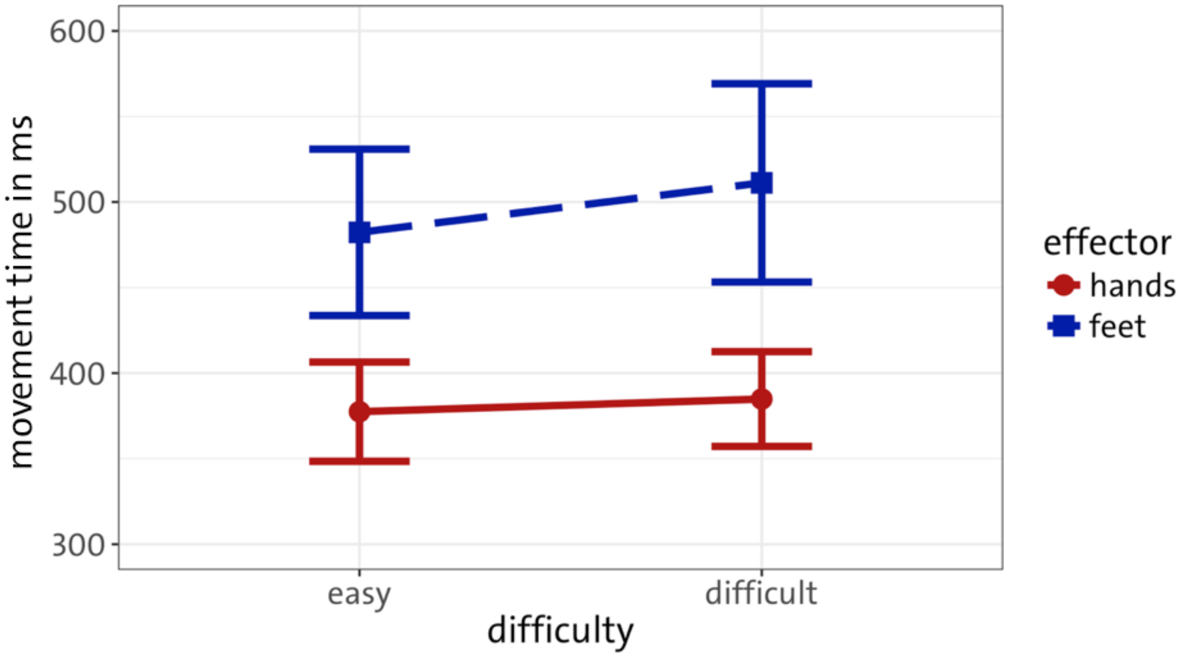

Figure 2.6. Movement time for hand (red, solid line) and foot (blue, dashed line) movements to easy and difficult targets. Both limbs were slower for difficult than easy targets. Whiskers indicate the standard error of the mean.

2.3.1.2 Reaction Time

Average RT is depicted in Figure 2.7. There was a main effect of effector ($\chi^2(1)$ = 38.46, *p* = 0.001). As predicted, there was no main effect of difficulty ($\chi^2(1)$ = 1.73, *p* = 0.18) and no interaction between effector and difficulty ($\chi^2(1)$ = 0, *p* > 0.99). RT was shorter for hand (M_{easy} = 364.03 ms, SE = 43.6 ms; $M_{difficult}$ = 365.23 ms, SE = 50.84 ms) than for foot movements (M_{easy} = 393.48 ms, SE = 41.05 ms; $M_{difficult}$ = 391.63 ms, SE = 46.58 ms).

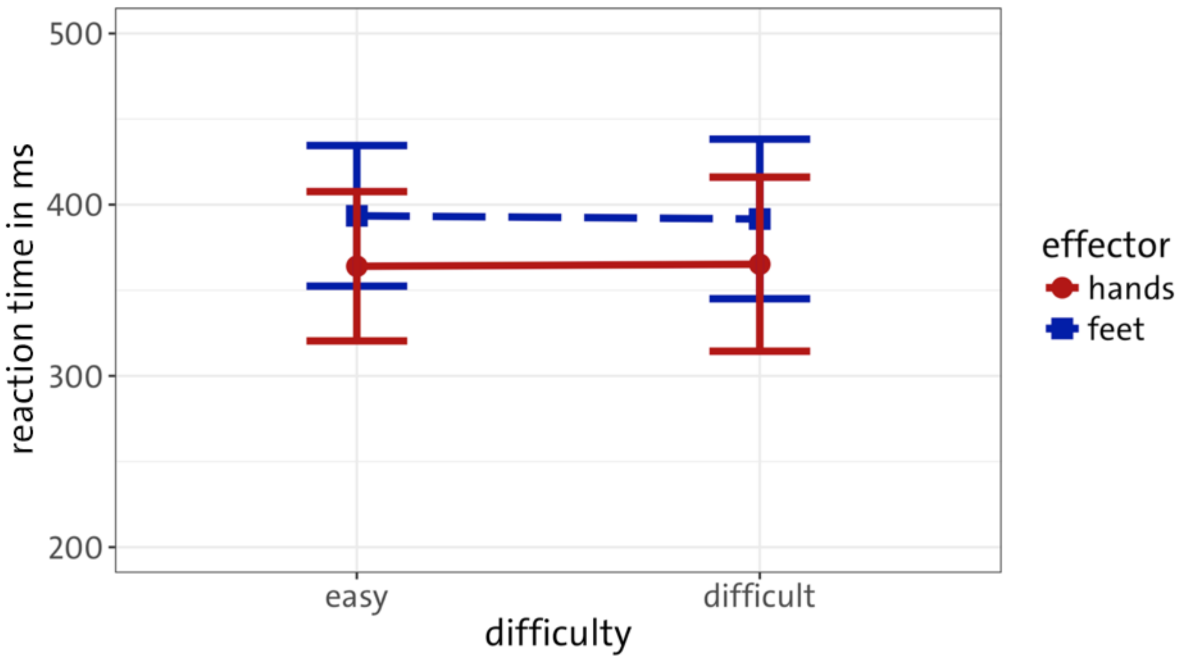

Figure 2.7. Reaction time of hand (red, solid line) and foot (blue, dashed line) movements to easy and difficult targets. Target difficulty did not affect reaction times with either limbs. Whiskers indicate the standard error of the mean.

2.3.1.3 Variable Error

The mean variable error is shown in Table 2.1. It served as a control for the difficulty manipulation. Since the variable error reflects the mean deviation per participant in itself, no variance measure is available for inferential analysis. Descriptively, endpoints of hand movements were more accurate than those of foot movements. No difference between easy and difficult targets was observed.

Table 2.1

Mean Variable Error (mm)

	hands	feet
easy	17.70 (± 1.14)	29.23 (± 2.72)
difficult	17.40 (± 0.87)	29.14 (± 2.74)

Note. Standard errors are in parentheses.

2.3.2 Kinematics

The velocity profile of hand and foot movements of each participant is shown in Figure 2.8. The profiles show a typical bell shape with lower peaks for movements to difficult targets than movements to easy targets with either effector.

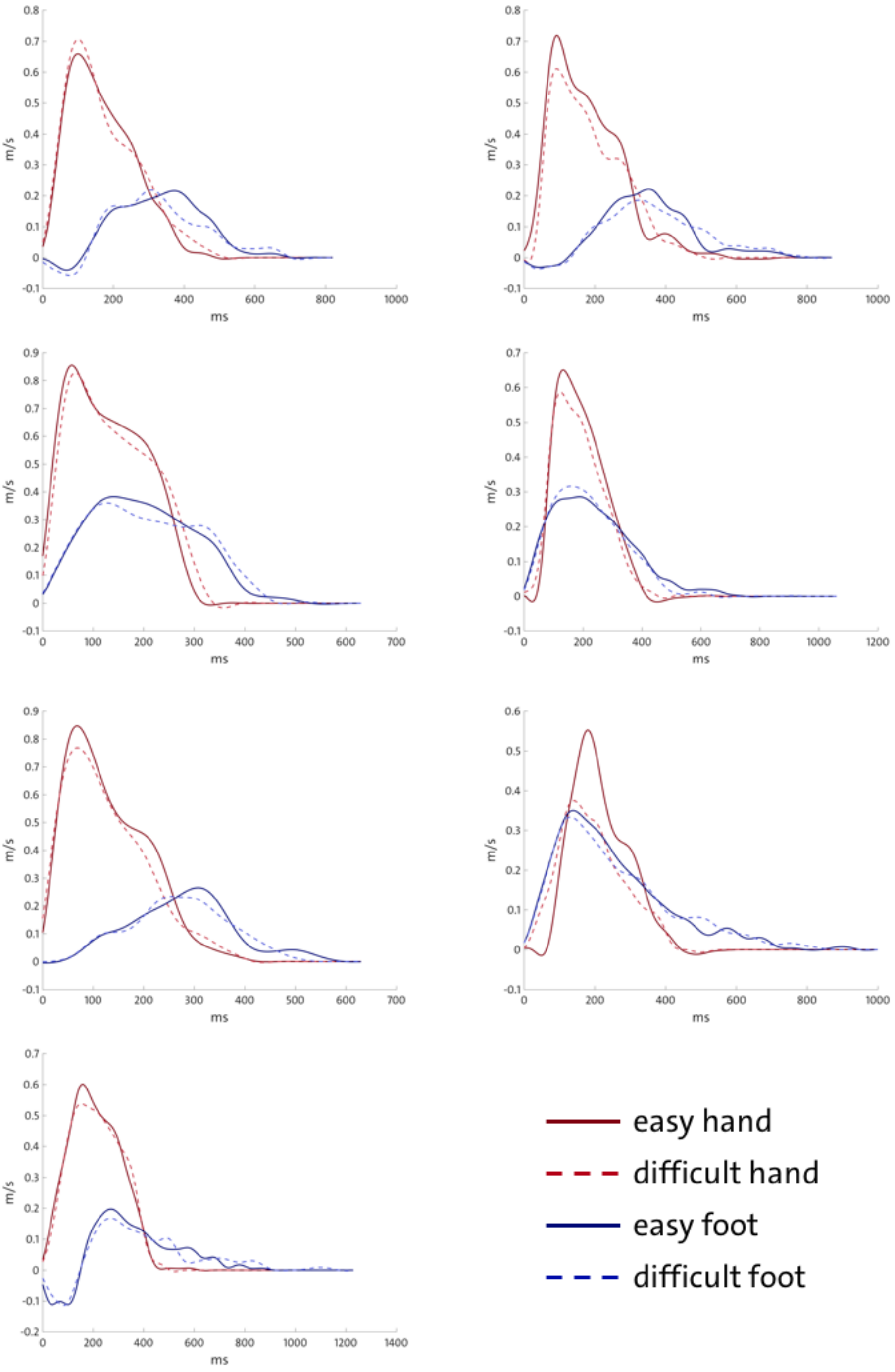

Figure 2.8. Velocity profile of hand (red) and foot (blue) movements to easy (solid) and difficult (dashed) targets per participant. Many participants show higher velocity peaks for easy than difficult targets with both effectors.

2.3.2.1 Peak velocity

The qualitative impression was confirmed in the statistical analysis of average peak velocity (Figure 2.9). There were main effects of effector ($\chi^2(1) = 1203.18$, $p = 0.001$) and difficulty ($\chi^2(1) = 8.21$, $p = 0.006$). As expected, there was no interaction between effector and difficulty ($\chi^2(1) = 0.13$, $p = 0.7$). Peak velocity was higher for movements to easy targets ($M_{hands} = 0.84$ m/s, SE = 0.07 m/s; $M_{feet} = 0.40$ m/s, SE = 0.03 m/s) than for movements to difficult targets ($M_{hands} = 0.82$ m/s, SE = 0.08 m/s; $M_{feet} = 0.39$ m/s, SE = 0.03 m/s). Peak velocity was also higher for the hands than for the feet, which is not surprising given that MT of the hands was shorter than MT of the feet.

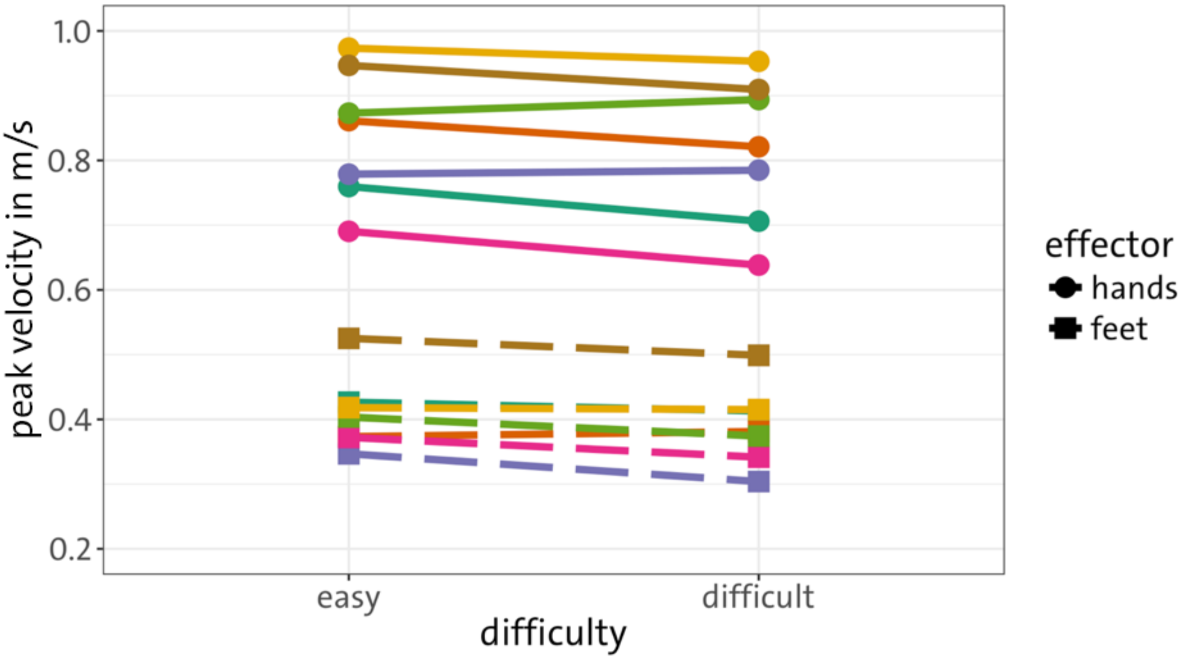

Figure 2.9. Mean peak velocity for hand (solid lines) and foot (dashed lines) movements to easy and difficult targets. Different colors represent different participants. Most participants show lower peak velocity for foot movements to difficult than easy targets. With the hand, only some participants show lower peak velocity for movements to difficult targets.

2.3.2.2 Acceleration Phase

The average duration of the acceleration phase is depicted in Figure 2.10. There was a main effect of effector ($\chi^2(1) = 608.48$, $p = 0.001$) for the duration of the acceleration phase. There was no main effect of difficulty ($\chi^2(1) = 1.53$, $p = 0.23$) and no interaction between effector and difficulty ($\chi^2(1) = 1.38$, $p = 0.23$). The acceleration phase was shorter for hand ($M_{easy} = 116.2$ ms, SE = 23.76 ms; $M_{difficult} = 107.68$ ms, SE = 21.24 ms) than for foot movements ($M_{easy} = 282.78$ ms, SE = 50.31 ms; $M_{difficult} = 276.68$ ms, SE = 50.51 ms). For hand movements, the acceleration phase made up approximately 30% of the entire duration of the movement. In contrast, it made up approximately 60% of MT of the feet. Thus, the duration of the acceleration phase does not seem to be a mere by-product of the overall longer duration of foot movements.

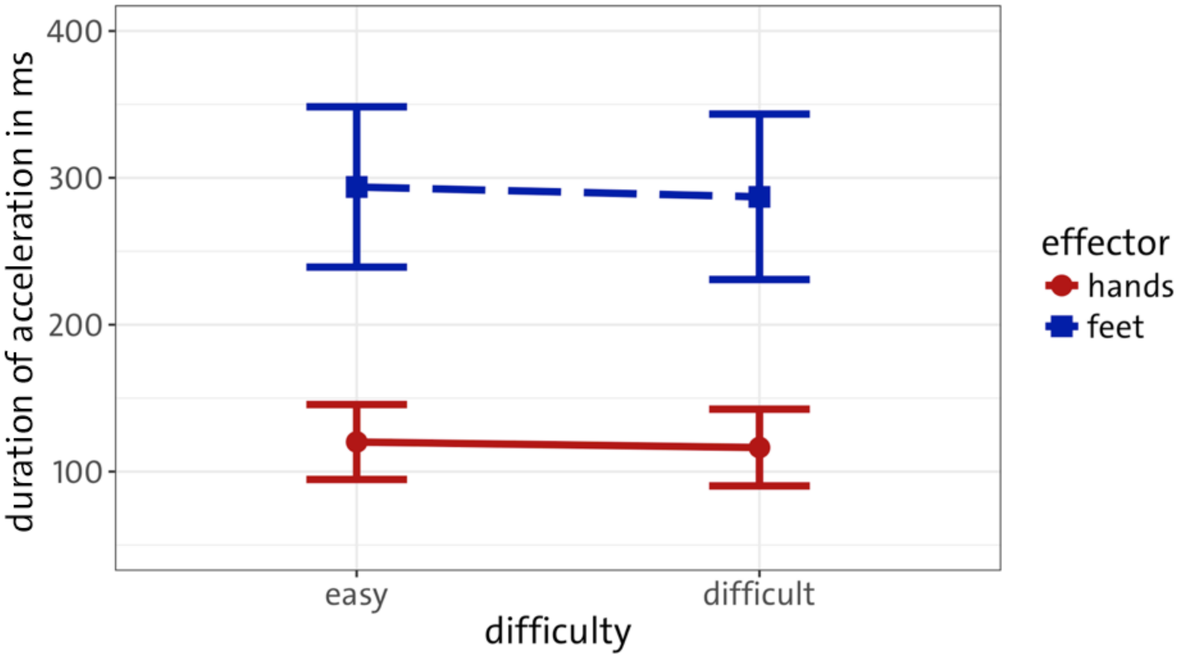

Figure 2.10. Duration of the acceleration phase for hand (red, solid line) and foot (blue, dashed line) movements to easy and difficult targets. Foot movements show a longer acceleration phase than hand movements. Target difficulty did not affect the acceleration phase. Whiskers depict the standard error of the mean.

2.3.2.3 Deceleration Phase

The average duration of the deceleration phase is depicted in Figure 2.11. There were main effects of effector ($\chi^2(1) = 116.97$, $p = 0.001$) and difficulty ($\chi^2(1) = 9.3$, $p = 0.004$). The interaction between effector and difficulty was not significant ($\chi^2(1) = 0.26$, $p = 0.62$). With both effectors, movements to difficult targets ($M_{hands} = 275.07$ ms, SE = 22.42 ms; $M_{feet} = 224.73$ ms, SE = 63.47 ms) decelerated longer than movements to easy targets ($M_{hands} = 259.65$ ms, SE = 23.88 ms; $M_{feet} = 194.24$ ms, SE = 59.41 ms). Corresponding to the duration of the acceleration phase, the deceleration phase was longer for hand than for foot movements, making up approximately 70% of the absolute MT for hand movements but only about 40% for foot movements.

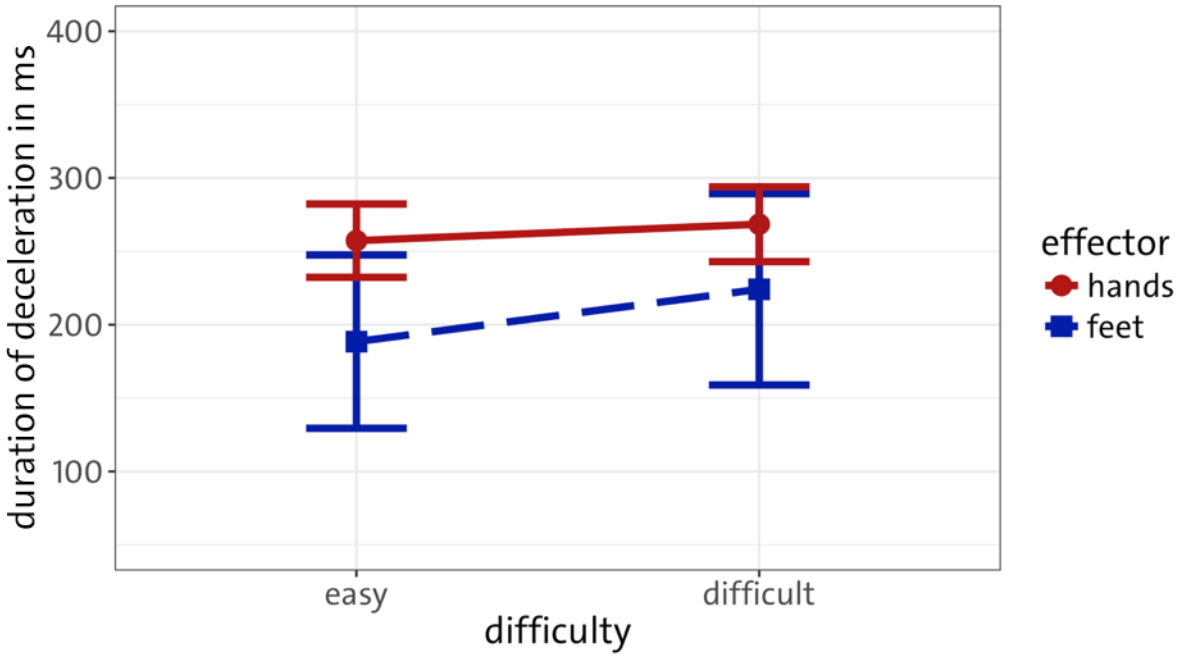

Figure 2.11. Duration of the deceleration phase for hand (red, solid line) and foot (blue, dashed line) movements to easy and difficult targets. Both effectors show a longer deceleration phase for difficult than easy targets. Whiskers depict the standard error of the mean.

2.4 Discussion

The aim of our study was to investigate Fitts' law in hand and foot movements as a measure of planning principles underlying different effectors. By using identical targets for both effectors we can rule out confounding attentional or perceptual effects. In accordance with previous studies, we found an increase in MT with increasing difficulty, which was accompanied by a decrease in peak velocity for both effectors. We replicated and extended the findings by Bootsma and colleagues (1994) by showing that hand as well as foot movements to difficult targets were marked by a longer deceleration phase than movements to easy targets. As expected, RT of both effectors did not differ between movements to easy and difficult targets. Unexpectedly, the VE was also unaffected by target difficulty, that is, reaching endpoints at easy targets were as accurate as those at difficult targets. Given that MT was modulated as predicted by Fitts' law, however, it is unlikely that participants failed to plan accurate movements. Rather, participants may have planned movements according to the current target size but were unable to execute them with the desired precision. These difficulties are presumably caused by the unusual seating position participants had to adopt. In studies investigating hand movements, participants are typically seated comfortably at a table with the feet placed on the floor. In the few studies investigating foot movements, participants were either seated regularly or performed the movements with one foot while standing up-right (Duarte & Latash, 2007; Hoffmann, 1991). In our study, participants adopted a frog-like posture and were asked to perform a reaching movement with one effector while remaining still with the rest of their body. Hence, they likely followed the instruction and intended to perform accurate movements, which is reflected by the increase in MT, but were hampered by the complex setup during movement execution.

Even though we were only able to include data of seven participants in the kinematic analysis, our results are in line with previous research (Bootsma et al., 1994). More specifically, movements with both effectors showed higher peak velocities when targets were easy rather than difficult. Furthermore, the deceleration phase of movements with either effectors was shorter in the easy than in the difficult condition. For both hand and foot movements, the acceleration phase remained unaffected. Early studies suggest that the acceleration phase is used to swiftly move the effector towards the target whereas the deceleration phase is used for fine-tuning movements (Jeannerod, 1984; Marteniuk, MacKenzie, Jeannerod, Athenes, & Dugas, 1987). This notion fits well with the observed extension of the deceleration phase for difficult targets.

Unsurprisingly, foot movements were generally slower than hand movements, paralleling the findings by Hoffmann (1991). However, the relative duration of the acceleration and deceleration phase differed between the two effectors. In our study, the deceleration phase made up approximately 70% of hand movements. For foot movements, however, it only made up about 40% of the entire duration. Thus, our data suggest that movements with the hands were more carefully adjusted than movements with the feet. This is also reflected in the smaller variable error we observed for hand than for foot movement endpoints. The observed sluggishness and imprecision of foot movements can likely be explained by physical factors, such as the weight (Paschalis et al., 2009). Crucially, the delayed Fitts task modulated foot movements in the same manner as it modulated hand movements. Because movements were performed to identical targets from the same starting position with both effectors, possible confounds in perceived difficulty were diminished. That is, hand and foot movements seem to follow the same motoric principles, independently from anatomical and habitual effects. Thus, even though hands and feet differ regarding their general ability to perform accurate goal-directed movements, they share common mechanisms on the behavioral level.

By using linear mixed effect models, we were able to augment our analysis despite the small number of participants. Mixed models are more suitable to deal with small sample sizes than classic ANOVAs, given that each trial rather than a mean value per participant contributes to the analysis (Bell et al., 2010; Maas & Hox, 2005). By modeling a random intercept for each participant, the estimated group means are more reliable than common averages because the inter-subject variability is taken into account. It has been suggested to model a maximal random effects structure, which would imply random slopes, in order to minimize the Type 1 error (Barr et al., 2013). However, maximal mixed models suffer from a loss of power (Matuschek, Kliegl, Vasishth, Baayen, & Bates, 2015). Simulations suggest that mixed models with random intercepts only are more sensitive to detect effects in studies with low power (Vasishth, 2014). Generally speaking, mixed models tend to fail to converge if sampling is too low, which was not the case here. Hence, the results provided by the mixed effects analysis are robust, even though the quality of motion data was not ideal.

To improve data quality in future studies adopting a similar setup, an additional motion tracker should be positioned in front of the participants. The recorded hand trajectories were generally more fragmented than those of the feet, suggesting that hands were occluded by the upper body. Additionally, each effector should be tracked with more than one infrared marker, ensuring continuous trajectories even when a finger or toe is tilted.

In sum, our study shows that that hand and foot movements are subject to the same behavioral and motoric principles. This suggests that similar mechanisms might underlie movements with different effectors on the cortical level as well, which we will investigate in the following chapters.

3 Effector-specific and effector-independent parameters of movement planning

3.1 Introduction

In everyday life, we perform goal-directed hand and foot movements with ease. Even though hands and feet differ physically, movements with the two limbs share many characteristics (cf. chapter 2). For instance, movements with hands as well as feet follow Fitts' law, that is, movements to difficult targets are slower than movements to easy targets (chapter 2; Drury, 1975; Duarte & Latash, 2007; Fitts, 1954; Fitts & Peterson, 1964; Hoffmann, 1991). Fitts' law is also reflected in the kinematic profile of movements with either limb, with a decrease in peak velocity and an extension of the deceleration phase for difficult as compared to easy targets (chapter 2; Bertucco & Cesari, 2010; Bootsma et al., 1994). Crucially, Fitts' law already manifests at the stage of movement planning and is not just a by-product of movement execution (Bertucco et al., 2013; Kourtis et al., 2012). Therefore, Fitts task offers a valuable manipulation to investigate movement planning of hands and feet while controlling for physical differences between them.

Whereas many studies assessed movements with different limbs behaviorally, research on the underlying neuronal processes that directly compares hand and foot movement planning is scarce. Heed and colleagues (2011) assessed activity preceding hand and foot movements by means of fMRI and found overlapping regions to be activated for the two limbs in in PPC. This finding clearly contradicts the widely held notion that PPC is organized in an effector-specific manner, with distinct sub-regions coding movement plans for different effectors (Astafiev et al., 2003; Connolly et al., 2003; Fernandez-Ruiz et al., 2007; Medendorp et al., 2005). In all previous studies, however, activity preceding hand movements was compared to that preceding eye movements. As we cannot directly manipulate objects with our eyes, a comparison of different limbs is crucial (cf. chapter 1).

If PPC does not follow a strict effector-specific organization, the question arises how movements plans for different limbs are distinguished. The more fine-grained resolution of EEG can shed light on this issue. ERP at central electrodes are typically marked by a negative amplitude before movement execution, a well-known phenomenon which is labeled the contingent negative variation (Walter et al., 1964). The CNV is typically modulated by the amount of information regarding specific movement parameters that is available during movement preparation, such as direction or force (Ulrich et al., 1998). Crucially, it also reflects which effector is going to perform the movement (Brunia & Vingerhoets, 1980, 1981). Movement difficulty, however, does not seem to affect the CNV (Kourtis et al., 2012). Rather, Fitts' law was found to be reflected in posterior ERPs (Kourtis et al., 2012). ERPs preceding movements to difficult targets were marked by a less negative N2 and a more positive P3 than movements to easy targets. This modulation was observed at medial parieto-occipital electrode sites from 310 to 370 ms after target onset, shortly before the CNV emerged. Hence, Fitts' law is evident in posterior ERP waveforms prior to movement onset but does not manifest in the CNV.

In order to eliminate target-related influences on the CNV, Miller (2012) subtracted the signal preceding foot movements from that preceding hand movements. The resulting positive difference wave at Cz was termed limb selection potential (LSP) and can be used to directly compare parameters of the movement plan, such as body side and difficulty, independently from the to-be-used effector (Miller, 2012). Thus, CNV and LSP are useful indicators of movement preparation with different limbs. However, the CNV is thought to originate from primary motor areas rather than parietal cortex (Deecke, Scheid, & Kornhuber, 1969; Ikeda et al., 1996). Given that Heed and colleagues (2011) found overlapping activity for hand and foot movement planning in PPC, the CNV cannot be used as a marker of possibly effector-specific processing in PPC.

In comparison to ERPs, oscillatory brain activity is more fine-grained and might be better able to differentiate between effector-specific activity during movement planning. A frequency band playing a central role in movement preparation is the beta-band (10-30 Hz). Power in the beta-band decreases before movements with different limbs are performed (Pfurtscheller & Lopes da Silva, 1999; Pfurtscheller et al., 1997). Moreover, the spatial profile of activity spreads over the scalp according to the somatotopic organization of M1, with a lateralized desynchronization preceding hand movements and a more medial desynchronization preceding foot movements (Pfurtscheller et al., 1997). The beta-band is, thus, sensitive to the to-be-used effector but, like the CNV, originates from primary motor areas.

Crucially, power modulations in the gamma-band were found to reflect the to-be-used effector (van der Werf et al., 2010). In one MEG study, participants performed delayed eye or hand movements to visual targets in both hemifields. In the subsequent analysis, targets were defined as ipsi- or contralateral with respect to each cortical hemisphere. Movement-unrelated processes that are common to both effectors were controlled for by subtracting the time-frequency representation (TFR) of the ipsilateral from the contralateral condition per effector. The TFR for eye movement planning was marked by an increase in power from 50-60 Hz whereas the TFR for hand movement planning showed an increase in power from 70-90 Hz. Source analyses revealed the hand-specific modulation to originate from a medial portion of PPC while the eye-specific modulation was located more centrally within PPC (van der Werf et al., 2010). Thus, power modulations of the gamma-band can inform us about the cortical mechanisms underlying movement planning with different effectors in PPC.

The aim of the present study was to investigate cortical effector-specificity by assessing both ERPs and TFRs preceding hand and foot movements. To this end, we recorded EEG while participants performed the delayed Fitts task that we established in study 1 (chapter 2). In line with previous behavioral results, we expected slower movements to difficult targets as opposed to easy targets for both hands and feet. RT should not be affected by Fitts task.

In the analysis of ERPs, we expected to find a more negative CNV for foot than hand movement planning, in line with earlier studies. In addition, we aimed at replicating the findings by Kourtis and colleagues (2012) for Fitts’ law in hand movements. That is, we expected a less negative N2 and a more positive P3 for difficult as opposed to easy targets when hand movements were prepared. Furthermore, we aimed at extending this result to foot movement planning. Here, we hypothesized that N2 and P3 are modulated analogously to hand movements, given that both effectors follow Fitts’ law on the behavioral level. Finally, by computing LSPs (hand-foot), we aimed at directly comparing target difficulty across effectors. Here, we expected similar LSPs for easy and difficult targets, because the CNV has previously been reported to be unaffected by Fitts task (Kourtis et al., 2012).

By assessing TFRs, we aimed at identifying effector-specific modulations in both low and high frequencies. In the beta-band, we expected a desynchronization over central electrodes preceding movements with all effectors. For hand movements, the desynchronization should be lateralized to the hemisphere contralateral to the effector. For foot movements, the desynchronization should be located at more medial electrode sites. In the gamma-band, we expected a modulation of different frequency ranges, depending on the to-be-used effector. Similar to van der Werf and colleagues (2010), we subtracted ipsilateral from contralateral TFRs for both limbs. For hand movement planning we expected a power increase from 50-60 Hz (cf. van der Werf et al., 2010). For foot movement planning, two scenarios seem plausible. On the one hand, planning for foot movements could evoke a similar modulation of gamma activity as hand movements, given that the two limbs can perform almost identical movements. On the other hand, movement plans of different effectors must be specified before a discrete motor command can be chosen in M1. Hence, we expected to find a distinct frequency range in the gamma-band that specifically codes for foot movement planning.

3.2 Method

The delayed Fitts task was used to investigate hand and foot movement planning in the EEG. Preliminary analysis of the first eight participants' datasets revealed unexpected results that potentially confound the interpretation of the data. Foremost, the fixation period was contaminated with movement-related and visual activity in the beta- and gamma-band, respectively. By implementing the first delay phase as a baseline, we were able to circumvent this issue to some extent. However, the jittered duration of the fixation period and, more importantly, the cue presentations proved to be suboptimal for this workaround. For these reasons, we stopped data acquisition at this point and adjusted the paradigm accordingly (chapter 4). We analyzed the present dataset nonetheless to give an indication of what to expect in the optimized experiment.

3.2.1 Participants

Eight healthy adults participated in the experiment. One participant had to be excluded from the analysis because of extensive artifacts in the EEG, resulting in a sample of seven (5 females, mean age = 23.57, range = 20-27 years). All participants were right-handed (M = 18.71, SD = 2.93, according to Edinburgh Handedness Inventory; Oldfield, 1971), three were right-footed (M = 11, SD = 6.1), and four were both-footed (M = 4.5, SD = 1.29, according to Waterloo Footedness Questionnaire - Revised; Elias et al., 1998). All participants had normal or corrected-to-normal vision and reported no neurological, sensory, or motor disorders. Participants gave written informed consent before the experiment and received course credit or monetary compensation (7 €/hour for the behavioral training, 8 €/hour for the EEG session).

3.2.2 Setup

The setup was similar to that in study 1 (chapter 2). In short, participants were seated in a custom-built chair and adopted a frog-like posture with each limb on a button. The head rested on a chin-rest. Movements were performed towards visual targets and movement endpoints of the limbs were recorded by a touchscreen. Unlike study 1, movement trajectories were not recorded. The experiment was controlled by the software Presentation (Version 16.2 Build 09.30.12; Neurobehavioral Systems, Inc., Berkeley, CA, United States).

3.2.3 Stimuli and Design

The design was identical to the final version in study 1 (Figure 2.5). In short, participants made delayed hand or foot movements with the left or right body side to easy (ID = 3.5) or difficult (ID = 2.5) targets in the left or right hemifield. The duration of the initial fixation period and all cue presentations were jittered. The fixation cross was presented for 300-400 ms, followed by effector symbols for 250-350 ms, and the target and body side cues for 450-550 ms. There were two delay phases: one after the effector had been cued (750 ms) and one after target and body side had been specified (1000 ms). Body side (left vs. right) and distance of the target from fixation (near vs. far) varied randomly from trial to trial in order to avoid stereotypical movements. Participants completed 13 blocks of 32 trials each (416 trials in total). Trials in which an error occurred were repeated at the end of a block. All participants practiced three experimental blocks at least one day before the EEG was measured. The feedback procedure was identical to that in study 1.

3.2.4 EEG acquisition

The continuous EEG was recorded with BrainVision Recorder (Brain Products GmbH, Gilching, Germany) using 74 passive Ag/AgCl electrodes. The electrodes were mounted in an elastic cap according to the 10-10 system (EASYCAP GmbH, Herrsching, Germany). The ground electrode was placed on the forehead. The signal was referenced online to the left earlobe and re-referenced offline to the average signal of the left and right earlobe. Horizontal eye movements were inferred from electrodes F9 and F10, which are located close to the outer canthi of the eyes. Vertical eye movements were monitored via electrode Fp1 and one additional electrode positioned below the left eye. Impedances were reduced by preparing the skin with an abrasive gel (Every, Gelimed, Bad Segeberg, Germany) and isopropyl alcohol. Conductivity between skin and electrodes was obtained by electrolyte gel (ECI Electrogel, Electrocap International, Eaton, OH, USA). The impedance of all electrodes on the scalp was kept below 20 kΩ (Ferree, Luu, Russell, & Tucker, 2001). Ground and reference electrodes had an impedance of <5 kΩ. The EEG was amplified (Brain Products GmbH, Gilching, Germany) with a band-pass filter of 0.1-100 Hz and digitized at a sampling rate of 500 Hz.

3.2.5 Analysis

All data were preprocessed in MATLAB (R2014a, The Mathworks, Natick, MA, USA). The four possible target locations were subsumed in the “easy” and “difficult” condition. Depending on the condition of interest, other sub-conditions were also averaged after checking for potential differences (see respective analysis for details). Trials with false responses (incorrect effector or target side), misses, and premature responses (<200 ms) were excluded from the analysis. Behavioral measures were subsequently analyzed with the statistical software R, version 3.3.3 (R Core Team, 2013). The EEG was preprocessed and analyzed with FieldTrip, version r7276 (Oostenveld, Fries, Maris, & Schoffelen, 2011).

3.2.5.1 Behavior

RT was defined as the time from the go-signal until button release. MT was defined as the time from button release until the touch screen response. Statistical effects were inferred with linear mixed models using the package lme4 (Bates et al., 2015; see chapter 2 for details). MT and RT were each analyzed with a model comprising fixed effects for the factors “effector” and “difficulty” (main effects and interaction). Random intercepts were modeled for each participant. P-values were obtained with parametric bootstrapping using the package afex (Singmann, 2015). Both dependent measures were box-cox transformed before setting up the model (Box & Cox, 1964).

3.2.5.2 EEG

Preprocessing

First, the continuous data were segmented into epochs lasting from 0.4 s before onset of the first cue (effector symbol) to 2.65 s, which was the maximal possible trial duration given the jittered presentation of the fixation cross and the cues. Next, trials containing artifacts caused by muscle contractions were rejected by visual inspection. The remaining trials were subjected to an independent component analysis (ICA; Hyvärinen, 1999; Hyvärinen & Oja, 2000) to eliminate stereotypical artifacts such as eye blinks and electrocardiographic activity (Jung et al., 2000). To optimize the ICA, a high-pass filter with a cut-off of 0.5 Hz was applied. Channels affected by continuous artifacts were not included in the ICA. The remaining data were reduced to 36 components by means of a principal component analysis before running the ICA (Hyvärinen, 1999). Independent components reflecting artifacts were identified based on their topography, time course, and frequency representation, which was obtained by a fast Fourier transformation (Hyvärinen, Ramkumar, Parkkonen, & Hari, 2010). Next, contaminations were removed from the signal by back-projecting all but the identified components (Schneider, Debener, Oostenveld, & Engel, 2008). Finally, data of noisy channels, which had temporarily been excluded from the dataset, were replaced by interpolating the signal of the nearest neighboring channels (Perrin, Pernier, Bertrand, & Echallier, 1989).

Event-Related Potentials

Data were down-sampled to 100 Hz and time-locked to the onset of the first (effector) cue. As information regarding body side and difficulty were only provided by the second (target) cue, data were baselined to the first 1000 ms of the trial rather than the fixation period. This baseline corresponds to the approximate duration of the first cue presentation and the first delay. Because the duration of cue presentations was jittered, the baseline interval could only be estimated.

ERPs were analyzed in three sub-conditions: First, to assess general movement preparation, ERPs were computed for each effector and body side, disregarding target difficulty. Second, to assess target difficulty per effector, ERPs were computed for each effector and difficulty condition, disregarding body side. Finally, to directly compare easy and difficult movement preparation of the effectors with one another, LSPs were computed for each difficulty condition. To this end, ERPs preceding foot movements were subtracted from ERPs preceding hand movements for each body side (Miller, 2012).

For statistical analysis of the ERPs and LSPs, cluster-based permutation tests (Maris & Oostenveld, 2007) were performed for each body side as follows: Two-sided dependent sample t-tests were used to compare the two conditions (hand vs. foot or easy vs. difficult) with a threshold of $p = 0.05$. Adjacent data points above this threshold were grouped into clusters and a cluster-level statistic was computed by summing all t-values within one cluster. The cluster-level statistic was compared to a randomization null distribution that was obtained by randomly swapping the conditions 1000 times within participants and calculating the maximum cluster-level statistic. The resulting Monte Carlo p-value is considered to be an accurate estimate of the true p-value (Maris & Oostenveld, 2007). Finally, grand average ERPs and LSPs were computed across participants to illustrate the effects.

Time-Frequency Representations

TFRs were computed separately for a low and a high frequency range. Low frequencies (5-30 Hz) were analyzed with a Hanning taper using a sliding window of 400 ms moving along the time axis of the entire trial in steps of 50 ms. Target side and effector were analyzed separately for each body side. High frequencies (30-100 Hz) were analyzed with a multitaper approach (Percival & Walden, 1993) using the same parameters as for low frequencies and a smoothing frequency of 10 Hz. All parameters were chosen based on the work by van der Werf and colleagues (2010). TFRs of single trials were again visually inspected for artifacts and averaged for each participant and condition afterwards. The change in power during the second (target) delay (1.6 – 2.6 s) was normalized relative to the first effector delay (400 – 800 ms). This baseline was used because it is considered to not reflect any target-related activity.

Finally, the TFRs in each condition were averaged across participants. After visually inspecting the respective sub-conditions for potential differences, data were averaged per condition of interest to increase power as follows. For both low and high frequencies, the easy and difficult condition were averaged per effector. For low frequencies, data from the left and right visual hemifield were averaged per effector. For high frequencies, data from the left and right body side were combined per effector and visual hemifield.

In the low frequency range, we assessed power modulations in the alpha (8-12 Hz) and beta band (15-30 Hz). In the high frequency range, we chose gamma ranges of interest (50-60 Hz and 70-90 Hz) to match those reported by van der Werf and colleagues (2010). Analogously to the analysis in that previous study, left and right targets were re-coded into ipsi- and contralateral with respect to each hemisphere, that is, left targets were coded as ipsilateral for electrodes of the left hemisphere and as contralateral for electrodes of the right hemisphere (vice versa for right targets). TFR of the ipsilateral condition was then subtracted from TFR of the contralateral condition for each effector type to infer directional selectivity. Owing to the small number of participants, we conducted no inferential analysis of the TFRs. Hence, all effects in the frequency domain are reported on a descriptive level.

3.3 Results

3.3.1 Behavior

3.3.1.1 Movement Time

Average MT is depicted in Figure 3.1. There were significant main effects of effector ($\chi^2(1) = 137.12$, $p = .001$) and difficulty ($\chi^2(1) = 65.19$, $p = .001$). The interaction did not reach significance ($\chi^2(1) = 1.50$, $p = .23$). Movements to difficult targets (M = 642.90 ms, SD = 317.35 ms) were significantly slower than movements to easy targets (M = 581.96 ms, SD = 258.23 ms) with both effector types, that is, Fitts' law was evident in our dataset. Overall, movements with the feet (M = 660.78 ms, SD = 319.13 ms) took longer than movements with the hands (M = 563.98 ms, SD = 250.35 ms).

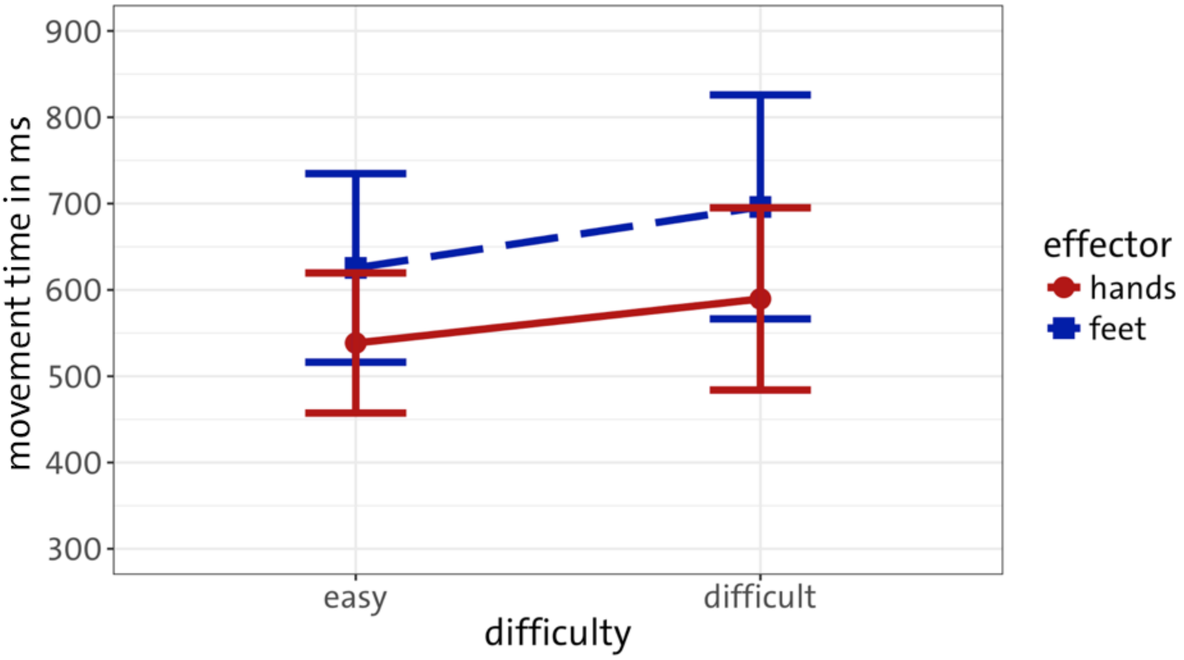

Figure 3.1. Movement time of hands (red, solid line) and feet (blue, dashed line) in the delayed Fitts task. With both effectors, movements to difficult targets were slower than movements to easy targets. Whiskers indicate the standard error of the mean.

3.3.1.2 Reaction Time

Average RT is depicted in Figure 3.2. There was a main effect of effector ($\chi^2(1)$ = 132.34, *p* = .001). As expected, there was no main effected of difficulty ($\chi^2(1)$ = 2.60, *p* = .11), and no interaction between the effector and difficulty ($\chi^2(1)$ = 0.02 *p* = .90). Similar to study 1, the RT was shorter for hand (M = 437.33 ms, SD = 116.72 ms) than for foot movements (M = 487.43 ms, SD = 126.95 ms).

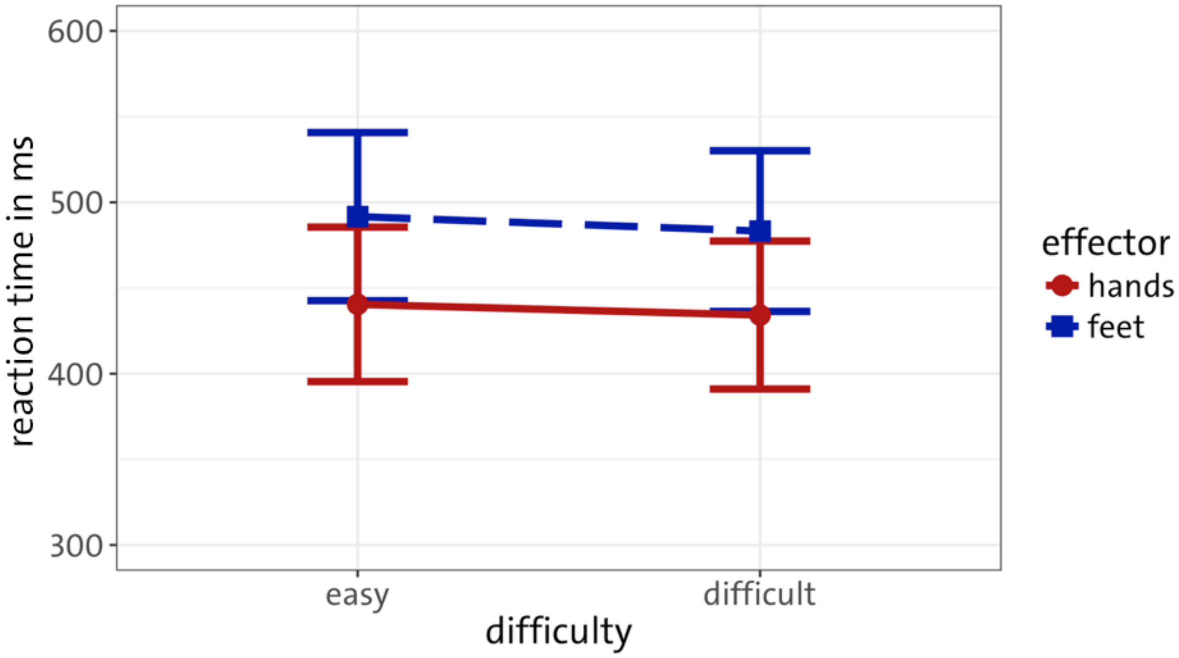

Figure 3.2. Reaction time of hands (red, solid line) and feet (blue, dashed line) in the delayed Fitts task. Reactions with the hands were slower than reactions with the feet. Difficulty did not affect reaction times with either limb. Whiskers indicate the standard error of the mean.

3.3.2 EEG

3.3.2.1 Event-Related Potentials

First, we assessed ERPs regardless of target difficulty. Both hand and foot movements of either body side were preceded by marked negative amplitudes over centro-parietal electrodes (FCz, Cz, CPz, Pz, C1, C2, CP1, CP2) after the second cue. The effect was most pronounced at electrode Cz, thus likely reflecting the CNV (Figure 3.3). The CNV preceding foot movements was significantly more negative than the CNV preceding hand movements, starting 450 ms after the cue for the left and 350 ms for the right body side.

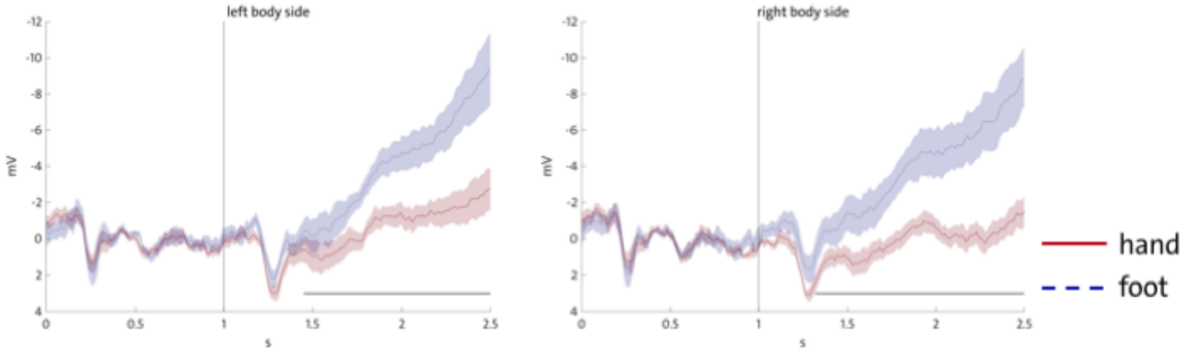

Figure 3.3. Event-related potential at Cz for hand (red) and foot (blue) for the left and right body side. Shaded areas depict the standard error. The vertical line marks the presentation of stimuli. Foot movements were preceded by markedly more negative amplitudes than hand movements. The gray horizontal lines indicate significant differences between hand and foot movement preparation.

Second, we assessed ERPs in the easy and difficult condition per effector type, disregarding body side. Figure 3.4 shows electrode P7 as an example of descriptive differences between easy and difficult targets for hand and foot. Preceding foot movements (blue, dashed line), difficult targets seemed to be characterized by a less negative N2 and a more positive P3 than easy targets over left posterior electrodes. Preceding hand movements (solid, red line), only P3 seemed to be modulated by target difficulty, showing a similar effect as in the foot condition. Overall, the waveforms in the hand condition were slightly more negative than in the foot condition. A cluster-based permutation test did not reveal any significant differences between the easy and difficult condition, though.

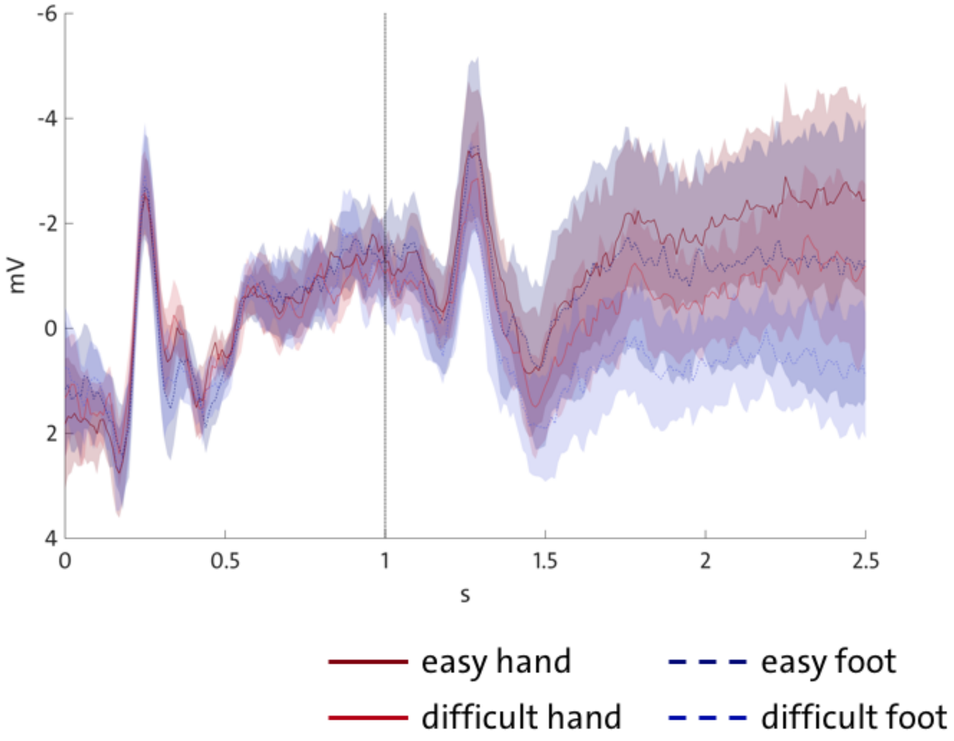

Figure 3.4. ERPs preceding hand (red) and foot (blue) movements to easy (solid) and difficult (dashed) targets at P7. Shaded areas depict the standard error.

Third, LSPs were computed for each body side in order to compare the response to easy and difficult targets across effectors. In both difficulty conditions, the LSPs were characterized by a positive amplitude on Cz (Figure 3.5). Over all electrodes, there was no difference between the easy and difficult LSP for either body side. In other words, effector-specific movement preparation was independent of Fitts' law.

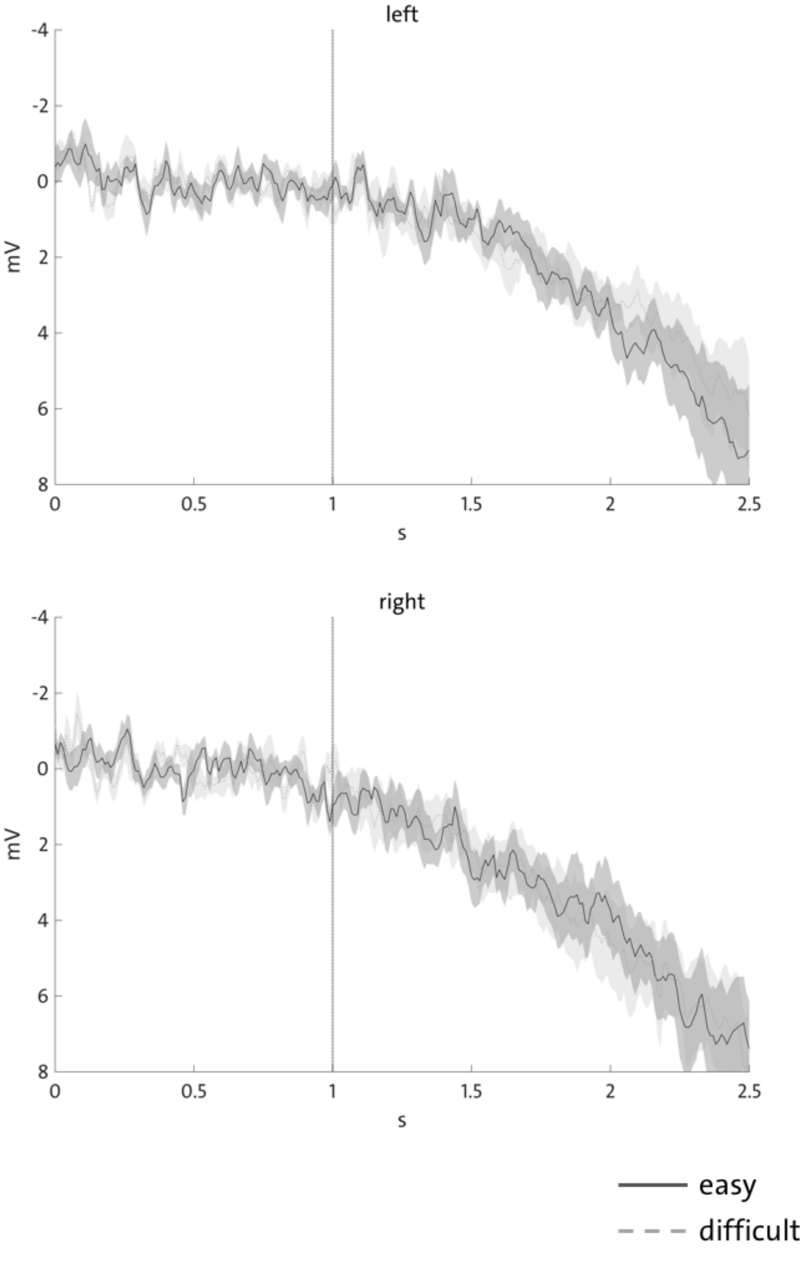

Figure 3.5. Limb selection potentials (hand-foot) of the left and right body side for easy (dark, solid) and difficult (light, dashed) targets at Cz.

3.3.2.2 Frequency Analysis

Low Frequencies

The alpha-band (8-12 Hz) was marked by a desynchronization over occipito-parietal areas in all conditions during the second delay (1.6 – 2.6 s, Figure 3.6). The decrease was highly similar for both hand and foot movement planning, suggesting that this modulation is independent of the to-be-used effector.

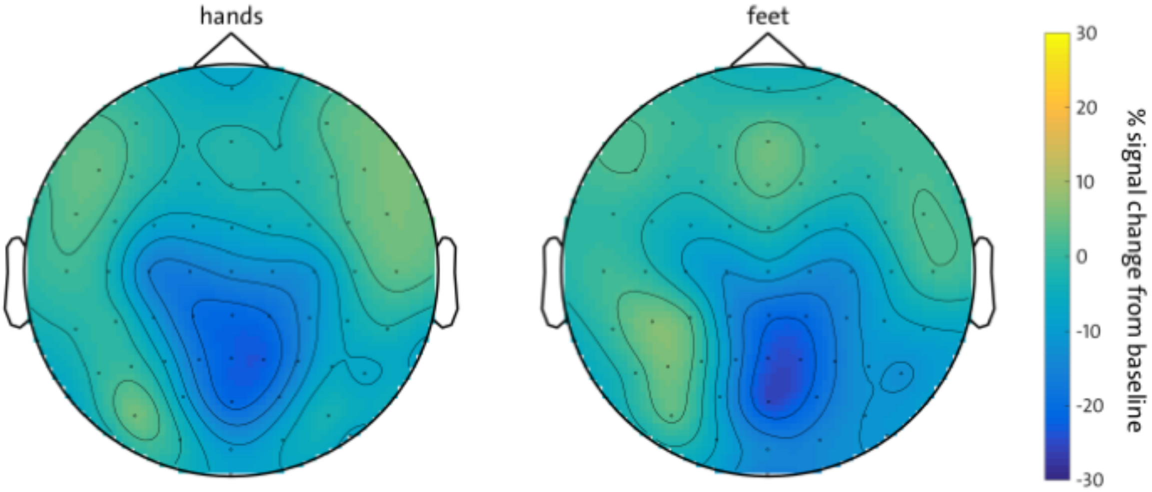

Figure 3.6. Topography of the alpha-band (8-12 Hz) during the second delay (1.6 – 2.6 s) preceding hand and foot movements. Both effectors showed a similar desynchronization.

The beta-band (15-30 Hz) showed a desynchronization over primary motor areas for all effectors (Figure 3.7). Preceding hand movements, the desynchronization was lateralized to the contralateral hemisphere. Preceding foot movements, the desynchronization was more medial, consistent with the homuncular organization of M1.

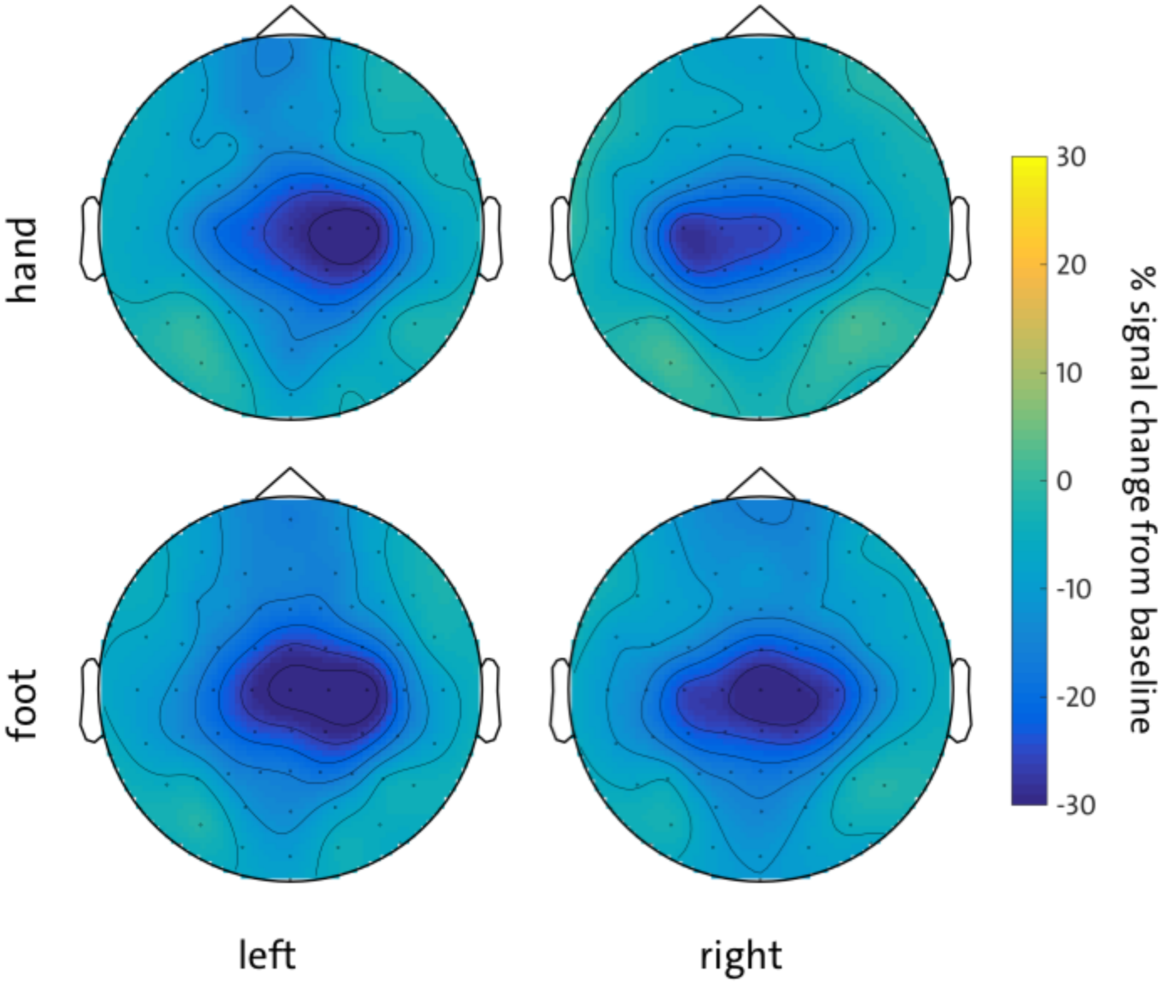

Figure 3.7. Topography of the beta-band (15-30 Hz) during the second delay (1.6 – 2.6 s) for all effectors. Both hand (top row) and foot (bottom row) movements were marked by a desynchronization following the somatotopic organization of M1.

High Frequencies

In the high gamma-band (70-90 Hz), the direction-selective activity for hand movement planning showed a slightly higher synchronization for contra- than for ipsilateral targets (Figure 3.8), resembling the effect reported by van der Werf and colleagues (2010). This effect was not observed for foot movement planning. No other frequency range was specifically modulated during foot movement planning.

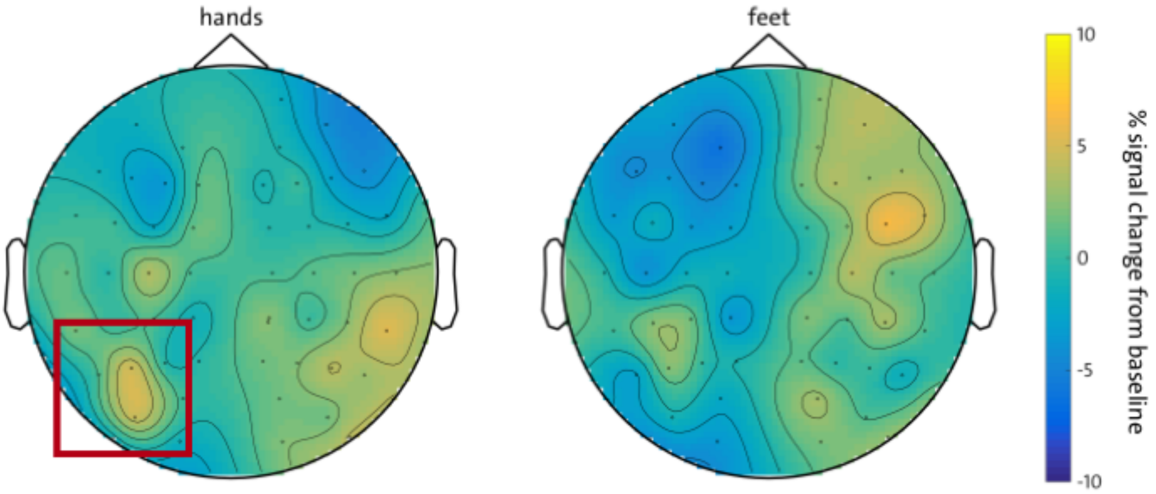

Figure 3.8. Topography of direction-selective activity (contralateral – ipsilateral target) for hand and foot movement planning from 70-90 Hz. The red square marks a modulation similar to the activity reported by van der Werf et al. (2010)

3.4 Discussion

Here, we report the first iteration of an EEG study on movement planning with different limbs. Our primary aim was to identify EEG signatures specifically coding for hand and foot movements. By using a modified version of Fitts task (Fitts, 1954), we were able to control for general differences between the two limbs. Participants performed delayed movements to easy and difficult targets, which were presented in the left or right hemifield. The to-be-used effector was instructed on a trial-by-trial basis and could be the hand or foot of either body side.

Behaviorally, movements with hands as well as feet followed Fitts' law, that is, they were significantly slower for difficult than easy targets. This adds further evidence to our findings from study 1 and underlines the similarity of hand and foot movements on the behavioral level.

The analysis of ERPs was three-fold: First, we investigated general preparation of hand and foot movements, disregarding target difficulty. In line with our hypothesis, we found a difference between the two effectors of each body side at central electrode sites, with a more negative amplitude preceding foot as compared to hand movements. The difference was statistically different starting 450 ms after the cue for the left and 350 ms for the right body side. The amplitudes diverged further until the end of the trial, that is, until a movement was executed. This modulation most likely reflects the CNV, fitting well with previous studies on hand and foot movements (Brunia & Vingerhoets, 1980, 1981; Jentzsch & Leuthold, 2002; Miller, 2012). This finding indicates that specific effector movements were successfully prepared in our study.

Second, we investigated how hand and foot movement planning was affected by target difficulty, disregarding body side. For foot movements, we observed a less negative N2 response to difficult as opposed to easy targets. For both hand and foot movements, the P3 was more positive for difficult than easy targets. These differences were most pronounced at electrodes P7 and P9, that is, over left parietal cortex. Likely owing to the small number of participants, the observed effects were not significant. Nonetheless, our findings fit well with those reported by Kourtis and colleagues (2012). They reported a significant difference between targets with varying difficulty from 310 to 370 ms after target onset when hand movements were prepared. In our dataset, the difference was most pronounced from 250 to 500 ms after the cue and thus considerably overlaps with the time-window in that study. The effect was lateralized to the left hemisphere in our study whereas it was located bilaterally over parieto-occipital cortex in the study by Kourtis and colleagues (2012). Yet, the resemblance to their results is striking, especially in light of the explorative character of our analysis. Thus, our findings indicate that Fitts' law is represented in movement plans of hands and feet alike.

Finally, we directly assessed target difficulty across effectors by computing LSPs (hand-foot) for each body side. LSPs were marked by a positive amplitude at Cz, resulting from the more negative CNV for foot than for hand movements. This observation is in line with findings by Miller (2012). In his study, the LSP was modulated depending on the RT of an upcoming movement. Accordingly, the LSP in our study could have been affected by MT, which reflects the behavioral manifestation of target difficulty. However, there was no difference between the easy and difficult condition, as we had expected based on the finding by Kourtis and colleagues (2012), who reported paralleling results for the CNV. Thus, target difficulty does not seem to be incorporated into the movement plan of different effectors at this stage of movement preparation.

Our analysis of the power spectrum focused on low as well as high frequencies. In the alpha-band (8-12 Hz), we found a pronounced desynchronization over parieto-occipital regions that was very similar for both limbs. Most likely, the alpha desynchronization reflects visuospatial attention in response to the target (Foxe, Simpson, & Ahlfors, 1998; Thut, Nietzel, Brandt, & Pascual-Leone, 2006; Worden, Foxe, Wang, & Simpson, 2000). Our observation is in line with the finding by van der Werf and colleagues (2010), who reported a similar desynchronization but no difference between upcoming eye and hand movement.

In the beta-band (15-30 Hz), we observed a somatotopic desynchronization over central electrodes. According to the somatotopic organization of M1, beta power decreased over contralateral electrodes preceding hand whereas it increased over medial electrodes preceding foot movements (Pfurtscheller et al., 1997). This effect was independent of both target side and difficulty, suggesting that the beta-band encodes effector-specific but goal-independent movement planning.

In the high gamma-band (70-90 Hz), we observed direction-selective hand movement planning to be encoded over left parietal electrodes, paralleling the findings by van der Werf and colleagues (2010). A similar, but less pronounced increase in synchronization was observed for foot movement planning. Based on the previous finding that the 50-60 Hz range was specifically modulated for saccade planning, we had hypothesized that yet another frequency band would encode foot movement planning. However, we did not observe any foot-specific modulations throughout the gamma-band. Surprisingly, directional selectivity seemed not to differ between left and right limbs, suggesting that the observed lateralization to the left hemisphere is independent from the body side executing the movement. This adds to the work by van der Werf and colleagues (2010), who only investigated right-hand movements.

With respect to the frequency analysis, a limitation specific to the current study deserves to be mentioned. The change in power during the second delay (1.6 – 2.6 s) was normalized relative to the first effector delay (400 – 800 ms). Originally, the fixation period at the beginning of each trial was intended to serve as baseline. However, preliminary analysis of the first datasets revealed that the signal during the fixation period was contaminated, likely by visual and movement-related activity. First, there was a pronounced response to the onset of the fixation cross evident in a broad increase in gamma power. Second, we observed a strong decrease in beta power throughout the trial, suggesting that participants were still engaged in moving their limbs back to the starting position at the end of the preceding trial. Using the fixation period thus potentially occluded the more subtle planning processes we are interested in. The first effector delay was used as baseline because it is considered to not reflect any target-related activity. Moreover, we decided to optimize the paradigm for another study (chapter 4) and stopped data acquisition at this point. Consequently, the results in this chapter a based on a small sample size. Still, the current results are indicative of what to expect in the next experiment.

In sum, even though the experimental design of our study needs to be optimized in some respects, we were able to replicate our first study and work by others, regarding behavioral as well as electrophysiological findings. The tentative analysis of our data suggests that ERP effects previously established for hand movement planning also hold for foot movement planning.

4 Unique representations of movement planning for different effectors in the EEG

4.1 Introduction

In daily life, we readily interact with our environment using different effectors. The underlying neural planning processes have been studied extensively by comparing eye and hand movements. Many studies suggest a parceled, effector-specific organization of PPC, similar to M1 (Astafiev et al., 2003; Connolly et al., 2003; Fernandez-Ruiz et al., 2007; Filimon, 2010; Hinkley et al., 2009; Medendorp et al., 2005). However, an fMRI study comparing hand and foot, which can perform virtually the same type of goal-directed movements, revealed largely overlapping activity in PPC (Heed et al., 2011). Thus, it remains unknown how movement plans for these limbs are differentiated in PPC before the movement is fully specified in M1. Whereas the temporal resolution of fMRI is rather low, EEG could provide more insight into movement planning of different effectors. For instance, upcoming eye and hand movements are preceded by power increases in different frequency bands of the gamma range (van der Werf et al., 2010). Akin to our second study on ERPs, the objective of this study was thus to assess neurophysiological correlates of movement planning of hand and foot, now also investigating the power spectrum.

Here, we conducted the following steps to improve the delayed Fitts' paradigm. First, to avoid movement-related artifacts during the baseline period, the ITI was extended to allow for a comfortable re-positioning of the limbs at the starting position. Second, to reduce visual responses at the beginning of a trial, the fixation cross changed into another symbol instead of disappearing as the go-signal. Third, to allow for a reliable analysis of both TFRs and ERPs, all stimulus durations were fixed rather than jittered. Fourth, to allow movement plans to unfold over time, the delay phases were extended. Fifth, to make the study comparable to previous work of other groups, eye movements were performed in addition to hand and foot movements. Finally, a new approach was chosen for the data analysis.

The analysis was two-fold. Similar to study 2, ERPs were analyzed for each effector (hand vs. foot vs. eyes) and target difficulty (easy vs. difficult). However, no limb selection potentials (hand-foot; Miller, 2012) were computed given that three rather than two effector types were moved. Based on our previous results and other studies (Jentzsch & Leuthold, 2002; Miller, 2012), we expected a more negative CNV for foot than for hand movement planning over central electrodes approximately 400 ms after target and body side were instructed. Similar to limb movements, ERPs preceding eye movements were previously found to be characterized by a negative deflection that is maximal at Cz (Becker, Hoehne, Iwase, & Kornhuber, 1972). This so-called pre-saccadic negativity emerges in a similar time range as the CNV (Evdokimidis, Liakopoulos, Constantinidis, & Papageorgiou, 1996; Everling, Krappmann, & Flohr, 1997; Miller, 2012; Wauschkuhn, Wascher, & Verleger, 1997). One study directly compared event-related activity preceding hand and eye movements and revealed a more negative deflection at central electrodes when hand as opposed to eye movements were prepared (Jentzsch & Leuthold, 2002). Hence, we expected the amplitude preceding eye movements to be less negative than those preceding movements with either limb.

With respect to target difficulty, we expected to replicate our previous findings for hand and foot movements. For either limb, movements to difficult targets should be slower than movements to easy targets while ERPs should be marked by a less negative N2 and a more positive P3 for difficult than easy targets. Regarding eye movements, however, previous findings are not as clear-cut. Whereas one study found saccades to follow Fitts' law in sequential movements (C.-C. Wu, Kwon, & Kowler, 2010), many others found no evidence when simple movements were performed (Chi & Lin, 1997; Grosjean et al., 2007; Kourtis et al., 2012). Hence, we did not expect ERPs in the eye condition to be affected by target difficulty.

Additionally, we performed a time frequency analysis of each effector condition. Previous studies reported increased synchronization in the gamma-band preceding eye and hand movements. For hand movement planning a power enhancement from 70-90 Hz was observed (van der Werf et al., 2010) whereas eye movements were found to be preceded by an increase in a much broader frequency range (64-128 Hz: Carl, Hipp, König, & Engel, 2015; 60-100 Hz Medendorp et al., 2007; 40-120 Hz: van der Werf, Jensen, Fries, & Medendorp, 2008). By taking target laterality into account, van der Werf and colleagues (2010) showed that the frequency range from 50-60 Hz was specifically involved in eye movement as opposed to hand movement planning (70-90 Hz). To this date, no study has investigated the oscillatory activity in the gamma-band for foot movement planning. Similar to study 2, we aimed at identifying effector-specific frequencies in the gamma-band. To this end, the power spectra preceding movements with each effector were analyzed. In accordance with previous work, we expected a modulation of the gamma-band depending on the effector. To control for general target processing, we assessed both laterality and difficulty of the target per effector. We expected similar frequency modulations for eye and hand movements as reported by van der Werf and colleagues (2010) and an additional frequency band coding for foot movement planning (cf. chapter 3).

4.2 Method

4.2.1 Participants

Twenty-five healthy adults participated in the experiment. In total, eight participants had to be excluded from the analysis, seven because of extensive error rates in the EOG (less than 50% of all trials left or no trials left in one condition) and one because of irreparable drift artifacts in the EEG. The final analyzed sample consisted of 17 participants (8 females, mean age = 25.53 years, range = 19-32 years). All participants were right-handed (M = 18.41, SD = 2.57, according to Edinburgh Handedness Inventory; Oldfield, 1971), 15 were right-footed (M = 12.07, SD = 3.36), and two were both-footed (M = -3.5, SD = 0.5, according to Waterloo Footedness Questionnaire - Revised; Elias et al., 1998). They were free of any neurological, sensory, or motor disorders and had normal or corrected-to-normal vision (evidenced by self-report). Participants gave written informed consent before the experiment and received course credit or monetary compensation (7€/hour for the behavioral training session, 8€/hour for the EEG session).

4.2.2 Setup

The setup was identical to that in study 2 (chapter 3). In short, participants were seated in a custom-built chair and adopted a frog-like posture with each limb on a button. The head rested on a chin-rest. Movements were performed towards visual targets and movement endpoints of the limbs were recorded by a touchscreen.

Additionally, limb movements were monitored online (but not recorded) with an infrared-camera (7Links PX-3719-675, PEARL, Buggingen, Germany) throughout the experiment.

4.2.3 Stimuli and Design

The delayed Fitts paradigm was used to assess movement planning of different effectors in the EEG. The general stimulus design was the same as in study 1 and 2, with an additional effector symbol depicting eyes. Furthermore, the timing of stimulus presentations was adapted. An example trial is depicted in Figure 4.1. Each trial began with the appearance of a white fixation cross for 1000 ms. Next, two gray symbols indicating the to-be-used effector (eyes, hands, or feet) were presented centrally for 300 ms, followed by the fixation cross (1000 ms; effector plan phase). After this first delay, the effector symbol reappeared along with a green target circle for 500 ms. The target could be in the left or right hemifield and was either easy (ID = 3.5) or difficult (ID = 2.5). In case of a saccade, both effector symbols were shown in green. In case of a hand or foot movement, only one of the two effector-symbols was green to indicate the body side (left or right). Opposite to the target, an isoluminant (0.4 cd/m^2) gray circle was shown to counterbalance potential visual responses. The target presentation was again followed by the fixation cross (1500 ms; target plan phase). Finally, the fixation cross was replaced by a white dot that served as the go-signal. In case of a saccade, the dot was shown for 1000 ms. In case of a hand or foot movement, the touch screen response ended the trial. The movement had to be initiated within 200 and 750 ms after the go-signal. The inter-trial interval was jittered from 2500 – 2700 ms (square distribution). The white dot was presented throughout the inter-trial interval to avoid pronounced visual responses when the fixation cross reappeared at the beginning of the next trial. Only the instructed effector was to be moved, that is, no buttons were to be released in the saccade condition and ocular fixation had to be maintained in the hand and foot conditions. As no real-time information regarding saccade performance was available (in contrast to the button and touchscreen responses from the limbs) trials containing errors were not repeated.

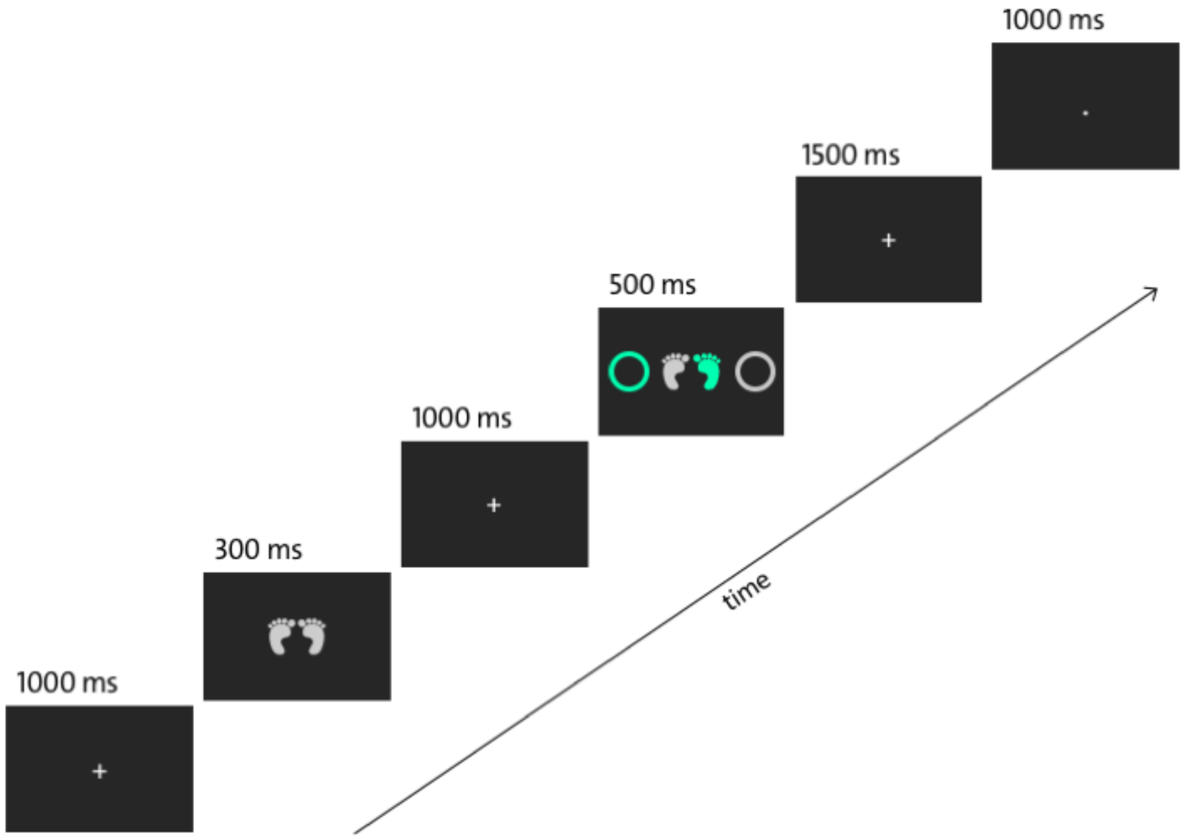

Figure 4.1. Example trial of the delayed Fitts paradigm. After a fixed baseline, the effector type was cued with two gray symbols. After a first delay, the body side was indicated (green effector) and the target (green circle) was shown. After a second delay, the fixation cross changed into a dot and the movement was executed. Note that all durations of stimulus presentations are now fixed rather than jittered.

Because the eyes cannot be moved independently, the factor “body side” used in the previous experiments was dropped and the factor “effector” now had five levels: left hand, right hand, left foot, right foot, and eyes. The factors “difficulty” (easy vs. difficult), “target side” (left vs. right), and “distance from fixation” (near vs. far) remained the same, resulting in 40 possible combinations. Each combination was presented once per block and participants completed 26 blocks (i.e., 1040 trials in total). The approximate duration of one trial including the inter-trial interval was 7.5 s, resulting in a block duration of approximately 5 minutes. Participants were encouraged to rest after each block and relax their arms, legs, and neck. After 13 blocks, they took a break of at least 15 and up to 30 minutes, in which they were allowed to get up. Overall, it took about 3 h to complete the experiment. One day before the experiment, participants took part in a practice session, in which visual feedback about their performance was provided (cf. study 2).

4.2.4 EEG acquisition

The continuous EEG was recorded with BrainVision Recorder (Brain Products GmbH, Gilching, Germany) using 74 passive Ag/AgCl electrodes. The electrodes were mounted in an elastic cap according to the 10-10 system (EASYCAP GmbH, Herrsching, Germany). The ground electrode was placed on the forehead. The signal was referenced online to the left earlobe and re-referenced offline to the average signal of the left and right earlobe. Horizontal eye movements were inferred from electrodes F9 and F10, which are located close to the outer canthi of the eyes. Vertical eye movements were monitored via electrode Fp1 and one additional electrode positioned below the left eye.

Impedances were reduced by preparing the skin with an abrasive gel (Every, Gelimed, Bad Segeberg, Germany) and isopropyl alcohol. Conductivity between skin and electrodes was obtained by electrolyte gel (ECI Electrogel, Electrocap International, Eaton, OH, USA). The impedance of all electrodes on the scalp was kept below 20 kΩ (Ferree et al., 2001). Ground and reference electrodes had an impedance of <5 kΩ. The EEG was amplified (Brain Products GmbH, Gilching, Germany) with a band-pass filter of 0.1-100 Hz and digitized at a sampling rate of 500 Hz.

4.2.5 Analysis

All data were preprocessed in MATLAB (R2014a, The Mathworks, Natick, MA, USA). Behavioral data were analyzed in R, version 3.3.3 (R Core Team, 2013) for statistical analysis. EEG analyses were performed using FieldTrip, version r7276 (Oostenveld et al., 2011). In order to increase the signal-to-noise ratio, we combined sub-conditions according to the current analysis after controlling for potential statistical differences between them (details below).

4.2.5.1 Behavior

For hand and foot movements, RT and MT were obtained from the button and touchscreen responses (cf. study 1 and 2). If movements were initiated too early or too late, if the wrong effector or multiple effectors were moved, or if the incorrect target was touched, the trial was rejected.

For saccades, each trial was inspected visually. Saccade onset was identified by a semi-automatic procedure using a custom written graphical user interface. When the difference between one data point and the sliding average of five preceding data points (i.e., 8 ms) exceeded 1 mV, the algorithm stopped and the detected point was displayed on the saccade trajectory for visual inspection. If the point did not truly reflect saccade onset, the algorithm was repeated iteratively. Saccade RT was computed by subtracting the time of the go-signal from that point. The following errors could occur: failure to maintain fixation during the delays (independent of effector condition), failure to maintain fixation during a hand or foot movement, saccade to the wrong target side, saccade initiation before the go-signal, or no saccade (in the eye condition). Trials with one or more of these errors were also excluded from the subsequent analyses. The average percentage of remaining trials in the behavioral analysis per condition of interest is displayed in Table 4.1.

The statistical analysis of MT was identical to that in study 1 and 2 because the measure was only available for hand and foot movements. Thus, the linear mixed model comprised fixed effects for the factors “effector” and “difficulty” (main effects and interaction). A random intercept was modeled for each participant.

For the statistical analysis of RT information regarding all effectors was available. Again, main effects and interactions were modeled for the fixed effects “effector” and “difficulty”. Both factors were specified with contrast coding (effector: eyes 0, hand 1, foot -1; difficulty: easy -1, difficult 1). Participants were entered as random effects (intercept only). The p-values of fixed effects were estimated using the package afex (Singmann, 2015). Fixed effects were considered significant at $p < 0.05$. In case of the factor “effector” significant effects were followed up by Tukey-adjusted (Tukey, 1949) post-hoc comparisons using the package lsmeans (Lenth, 2016). Dependent measures were box-cox transformed before setting up the model (Box & Cox, 1964).

Table 4.1

Percentage of Remaining Trials in the Behavioral Analysis

	hands	feet	eyes
easy	79.71 (± 14.86)	84.21 (± 15.39)	79.45 (± 16.13)
difficult	77.27 (± 16.43)	82.29 (± 16.59)	79.35 (± 16.39)

Note. Standard deviations are in parentheses.

4.2.5.2 EEG

Preprocessing

First, data were re-referenced to a common average (Lehmann & Skrandies, 1980; Schneider et al., 2008). Trials were aligned to the first effector cue and segmented into epochs from 1 s preceding the cue to 3.3 s after. Each epoch was inspected for non-stereotyped artifacts and channels suffering from poor data quality throughout the recording. Line noise was removed by subtracting the 50 Hz component and its harmonics (100 Hz and 150 Hz) estimated by a discrete Fourier transform (van Ede, de Lange, Jensen, & Maris, 2011). An independent component analysis approach was used to reduce stereotypical artifacts (cf. chapter 3).

Data in the hand and foot conditions were pooled over the left and right body side by remapping electrode channels to the ipsi- and contralateral hemisphere relative to the limb. Consequently, data are presented here as if limb movements were always performed with the right body side. Data of the eye condition remained unaltered.

The dataset was analyzed separately for low and high frequencies. The TFR of each trial was visually inspected for artifacts on the single-subject level before averaging. Given that low frequencies are less affected by artifacts than high frequencies (>20 Hz; Muthukumaraswamy, 2013), more trials could be included in the analysis of the former. The average percentage of remaining trials in the analysis of low and high frequencies are depicted in Table 4.2 and Table 4.3, respectively. For the analysis of ERPs, the same trials as in the analysis of low frequencies were used.

Table 4.2

Percentage of Remaining Trials in the Analyses of Low Frequencies and ERPs

	hands	feet	eyes
easy	63.26 (± 14.20)	59.16 (± 16.51)	69.06 (± 12.31)
difficult	61.54 (± 14.01)	55.54 (± 16.47)	69.97 (± 12.79)

Note. Standard deviations are in parentheses.

Table 4.3

Percentage of Remaining Trials in the Analysis of High Frequencies

	hands	feet	eyes
easy	44.85 (± 11.75)	40.47 (± 16.11)	50.00 (± 11.98)
difficult	44.26 (± 13.62)	38.97 (± 15.89)	50.45 (± 14.09)

Note. Standard deviations are in parentheses.

Event-Related Potentials

Data were down-sampled to 100 Hz and time-locked to the onset of the first (effector) cue. The fixation period (-1 – 0 sec) was used as baseline. ERPs were computed for each effector and difficulty condition (regardless of stimulus hemifield). To assess whether the difficulty effect differed between effectors, differences waves were computed by subtracting easy from difficult ERPs for each effector condition.

For statistical comparison of ERPs and difference waves between effectors (hand vs. foot vs. eyes), cluster-based permutation F-tests (Maris & Oostenveld, 2007) were performed with 1000 randomizations and an alpha-level of 5% (cf. chapter 3). Significant effects were followed up with Bonferroni-corrected t-tests. Per effector, the difference between easy and difficult targets was assessed with a cluster-based permutation t-test.

Time-Frequency Representations

TFRs were computed separately for a low and a high frequency range. In the low frequency range (5-30 Hz), TFRs were computed based on the Fourier approach using a Hanning taper of 400 ms that was moved along the time axis (-1 – 3.3 s) in steps of 50 ms. In the high frequency range, analysis was performed for frequencies from 20-100 Hz, using a multitaper approach with orthogonal Slepian tapers (Percival & Walden, 1993). A fixed time window of 200 ms and a frequency smoothing of 10 Hz were used, resulting in three tapers being applied to the sliding time window.

For both frequency ranges, a normalization with respect to a baseline interval preceding the first cue by 400 m was performed *((active period – baseline)/baseline)*. Finally, TFRs of single trials were averaged for each participant and condition of interest. To illustrate the change of activity to baseline, grand mean TFRs were computed over all participants. For all analyses, data from both target distances (near vs. far) were combined. The following conditions were assessed: “effector” (hand vs. foot vs. eyes; disregarding difficulty and hemifield), “difficulty” (easy vs. difficult; disregarding hemifield, both per effector and averaged over all effectors), and “hemifield” (ipsilateral vs. contralateral; per effector, disregarding difficulty). The latter analysis mirrored that in chapter 3, which had originally been suggested by van der Werf and colleagues (2010). To make our results as comparable as possible to this earlier study, the original electrode positions were used for this analysis, hence including an additional factor “body side”.

To assess statistical differences between conditions, cluster-based permutation tests were computed (Maris & Oostenveld, 2007). The tests were performed on the second delay phase (1.8 – 3.3 s) (cf. chapter 3). The resulting t-scores were transformed into z-scores to illustrate the effects (Medendorp et al., 2007).

4.3 Results

4.3.1 Behavior

4.3.1.1 Movement Time

Average MT is depicted in Figure 4.2. There were main effects of effector ($\chi^2(1) = 569.38$, $p = 0.001$) and difficulty ($\chi^2(1) = 22.89$, $p = 0.001$). There was no interaction between effector and difficulty ($\chi^2(1) = 1.29$, $p = 0.26$). Similar to study 1 and 2, movements with the feet (M = 409.78 ms, SE = 25.87 ms) took longer than movements with the hands (M = 369.28 ms, SE = 22.09 ms). With both effector types, movements to difficult targets (M = 393.55 ms, SE = 25.27 ms) were slower than movements to easy targets (M = 383.91 ms, SE = 23.65 ms). That is, MT of both hand and foot movements followed Fitts' law.

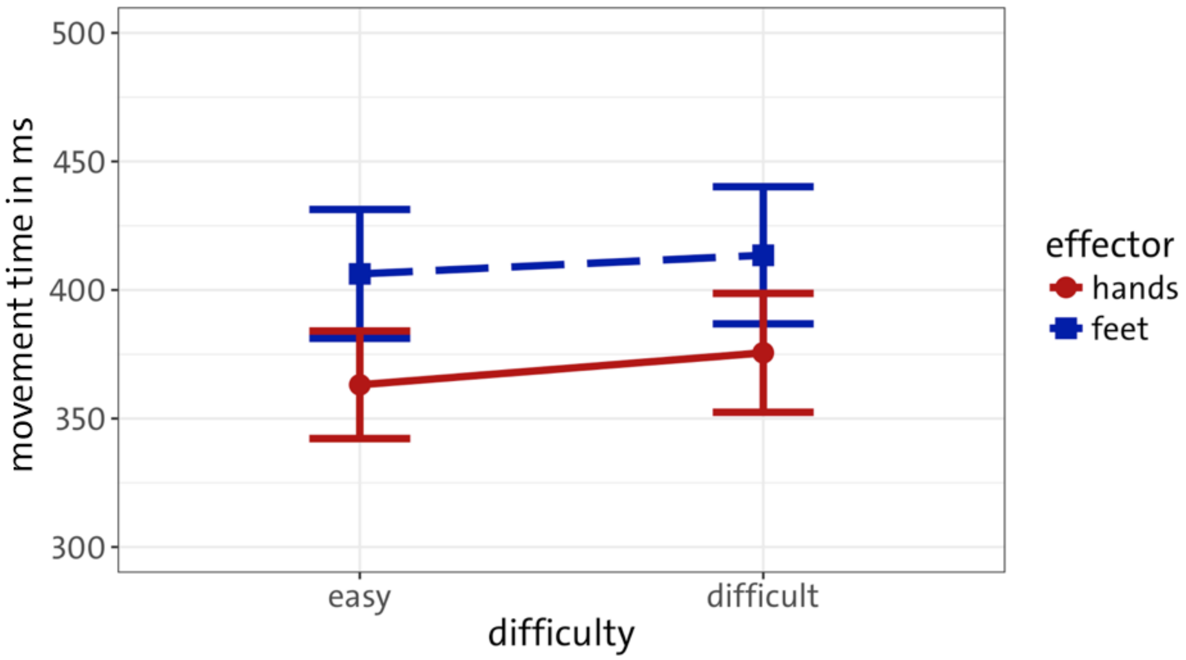

Figure 4.2. Movement time of hands (red, solid line) and feet (blue, dashed line) in the delayed Fitts task. Movements to easy targets were faster than movements to difficult targets with both effectors. Whiskers depict the standard error of the mean.

4.3.1.2 Reaction Time

Average RT is depicted in Figure 4.3. Overall, RT in the easy condition (M = 363.83 ms, SE = 23.06 ms) was slower than in the difficult condition (M = 356.75 ms, SE = 23.30 ms). RT of the limbs (M_{hands} = 365.20 ms, SE = 20.90 ms; M_{feet} = 377.86 ms, SE = 21.33 ms) was slower than that of the eyes (M_{eyes} = 328.68 ms, SE = 26.83 ms). There were main effects of effector ($\chi^2(2) = 528$, $p = .001$) and difficulty ($\chi^2(1) = 19.08$, $p = .001$), though no interaction ($\chi^2(2) = .63$, $p = .74$). Post-hoc comparisons revealed RT of hand and foot to differ significantly from that of the eyes (both $p < .0001$) and also from one another ($p < .0001$).

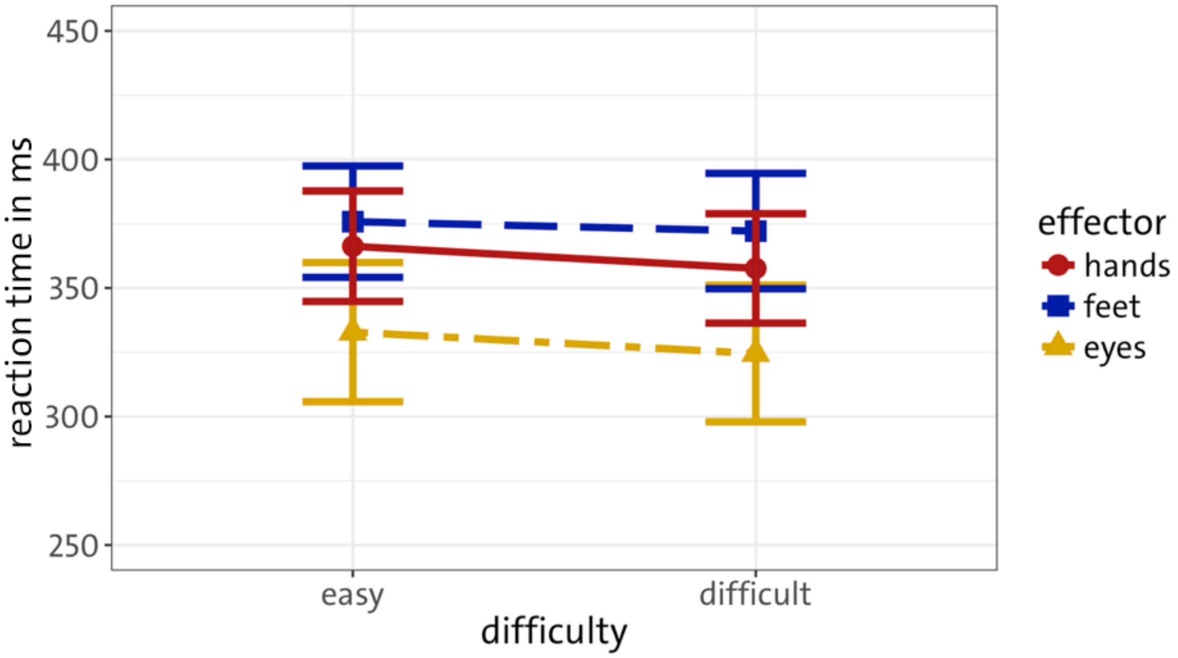

Figure 4.3. Reaction time of hand (red, solid), foot (blue, dashed), and eye (yellow, dash-dotted) movement in the delayed Fitts task. Reaction times were slower for difficult than easy targets with all effectors. Whiskers depict the standard error of the mean.

4.3.2 EEG

4.3.2.1 Event-Related Potentials

First, ERPs were assessed with respect to the to-be-used effector (regardless of difficulty). During the first delay, ERPs in all effector conditions showed an identical response to the visual cue. Approximately 600 ms after the cue, there was an increase in negativity over centro-parietal electrodes for all effectors (Cz, C1, C2, CPz, CP1, CP2). As an example, electrode Cz is depicted in Figure 4.4. Starting from 800 ms, ERPs in the foot condition diverged from those in the eye and hand conditions. During the second delay, this difference between effectors was even more pronounced, with a continuing increase of negativity in the foot condition. ERPs in the hand condition diverged from those in the eye condition only late in the trial. Post-hoc comparisons of the effector conditions are depicted in Figure 4.5. ERPs in the foot condition already differed significantly from those in the hand condition after 900 ms (top panel). The difference between the foot condition and the eye condition was significant after 1600 ms (middle panel), that is, at the beginning of the second delay. The difference between the hand condition and the eye condition was significant after 2700 ms (bottom panel), that is, at the end of the second delay.

To control whether the differences in the second delay depended on those already emerging during the first delay, ERPs were additionally normalized to a baseline preceding the second cue by 200 ms. The results confirmed those from the analysis of the entire trial, revealing even slightly earlier differences between effectors after the second cue (data not shown here).

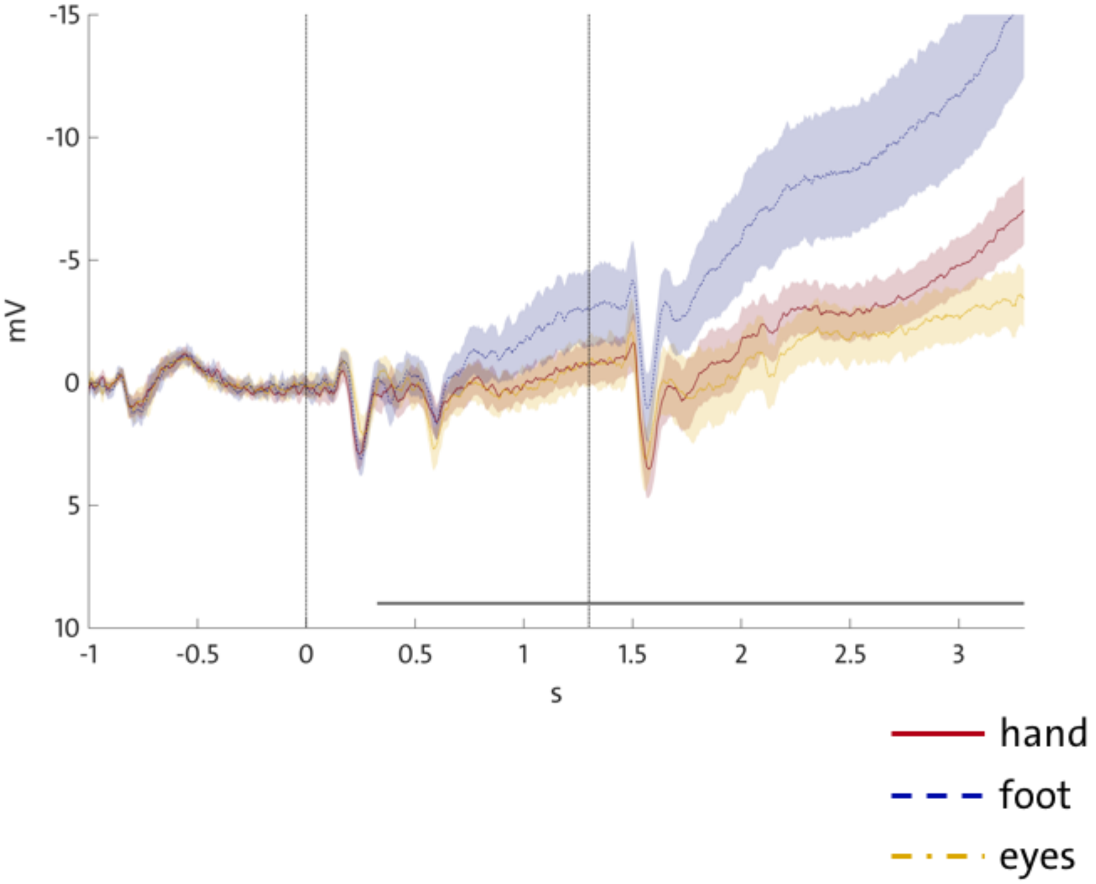

Figure 4.4. Contingent negative variation at Cz preceding movements with the hand (red, solid), foot (blue, dashed), and eyes (yellow, dash-dotted). Shaded areas represent the standard error. Vertical lines depict the presentation of stimuli. The gray horizontal marks significant differences between all conditions.

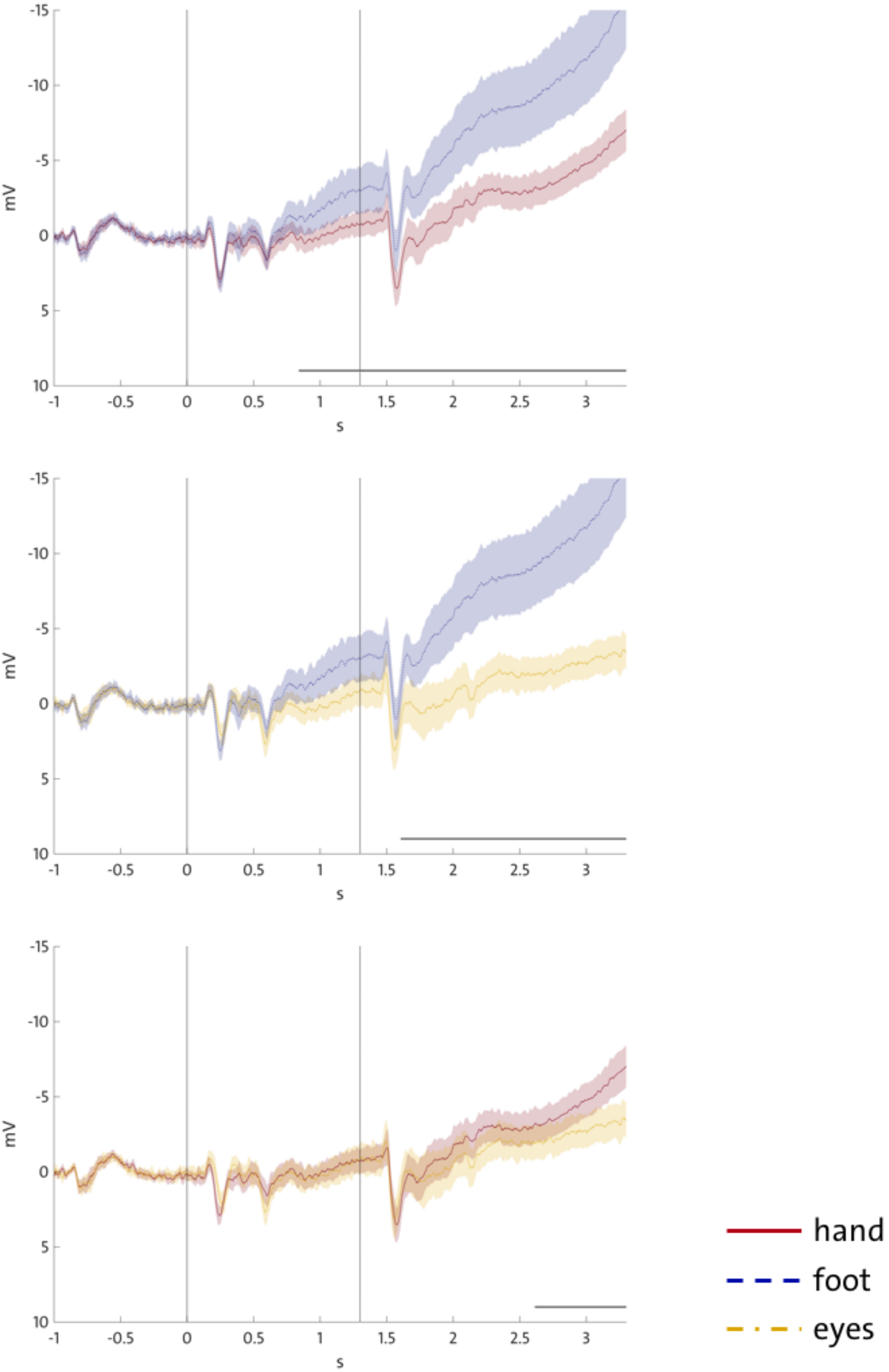

Figure 4.5. Post-hoc comparisons of the contingent negative variation at Cz. Shaded areas represent the standard error. Vertical lines depict the presentation of stimuli. Gray horizontal lines mark significant differences between the conditions. ERPs preceding hand and foot movements (top) different already during the first delay. Foot and eye movements (middle) differed at the beginning of the second delay. Hand and eye movements (bottom) only differed at the end of the delay.

Second, ERPs were assessed with respect to target difficulty per effector. As expected, there were no differences between the easy and difficult condition for all effectors during the first delay, as target size was unknown during this interval. The second delay for all effectors is depicted in Figure 4.6. When hand movements were prepared, ERPs in the easy and difficult condition differed from one another during the second delay (top panel). There was a more positive deflection after cue offset at parieto-occipital electrode sites (PO3, PO4, POz, P3, Pz, P5, P4, P6, Oz, O1, O2) in the difficult than in the easy condition. The reverse was true for fronto-central electrodes (AF, FC3, FC5, F3, F5). Here, the deflection was more positive in the easy than in the difficult condition in the same time-window. These differences were significant from 1800 – 2200 ms, that is, during a 400 ms time-window following the presentation of the target cue.

When foot movements were prepared, a similar pattern emerged (middle panel). ERPs in the difficult condition were more positive following cue presentation than ERPs in the easy condition over parieto-occipital electrodes and vice versa over fronto-central electrodes. Correspondingly, the topography was very similar to that observed in the hand condition. However, the observed differences were not statistically significant.

When eye movements were prepared, only small differences between the easy and difficult condition were observed (bottom panel). The topography of the difference differed from that of the limb conditions, with the posterior effect being lateralized to the left. However, there were no statistical differences between easy and difficult targets for eye movements.

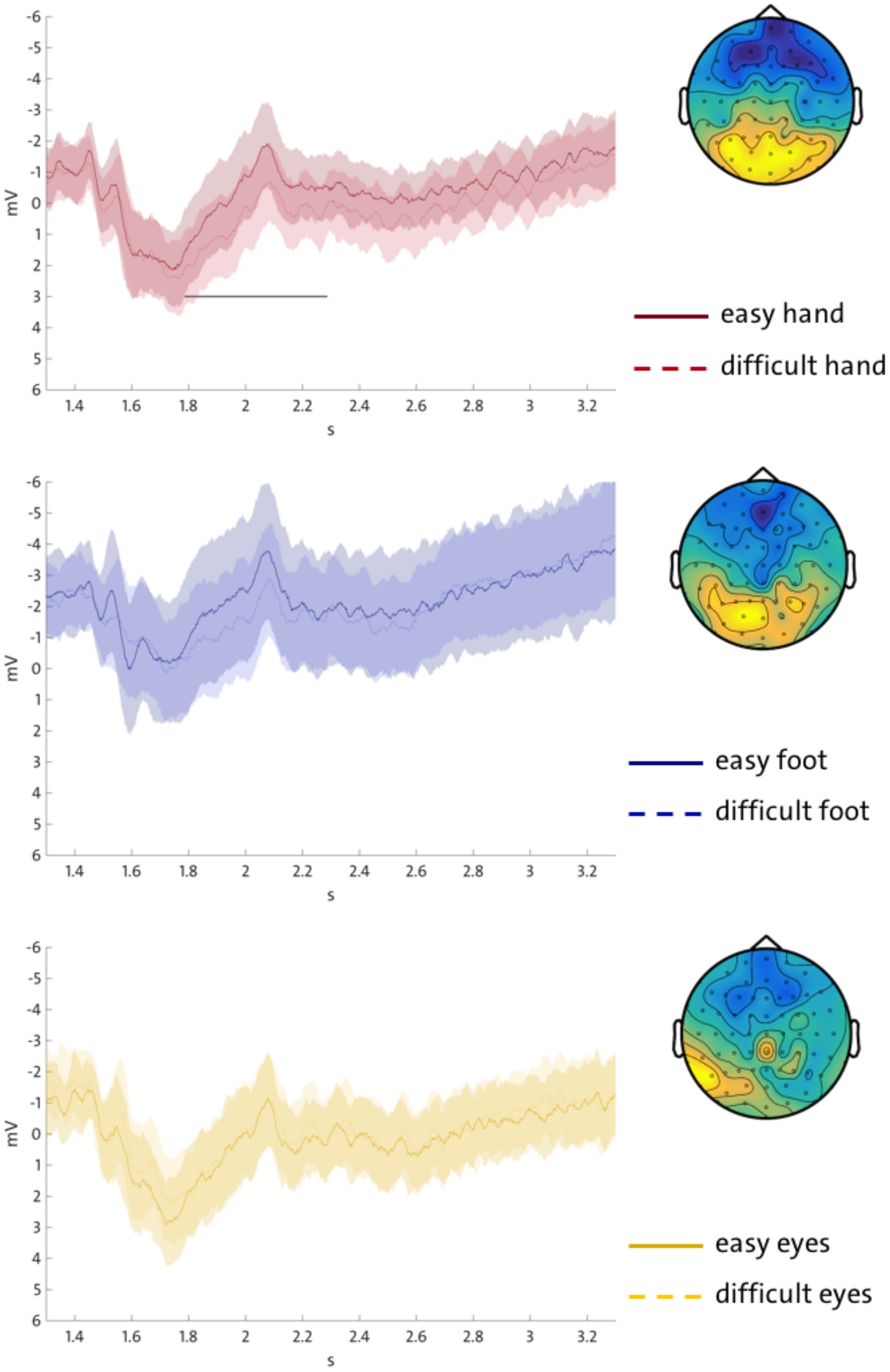

Figure 4.6. Comparison of the easy (solid line) and difficult (dashed line) condition for hand (top), foot (middle) and eye (bottom) movements at Pz during the second delay. Shaded areas represent the standard error. Only ERPs preceding hand movements were affected by difficulty (significance marked by gray horizontal line), but the difference topographies were similar across effectors.

Finally, difference waves (difficult-easy) were computed per effector and compared to one another. There were no significant differences between the three effector conditions, suggesting a similar effect of target difficulty on the ERPs, even though the difference between easy and difficult targets was only significant for hand movements.

4.3.2.2 Time-Frequency Representations

Low Frequencies

TFRs were first assessed with respect to the to-be-used effector (regardless of difficulty). In all conditions, there was a bilateral increase in theta-band activity (< 10 Hz) in response to the first (0 – 0.3 s) and second (1.3 – 1.8 s) visual cue over occipital areas. During the first delay (0.3 – 1.3 s), alpha-band activity (10-15 Hz) was desynchronized over occipital areas in all conditions (data not shown here). Preceding limb movements, this alpha-decrease was slightly lateralized to the contralateral hemisphere while the activity was clearly bilateral preceding eye movements. At the same time, activity in the beta-band (15-25 Hz) desynchronized weakly over parietal areas in all effector condition. Again, this beta-decrease was slightly lateralized to the contralateral hemisphere preceding limb movements while the activity was bilateral preceding eye movements.

During the second delay, the desynchronization in the beta-band was more pronounced for all effectors. It was now localized to centro-parietal areas, reflecting the somatotopic organization of M1 (Figure 4.7). More precisely, it was located medially when foot movements were prepared and more lateralized to the contralateral hemisphere when hand movements were prepared. In case of eye movements, the beta-decrease was also localized to central electrodes, but the activity was weaker than for limb movements.

Next, TFRs were assessed with respect to target difficulty, both per effector and averaged over all effectors. For both easy and difficult targets, alpha- and beta-activity were modulated in a similar fashion as in the overall effector comparison. However, no differences between the easy and difficult condition were observed throughout the entire frequency range for any of the effectors.

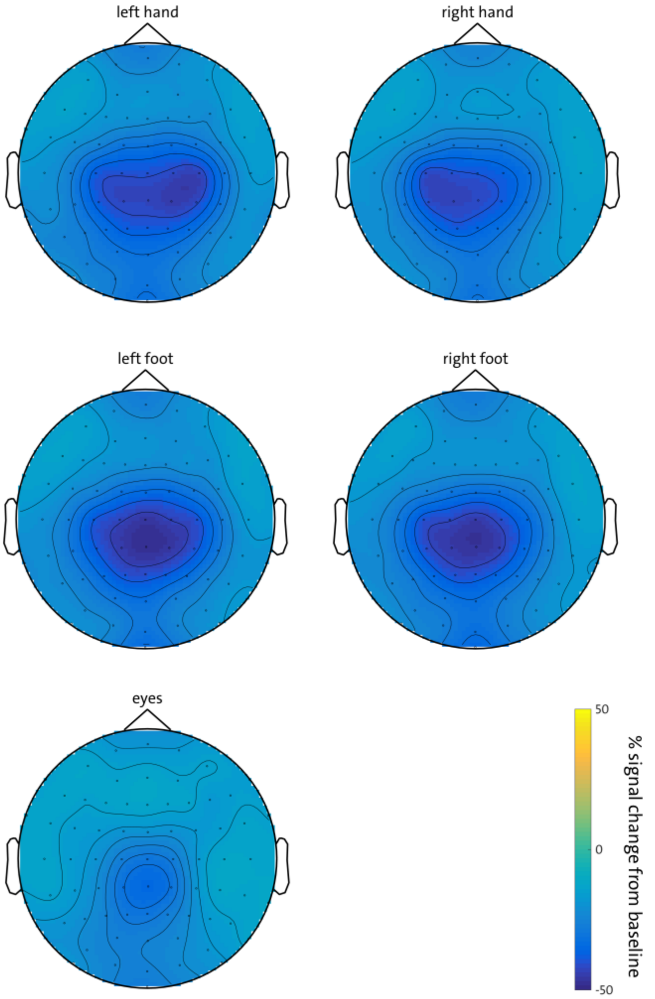

Figure 4.7. Topography of the beta-band (15-25 Hz) during the second delay (1.8 – 3.3 s) for all effectors. Both hand (top row) and foot (middle row) movements were marked by a desynchronization following the somatotopic organization of M1. Eye movements (bottom) were preceded by a weaker desynchronization.

High Frequencies

First, TFRs were assessed with respect to the to-be-used effector (regardless of difficulty and hemifield). In all conditions a widespread, rather unspecific desynchronization throughout the entire gamma-band (30-100 Hz) was observed during both delay phases. It started after the first cue (0.3 s) and intensified during the second delay. To control for possible differences between conditions in the baseline interval, we applied the same statistical procedure as in the delay phase. No differences were observed. Thus, all reported effects truly reflect differential activity in the delay phase and are not caused by differences in the baseline.

When foot movements were prepared, however, synchronization increased relatively in the higher gamma-range (approx. 60-80 Hz) over central electrodes after the second cue (1.8 s). Cluster-based permutation tests revealed the relatively increased synchronization to be significantly stronger in the foot than in both the hand and the eye condition.

When foot and hand TFRs were compared, this difference emerged over midline electrodes (FCz, Cz, CPz) early during the second delay, covering the entire frequency range from 55-85 Hz. At the end of the delay (about 2.6 s after the first cue, i.e., 0.8 s after the second cue), it covered a central cluster (FCz, Cz, C1, C2, CPz, CP2) that was most pronounced from 60-80 Hz (Figure 4.8). In addition, there was a significant modulation at 45 Hz in the first half of the second delay, which was caused by stronger de-synchronization in the hand condition.

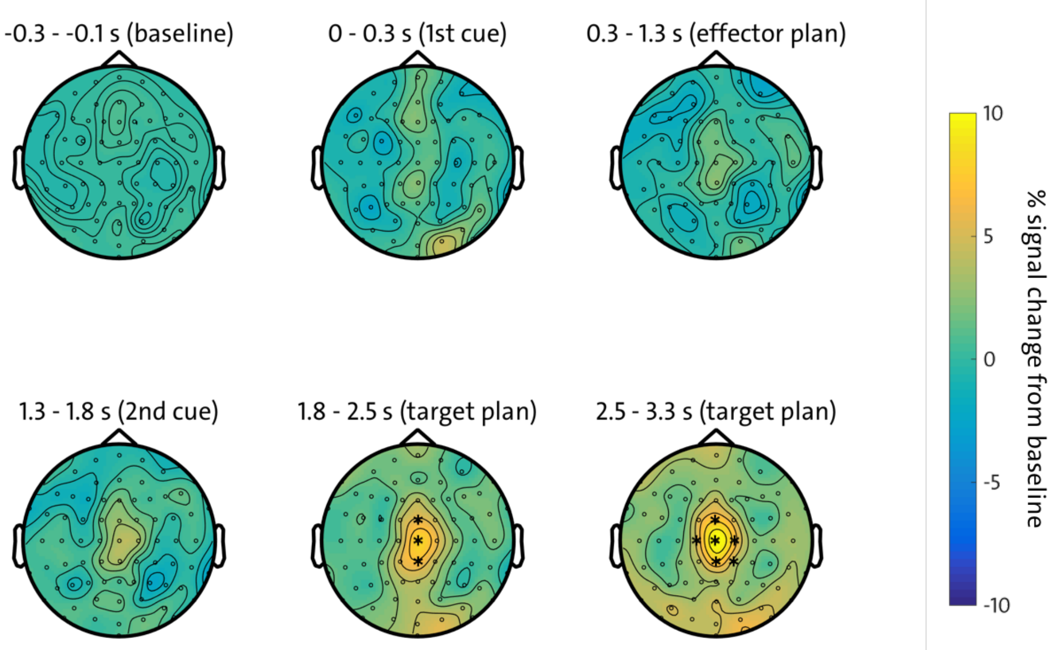

Figure 4.8. Topography of the difference between foot and hand movement planning from 60-80 Hz. Foot movements were preceded by a relatively higher synchronization than hand movements. Sensors showing significant differences for the entire frequency range are marked by asterisks.

When foot and eye TFRs were compared, a similar though slightly weaker pattern emerged (Figure 4.9). Early in the second delay, synchronization was significantly stronger preceding foot than eye movements over midline electrodes (Fz, FCz, Cz, CPz) in the range from 60-80 Hz. By the end of the trial, this difference also clustered around central electrodes (FCz, Cz, C1, C2, CPz).

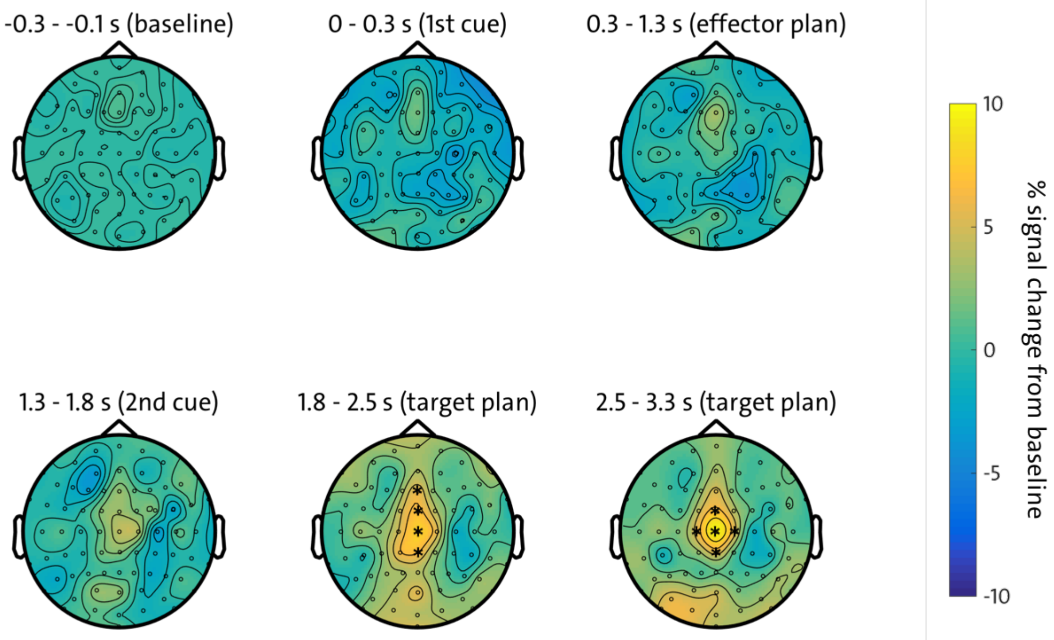

Figure 4.9. Topography of the difference between foot and eye movement planning from 60-80 Hz. Foot movements were preceded by a relatively higher synchronization than saccades. Sensors showing significant differences for the entire frequency range are marked by asterisks.

When hand and eye TFRs were compared, no significant differences were observed for frequencies exceeding 60 Hz. In the lower gamma-band, however, desynchronization was stronger preceding hand than eye movements from 40-60 Hz (Figure 4.10). The effect was bilateral, covering central and parietal electrodes (C3, CP3, C4, CP1, CP2, P2.)

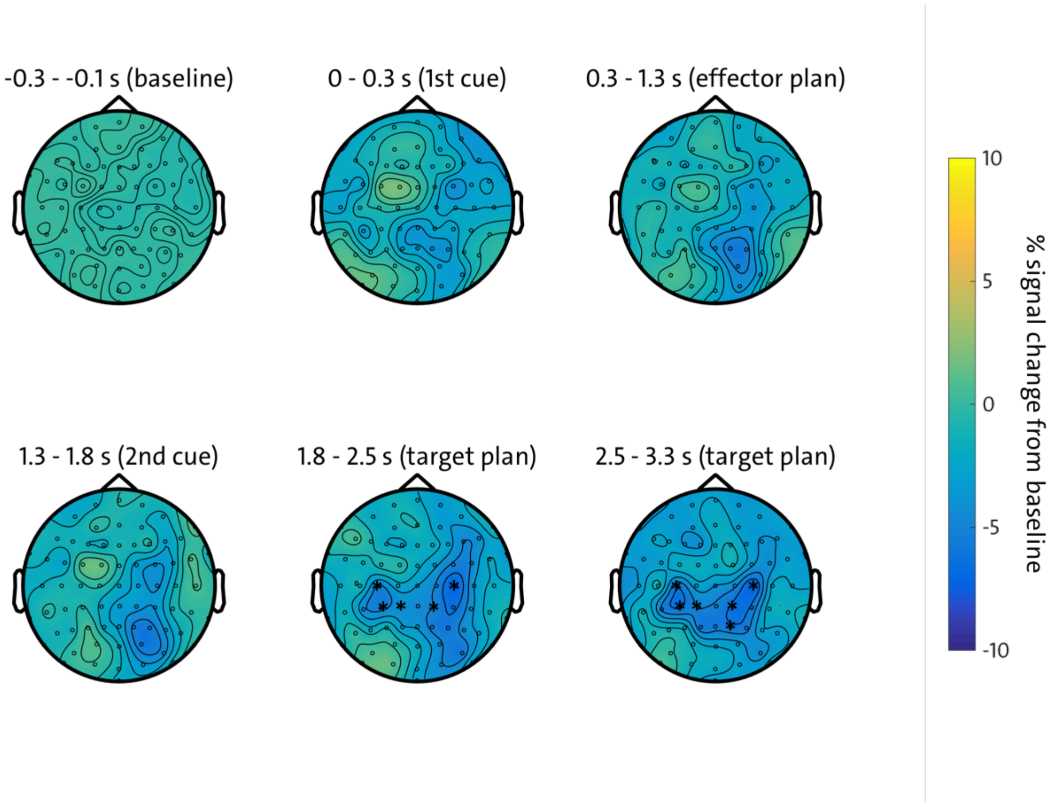

Figure 4.10. Topography of the difference between hand and eye movement planning from 40-60 Hz. Hand movements were preceded by a higher desynchronization than saccades. Sensors showing significant differences for the entire frequency range are marked by asterisks.

Second, TFRs were assessed regarding the visual hemifield, following the same rationale as in study 2 (chapter 3). To this end, targets were coded as ipsi- or contralateral with respect to each cortical hemisphere. Targets were then compared to each other per effector and body side. No statistical differences were found between ipsi- and contralateral targets in any of the effector conditions.

In a final explorative analysis, TFRs were assessed with respect to target difficulty, both per effector and averaged over all effectors. As for lower frequencies, there were no statistical differences between the easy and difficult condition for any of the effectors throughout the entire high frequency range.

4.4 Discussion

Here, we report the second iteration of an EEG study on movement planning with different effectors. Our aim was to identify effector-specific signatures in the EEG by investigating both ERPs and TFRs in a delayed movement paradigm with hands, feet, and eyes. We used a modified version of Fitts task (1954) to control for possible differences in movement difficulty across effectors.

On the behavioral level, we replicated our own and other’s findings by showing that both hand and foot movements follow Fitts’ law, that is, they were significantly slower for difficult than easy targets (Fitts, 1954; Hoffmann, 1991). In the EEG, both measures were significantly modulated by the type of effector during movement preparation. In the first analysis, ERPs showed a late negative deflection on central electrodes that reflected the to-be-used effector, that is, CNV and pre-saccadic negativity. In line with our hypotheses, the amplitude was maximal when foot movements were prepared and minimal when eye movements were prepared, with an intermediate amplitude preceding hand movements (Jentzsch & Leuthold, 2002; Miller, 2012). This effect was independent of Fitts' law, that is, there were no differences between easy and difficult targets at central electrodes. In line with our hypotheses, target difficulty was reflected over posterior electrodes with a less negative N2 and a more positive P3 for difficult than easy targets (cf. Kourtis et al., 2012). Descriptively, this effect was very similar across effectors, indicating that this parameter of the movement plan was encoded independently from the to-be-used effector.

In the second analysis, TFRs of all effectors were marked by unique modulations of the beta- and gamma-band. In the range from 15-25 Hz, the desynchronization reflected the somatotopic organization of M1, with a contralateral effect for upcoming hand movements and a medial effect for foot movements. In the range from 60-80 Hz, foot movements were preceded by a significantly higher relative synchronization over central areas than eye and hand movements. At the same time, upcoming hand movements were marked by a significantly higher desynchronization than eye movements in the range from 40-60 Hz. In the following, we will discuss the results of each analysis in more detail.

The behavioral results confirmed our hypothesis regarding movement time, showing Fitts' law for both hand and foot movements. Unexpectedly, reaction time was also affected by target difficulty, with slower responses to easy than to difficult targets for both limbs. This is somewhat counterintuitive, as one could expect the preparation of a difficult movement to take longer than that of an easy movement.

Reaction time and movement time are often considered as independent processes. Reaction time has been suggested to reflect the duration of a movement plan (Cisek, 2007; Donders, 1969; Erlhagen & Schöner, 2002; but see Haith, Pakpoor, & Krakauer, 2016). In the present study, however, a delayed movement paradigm was applied, which renders the idea that reaction time reflects planning unlikely.

The analysis of ERPs confirmed our hypothesis that the to-be-used effector is reflected in a late negative deflection at central electrodes. Foot movements were preceded by a more negative CNV than hand movements while eye movements were preceded by a pre-saccadic negativity. Strikingly, the CNV differed between hand and foot movements already during the first delay. Thus, the distinction between effectors with similar properties (i.e., the limbs) seemed to evolve earlier than the distinction between limbs and eyes. Furthermore, the difference between ERPs in the hand and foot condition was significant even before body side and target were specified.

Early theories of motor control postulated so-called generalized motor programs (GMP), which are defined as abstract representations of movement plans (Keele, 1968; Schmidt, 1975). Before a movement can be executed, specific parameters of the GMP, such as the effector or target, need to be specified. Studies investigating GMPs typically vary the amount of information about these parameters and the time point at which it is available. At the beginning of a trial, either full, partial, or no information about the parameters is presented. As an example for partial information, participants first receive information about which body side to use and only learn how far to move after a delay (Rosenbaum, 1980). Generally speaking, the provided amount of information is reflected in behavioral and neurophysiological measures (Leuthold, Sommer, & Ulrich, 2004; Rosenbaum, 1980). Crucially, some parameters (e.g., target location and body side) are invariant across effectors, at least for effectors that are characterized by similar features, such as hands and feet. In two experiments, Jentzsch and Leuthold (2002) provided either full, none, or partial information about the to-be-used effector and the response side (here, target and body side coincided). In their first experiment, either hand or eye movements were performed. When full information about the effector was available, the amplitude of the CNV already differed from the condition with no information during the delay. When only partial information about the response side was available, the signal did not differ from the condition with no information until the missing information about the effector was provided. In a second experiment, the same task was performed with hands and feet. In contrast to the first experiment, the amplitude in the “partial” condition (i.e., response side only) already differed from the condition with no information during the delay even though the effector was unknown. In other words, this parameter of the GMP was already prepared in case of two possible limb movements but not in case of a possible eye movement, underlining the similarity of these effectors. Our delayed Fitts’ paradigm can be directly compared to this study, because information about the effector was available during the first delay whereas information about target and body side was only provided by the second cue. Accordingly, the observed difference between ERPs in the hand and foot condition during the first delay can be related to GMPs, indicating effector-specific movement preparation when only abstract information is available. In contrast, movements were not prepared when the effectors cannot perform the same type of movement, as is the case for eye movements.

With regard to target difficulty, we expected Fitts' law to be reflected in the ERPs preceding both hand and foot but not eye movements, with a decreased N2 and an increased P3 at posterior electrodes for difficult in comparison to easy targets. This hypothesis was only partially confirmed. While target difficulty affected movements of both limbs on the behavioral level, only ERPs in the hand condition were significantly modulated. Consistent with our previous study and the findings by Kourtis and colleagues (2012), we found ERPs in the difficult condition to be more positive than in the easy condition, resulting in a less negative N2 and a more positive P3. This effect occurred at parieto-occipital electrode positions, which largely overlapped with those reported previously (Kourtis et al., 2012). The difference was starting 500 ms after cue onset, which is approximately 200 ms later than in the study by Kourtis and colleagues (2012). In their experiment, however, the cue was only presented for 150 ms in comparison to 500 ms here. In addition, they performed post-hoc analyses on restricted time-windows whereas the cluster based permutation test used here provides a more flexible approach. These methodological differences likely explain the observed latency difference. Unlike Kourtis and colleagues (2012) we additionally observed a reversed effect at frontal electrodes, with a more negative deflection for difficult than easy targets. The effect mirrored the one observed at posterior electrode sites, suggesting a dipole.

In the foot condition, the same pattern as in the hand condition was observed: ERPs in the difficult condition were marked by more positive amplitudes than ERPs in the easy condition even though this effect failed to reach significance. Additionally, the topography of the difference showed a striking similarity to that of the hand condition.

In contrast to our hypothesis, easy and difficult targets also differed descriptively in the eye condition. Accordingly, the difference waves in the eye condition did not differ from those in the limb conditions. It is possible that a movement with an uninstructed effector, likely the hand, was prepared in parallel, likely owing to the fact that hand and eye movements are tightly coupled in natural behavior (Gielen, van den Heuvel, & van Gisbergen, 1984). The recurring finding that saccades do not follow Fitts' law adds to this idea (Chi & Lin, 1997; Grosjean et al., 2007; Kourtis et al., 2012). Taken together, our analysis of ERPs suggests that the to-be-used effector is encoded independently from other visuospatial parameters (here: difficulty) of a movement.

The analysis of the power spectrum confirmed our hypothesis insofar as different effector plans were marked by discriminable frequency modulations of the gamma-band. Unexpectedly, all movement plans were marked by a broad decrease in the gamma-band. In direct comparison of the effectors, the range 60-80 Hz was significantly modulated when foot movements rather than hand or eye movements were prepared. Hand and eye movement planning differed in the range from 40-60 Hz, with a higher desynchronization for hand than eye movements. Hence, movement plans of different effectors were marked by modulations of distinct frequency bands in the EEG. By disentangling target laterality and difficulty we aimed at eliminating movement-unrelated processes and making our study comparable to previous work. In both analyses, however, no significant effects were observed.

One could argue that the observed synchronization at central electrodes preceding foot movements merely reflects the fact that goal-directed foot movements are more effortful or less common than hand and eye movements. However, movement difficulty, which was induced by Fitts task, had no measurable effect on the oscillatory power.

Thus, our analyses of the power spectrum suggest that movements with different effectors are uniquely encoded in the gamma-band. It remains to be determined where these oscillatory differences originate. Source reconstruction in the study by van der Werf and colleagues (2010) suggested PPC as a likely candidate. Given that hand and foot movements seem to be encoded in the same portion of PPC (Heed et al., 2011), the gamma-band activity observed here might serve as an ideal mechanism to differentiate between the two. Further analyses of our data, using adaptive spatial filtering techniques (Gross et al., 2001), could shed light on this issue. Nonetheless, we were able to identify potential cortical correlates of movement plans for effectors that share many behavioral properties.

5 Dissociating cortical movement plans of multiple effectors

5.1 Introduction

In everyday life, we are readily able to execute movements with multiple effectors at the same time. Steering a car with one hand, changing gears with the other, and simultaneously pressing the clutch pedal with our foot poses no challenge to us. These kinds of goal-directed movements are preceded by unique signatures in oscillatory EEG activity. In our third study (chapter 4), we found an enhancement of the gamma band in the range from 40-60 Hz when eye as opposed to hand movements were prepared. In addition, we identified a distinct enhancement of the 60-80 Hz range when foot as opposed to both eye and hand movements were prepared. Similarly, ERPs serve as a marker for the to-be-used effector, with the so-called CNV (Walter et al., 1964) being maximal preceding foot movement, intermediate preceding hand movements, and minimal preceding eye movements at electrode Cz (cf. chapter 4). However, we only assessed single movements to a target in one hemifield. In such a design the possibility remains that movements with an uninstructed effector are covertly prepared in parallel. For example, participants might automatically plan (but not execute) a hand movement to the target even though a foot movement was instructed. This might especially be the case for these two limbs, because they are able to perform virtually the same type of goal-directed movements.

In order to disentangle the observed signal related to movement planning of one effector from that possibly related to another, we introduced the so-called dissociation task (Snyder et al., 1997) in the current study. Here, two effectors are simultaneously moved to targets in opposite hemifields. By doing so, the neural signatures of potential plans for movements that are not executed can be eliminated.

The dissociation task was adopted for humans by van der Werf and colleagues (2010), who were able to corroborate their previous findings: When participants prepared simultaneous eye and hand movements to targets in opposite hemifields, a direction-selective frequency band from 70-90 Hz was observed for hand movements over left parietal sensors. This analysis revealed no activation reflecting eye movement direction, rendering covert saccade planning unlikely. Thus, the dissociation task offers the opportunity to balance spatial attention across hemifields and consequently allows to infer which effector plans constitute the observed signal.

In the present study, we asked participants to prepare and execute simultaneous movements to targets in opposite hemifields with three possible effector combinations: right hand and right foot, right hand and eyes, and right foot and eyes. Our primary aim was to dissociate the frequency modulations we observed for foot movement planning in our previous study from potential covert movement plans for hand and eyes. Akin to study 3, we expected a foot-specific enhancement of the gamma-band from 60-80 Hz when hand or eye movements were prepared at the same time. This would corroborate the idea that movement plans for different effectors are encoded in separate frequency bands of the power spectrum.

Simultaneous hand and foot movements have also been investigated by means of ERPs. In one study, participants simultaneously released buttons with one hand and one foot (Miller & Gerstner, 2013). The authors predicted a superimposition of the CNV at electrode Cz, presuming movement plans of different effectors to be independent from one another. In other words, they expected the ERPs observed for single movements to sum up when both effectors were moved at the same time, resulting in an amplitude intermediate between those observed for single effector movements. However, the amplitude preceding combined movements was very similar to that for foot movements only, arguing against the superimposition hypothesis (Miller & Gerstner, 2013). Rather, movement plans for the two limbs seem to interact when simultaneous movements are prepared. Hence, we expected to find modulated CNVs in all conditions. This would indicate that participants were successfully preparing movements with both effectors simultaneously. Our secondary aim was thus to verify that the experimental manipulation did in fact work. Even though we cannot directly compare the present study to the results from study 3, we expected the amplitude preceding "hand + foot" and "foot + eyes" movements to be markedly more negative than the amplitude preceding "hand + eyes" movements, because the CNV is most pronounced preceding foot movements (cf. chapter 4).

5.2 Method

5.2.1 Participants

All participants from our third study also took part in this experiment. The EEG session usually took place on the day after the data acquisition of study 3. The data from six participants had to be excluded because of extensive saccade error rates (>50% of trials; n = 5) and artifacts in the EEG (n = 1). The final sample consisted of 17 participants (13 female, M_{age} = 23.79, range = 19-30 years), all of whom were right-handed (M = 17.89, SD = 2.58), according to the Edinburgh Handedness Inventory (Oldfield, 1971). Fourteen participants were right-footed (M = 13, SD = 3.81) and three were both-footed (M = -2.33, SD = 2.08), according to the Waterloo Footedness

Questionnaire - Revised (Elias et al., 1998).

5.2.2 Setup

The setup was similar to that of our previous studies. Movements were performed with the hand and foot of the right body side, each resting on one of two buttons at the starting position. The limbs of the left body side rested comfortably on the chair in a normal sitting position. Participants were instructed to move two effectors to two targets in opposite hemifields simultaneously.

5.2.3 Stimuli and Design

An example of a trial is depicted in Figure 5.1. The trial began with the presentation of a central fixation cross for 1000 ms in the lower half of the screen (90 mm below center). Next, two target circles (diameter = 60 mm), each containing a different effector symbol (hand, foot, or eye), appeared simultaneously, one in each hemifield. The distance of the targets from the fixation cross varied in the horizontal direction to prevent stereotypical movements (70.6 or 127 mm), but was the same in the left and right hemifield in one trial. In addition, each circle and the accompanying symbol were colored in pink, blue, or yellow to make the distinction of the effector symbols easier. For instance, eye symbols were always presented in pink, hand symbols in yellow, and foot symbols in blue throughout the experiment. The color assignment was balanced across participants. After 750 ms, the targets disappeared and only the fixation cross was shown for 1500 ms (planning delay). Then, the fixation cross changed into a dot, serving as the go-signal. The dot was presented for up to 1000 ms, but the trial ended if a touchscreen response was registered earlier. The ITI was jittered from 2500 to 2700 ms (square distribution). The white dot was presented throughout the ITI. Only the instructed effectors were to be moved, that is, only one button was to be released when “hand + eyes” or “foot + eyes” movements were cued and both buttons had to be released when “hand + foot” movements were cued. Owing to the arrangement of the setup, it was not possible to control for saccade errors with an eye tracker. Accordingly, trials containing limb errors were not repeated to keep trial numbers balanced and avoid practice effects.

The factor “effector pair” had three levels (“hand + eyes” vs. “foot + eyes” vs. “hand + foot”), the factor “target side” had two levels (“left/right” vs. “right/left”, with the first side specifying the target for the first effector in the pair), and the factor “distance from fixation” had two levels (“near” vs. “far”), resulting in 12 possible factor combinations. Each combination was repeated four times per blocks (i.e., 48 trials per block). Participants completed 13 blocks (i.e., 624 trials) in total, resulting in 208 trials per effector pair. Due to technical failure, trials in the condition “foot + eyes” were unbalanced across target sides, resulting in only 52 trials being cued to the “left/right” and 156 to the “right/left” (rather than 104 each).

The maximum possible trial duration including the ITI was 6.95 s, resulting in a block duration of approximately 5.5 min. Including breaks, the experiment took about 1.5 h to complete. Participants practiced the experiment with visual feedback in the same session as for study 3. Because study 3 took place between the practice session and this study, participants completed another practice block (without visual feedback) just before the experiment began.

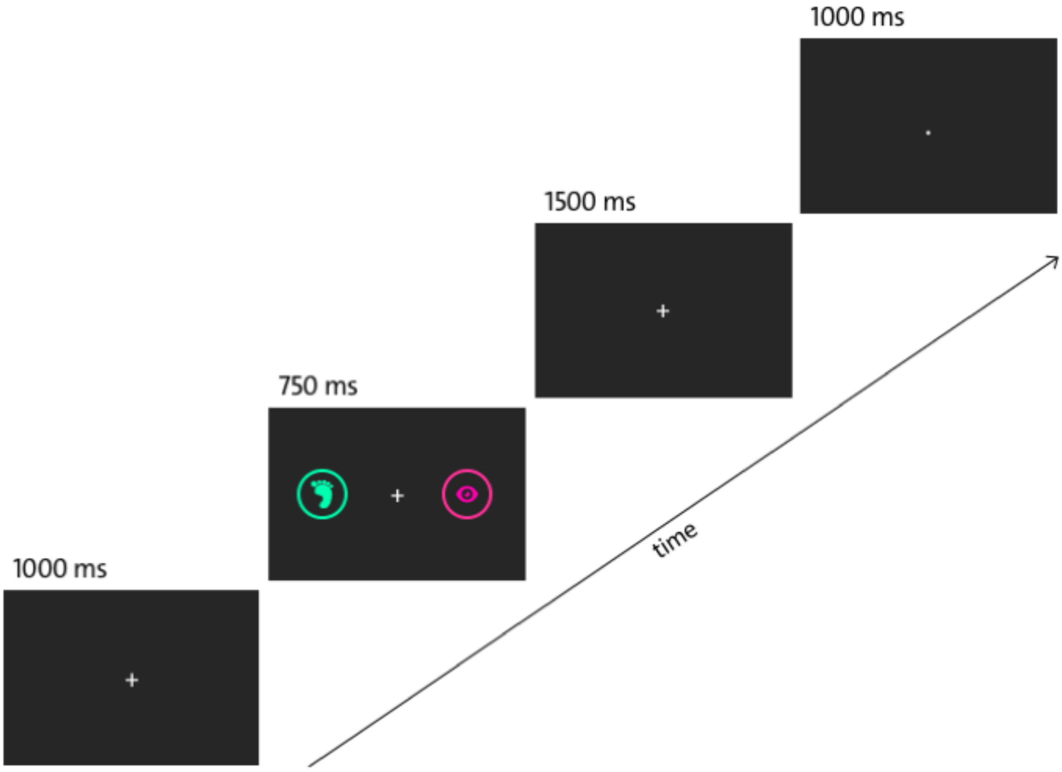

Figure 5.1. Example trial of the dissociation task. After a fixed baseline, two targets were shown in opposite hemifields. The effectors were cued with colored symbols in the center of target circles. After a planning delay, the fixation cross changed into a dot and the movements were executed simultaneously.

5.2.4 EEG acquisition

The continuous EEG was recorded with BrainVision Recorder (Brain Products GmbH, Gilching, Germany) using 74 passive Ag/AgCl electrodes. The electrodes were mounted in an elastic cap according to the 10-10 system (EASYCAP GmbH, Herrsching, Germany). The ground electrode was placed on the forehead. The signal was referenced online to the left earlobe and re-referenced offline to the average signal of the left and right earlobe. Horizontal eye movements were inferred from electrodes F9 and F10, which are located close to the outer canthi of the eyes. Vertical eye movements were monitored via electrode Fp1 and one additional electrode positioned below the left eye. Impedances were reduced by preparing the skin with an abrasive gel (Every, Gelimed, Bad Segeberg, Germany) and isopropyl alcohol. Conductivity between skin and electrodes was obtained by electrolyte gel (ECI Electrogel, Electrocap International, Eaton, OH, USA). The impedance of all electrodes on the scalp was kept below 20 kΩ (Ferree et al., 2001). Ground and reference electrodes had an impedance of <5 kΩ. The EEG was amplified (Brain Products GmbH, Gilching, Germany) with a band-pass filter of 0.1-100 Hz and digitized at a sampling rate of 500 Hz.

5.2.5 Analysis

All data were preprocessed in MATLAB (R2014, The Mathworks, Natick, MA, USA). Behavioral data were analyzed in R, version 3.3.3 (R Core Team, 2013). The EEG was analyzed in MATLAB (R2015b) using FieldTrip, version r7276 (Oostenveld et al., 2011).

5.2.5.1 Behavior

For trials involving hand and foot movements, RT and MT were computed from the button and touchscreen responses. The EOG of all trials was inspected for errors and RT of eye movements was obtained with a semi-automatic procedure (see chapter 4 for details). Trials in which a non-instructed effector was moved, only one effector was moved, or movements were initiated prematurely (< 80 ms after the go-signal) were excluded from the analysis. After controlling for possible behavioral differences between movements to the left and movements to the right target side, data from both hemifields were collapsed for the behavioral analysis. The percentage of remaining trials per effector pair is shown in Table 5.1.

Table 5.1

Mean Percentage of Remaining Trials

	foot + eyes	hand + eyes	hand + foot
behavior	58.86 (± 12.69)	65.41 (± 15.20)	58.30 (± 14.74)
EEG	48.30 (± 13.05)	52.99 (± 10.47)	51.42 (± 12.01)

Note. Standard deviations are in parentheses.

Due to technical limitations of the touchscreen, only one movement endpoint could be registered per trial. Hence, MT (touchscreen response – button release) was available for conditions involving only one limb (i.e., “hand + eyes”, “foot + eyes”) but was ambiguous in the “hand + foot” condition. Given that no information was available about which limb reached the touchscreen first, MT could only be estimated in this condition. To this end, we subtracted the time of button release of each effector from the time of touchscreen response that could have been caused by either effector.

In case of RT, two measures were available per trial, one for each of the simultaneously moved effectors. To differentiate between these two, the levels of the factor “effector pair” were recoded as follows: The condition “hand + eyes” is called “hand (+ eyes)” if the RT refers to the hand and “eyes (+ hand)” if the RT refers to the saccade. Accordingly, “foot (+ eyes)” refers to the foot RT when the eyes were moved simultaneously and “eyes (+ foot)” refers to the saccadic RT when the foot was moved simultaneously, and so on.

RT and MT were subjected to linear mixed-effects analyses with the package lme4 (Bates, 2010). The models comprised a fixed effect for “effector pair” and a random intercept for each participant. All levels of the factor “effector pair” were specified with deviation coding (see Table 5.2 for MT and Table 5.3for RT). P-values of fixed effects were estimated using the package afex (Singmann, 2015). Fixed effects were considered significant at $p < 0.05$. Post-hoc comparisons were performed with the package lsmeans (Lenth, 2016). P-values were adjusted with the Tukey method (Tukey, 1949).

5.2.5.2 EEG

Preprocessing

The preprocessing procedure included the same steps as in study 3. In short, data were re-referenced to common average, aligned to the cue, and segmented into trials from 1 s preceding the cue to 2.25 s after. Trials with non-stereotypical artifacts (e.g., muscle contractions) were rejected manually before entering the data into an ICA that was used to reduce stereotypical artifacts (see chapter 3 for details).

Event-Related Potentials

Data were down-sampled to 100 Hz and time-locked to the onset of the cue. The fixation period (-1 – 0 s) was used as baseline. ERPs were computed per effector pair. For statistical comparison of ERPs, cluster-based permutation F-tests (Maris & Oostenveld, 2007) were performed with 1000 randomizations and an alpha-level of 5 % (see chapter 3 for details). Post-hoc comparisons were performed with Bonferroni-corrected t-tests.

Time-Frequency Representations

A time-frequency analysis was performed for frequencies from 20-100 Hz, using a multitaper approach with orthogonal Slepian tapers (see chapter 3 for details). A fixed time window of 200 ms and a frequency smoothing of 10 Hz were used, resulting in three tapers being applied to the sliding time window. TFRs were normalized to a baseline interval preceding the cue (-0.4 – 0 s) and averaged per participant. For illustration purposes, grand mean TFRs were computed.

We chose three different approaches to analyze the power spectrum. In the first approach (see Figure 5.2 for schematic), we performed the following analysis in order to disentangle possible effector-specific frequency representations from one another: In a first step, target sides were contrasted per effector pair, based on the assumption that spatial information about visual targets is primarily processed contralaterally. For example, activity in the “hand to left + foot to right”-condition (middle panel of Figure 5.2) was subtracted from activity in the “hand to right + foot to left”-condition (top panel of Figure 5.2). If frequency A coded for foot targets, then the power of frequency A should increase in the hemisphere contralateral to the foot target, and decrease in the ipsilateral hemisphere. If, at the same time, frequency B coded for hand targets, power of frequency B should increase in the hemisphere contralateral to the hand target, that is, ipsilateral to the foot target, and decrease in the other hemisphere, that is ipsilateral to the hand target and contralateral to the foot target. In analogy, the reverse activity patterns should be observed for the hemisphere ipsilateral to the foot target (i.e., contralateral to the hand target). By subtracting target-related activity (i.e., “left-right target” for foot movements and vice versa for hand movements), the effector-specific frequency should decrease in one hemisphere while increasing in the other (depending on the contrast). In the above example, activity preceding foot movements to the right (i.e., hand movements to the left), which are represented in the left hemisphere, are subtracted from activity preceding foot movements to the left (i.e., hand movements to the right), which are represented in the right hemisphere. In the left hemisphere, high power of frequency A (contralateral to the foot target) is subtracted from low power of frequency A (ipsilateral to the foot target), resulting in a left-hemispheric relative decrease of the power of A. In the right hemisphere, low power of frequency A (ipsilateral to the foot target) is subtracted from high power of frequency A (contralateral to the target), resulting in a relative increase of the power of A. The reverse pattern should emerge for the hand-related frequency B, with a relative power increase in the left hemisphere and a relative power decrease in the right hemisphere. These two subtractions were then combined by comparing target-related contrast activity in the left to that in the right hemisphere (bottom panel of Figure 5.2). In the above example, foot-related frequency A is expected to be low in the left hemisphere and high in the right hemisphere; accordingly, the expected difference value in frequency A is negative. In contrast, hand-related frequency B is expected to be high in the left hemisphere and low in the right hemisphere; accordingly, subtracting the right from the left hemisphere will result in a negative difference in frequency range B. In theory, this analysis allows us to reveal effector-specific frequencies within one comparison.

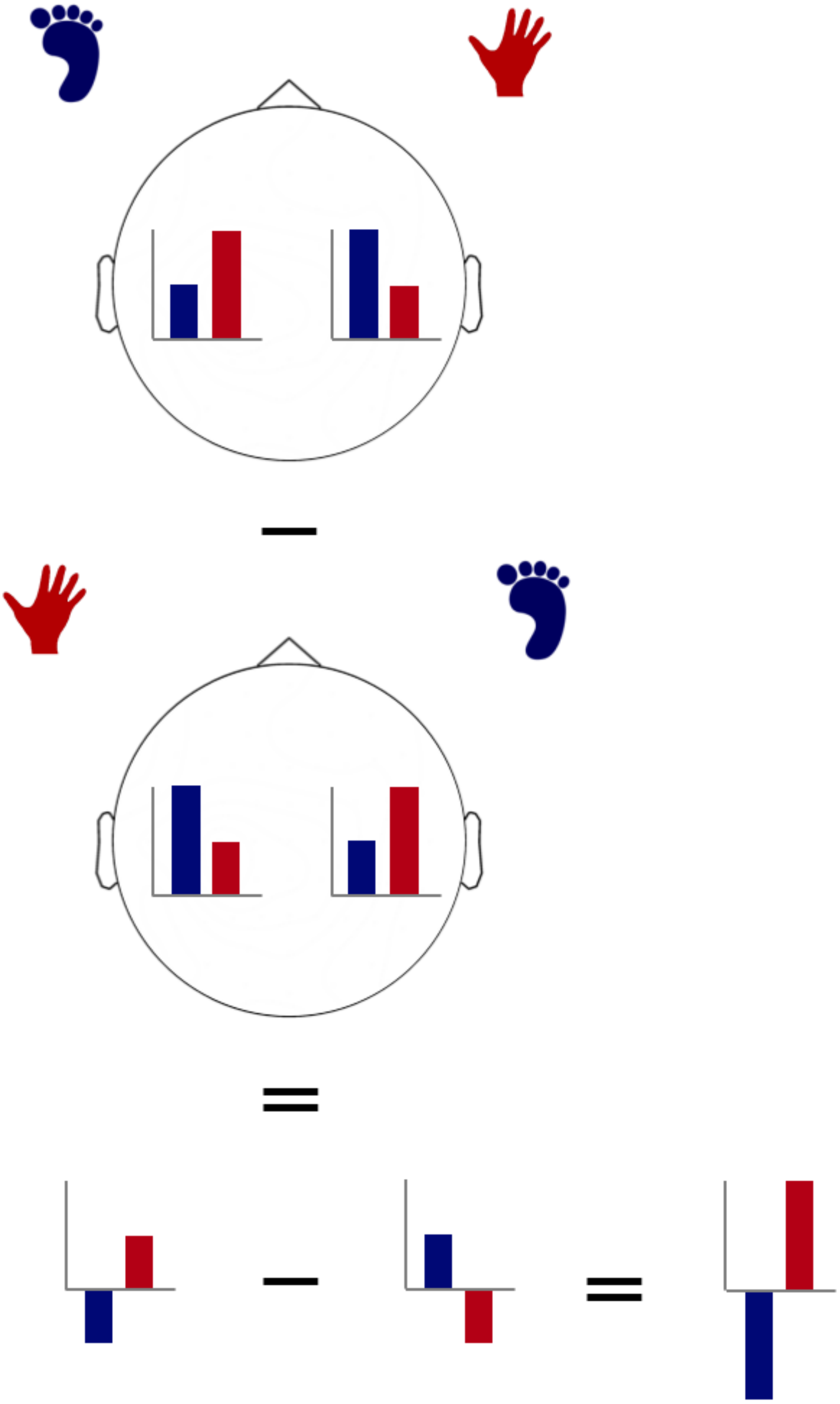

Figure 5.2. Schematic of the Target x Hemisphere contrast. Blue bars represent frequency A, which is responsive to foot movement planning. Red bars represent frequency B, which is responsive to hand movement planning. Activity preceding foot movements to the right and hand movements to the left (middle panel) is subtracted from that preceding foot movements to the left and hand movements to the right (top panel). Target-related activity in the right hemisphere is subtracted from that in the left hemisphere (bottom panel).

In the second approach, we compared all effector pairs to one other, disregarding target side. The aim of this analysis was to extract activity related to a single effector in contrast to another under the assumption that movement plans of two simultaneously moved effectors are independent. For instance, when comparing “hand + eyes” to “foot + eyes”, activity related to eye movement planning should cancel out, leaving a comparison of foot and hand movement planning comparable to study 3 while explicitly controlling for a possible co-activation of eye movement planning.

In the third approach, we performed the analysis suggested by van der Werf and colleagues (2010) for the “hand + eyes” condition in order to make our results comparable to this earlier study. To this end, hand targets were coded as ipsi- or contralateral with respect to each cortical hemisphere. That is, a hand target in the right hemifield was defined as ipsilateral to the right hemisphere and as contralateral to the left hemisphere. The reverse held for eye movement targets. Next, activity in the “ipsilateral” condition was compared to that in the “contralateral” condition for hand movements (vice versa for the eyes). By taking target side into account, this analysis also controls for potential covert movements plans.

For all statistical comparisons in sensor space, cluster-based permutation tests with 1000 randomizations were computed (Maris & Oostenveld, 2007; see chapter 3 for details). The tests were performed for the frequency range from 30-100 Hz and the entire delay phase (0.75 – 2.25 s). The resulting t-scores (maximum sum per cluster, cf. Spaak, Lange, & Jensen, 2014) were transformed into z-scores to illustrate the effects (Medendorp et al., 2007).

Source Reconstruction

To localize the cortical sources of the observed oscillatory activity, a linear beamformer approach was applied (Gross et al., 2001). The beamformer technique uses an adaptive spatial filter that passes activity from one location (i.e., grid point) with unit gain while suppressing activity from all other locations (Gross et al., 2001; van Veen, van Drongelen, Yuchtman, & Suzuki, 1997). To this end, a volume conduction model was derived from the MNI template brain (Montreal Neurological Institute, Montreal, Canada), resulting in an anatomically realistic three-shell model. The head model was divided into a regular 8 mm three-dimensional grid. The leadfield matrix was calculated using the boundary element method for each grid point (Fuchs, Kastner, Wagner, Hawes, & Ebersole, 2002). A cross-spectral density (CSD) matrix was calculated between all electrode positions, which were provided by a template from the cap manufacturer (EASYCAP GmbH, Herrsching, Germany). The CSD was computed with a multitaper Fast-Fourier transform approach using Slepian tapers for 70 (± 10 Hz). The selected frequency was based on the results of the sensor level analysis. The leadfield and the CSD matrix were used to construct a spatial filter estimating the source activity at each grid point. In accordance with the sensor level analysis, the source activity was estimated separately for a segment of the baseline (-0.25 – 0 s) and the end of the delay interval (2 – 2.25 s) for each participant and condition. The source estimate of each condition was compared to the respective baseline interval. Statistical differences between delay interval and baseline in source space were assessed with a cluster-based permutation test using dependent t-statistics (maximum value per cluster, cf. Spaak et al., 2014) and corrected for multiple comparisons (Maris &

Oostenveld, 2007). The resulting statistical maps were z-transformed and interpolated with the MNI template brain to illustrate the effects.

5.3 Results

5.3.1 Behavior

5.3.1.1 Movement Time

The average MT for limb movements is depicted in Figure 5.3. Note that MT for “hand (+ foot)” and “foot (+hand)” could only be estimated. There was a main effect of effector pair, $\chi^2(3) = 943.38$, $p = .001$. Tukey-adjusted post-hoc tests revealed that all conditions differed significantly from one another (all $p < .001$, except for “hand (+ eyes)” vs. “foot (+hand)”, $p = .03$). Movements of each limb were faster when they were paired with the eyes than when they were paired with another limb (Table 5.2).

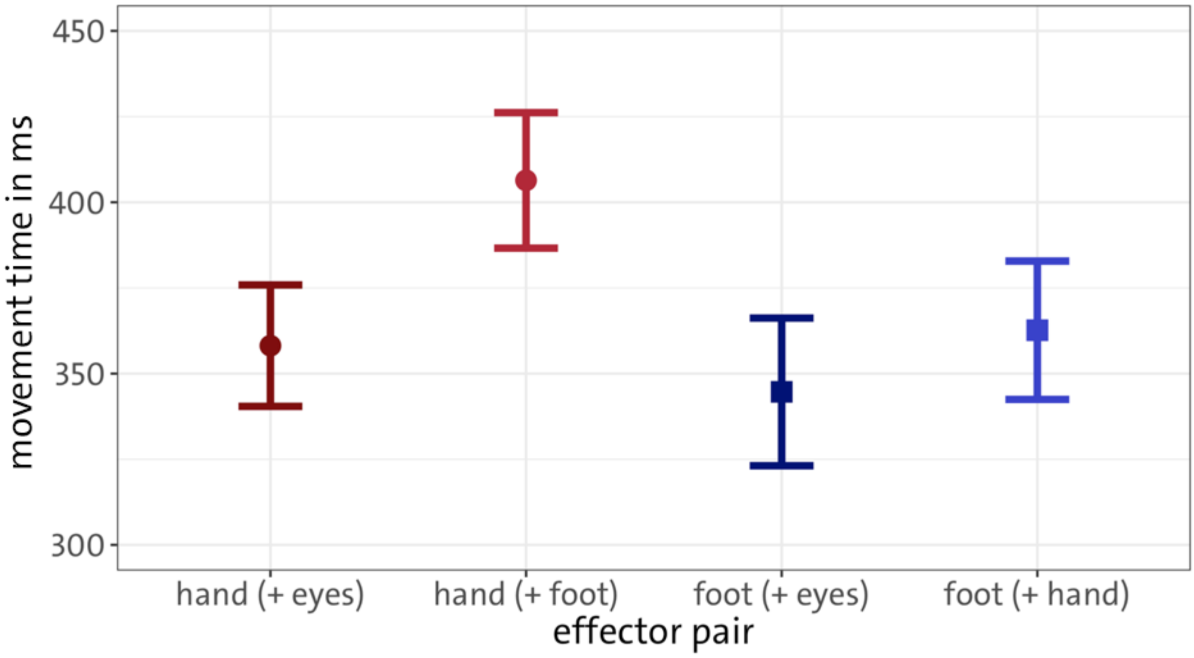

Figure 5.3. Movement time of hand (red circles) and foot (blue squares) movements. Dark colors represent a paired saccade, light colors another limb. Whiskers represent the standard error of the mean. Simultaneous limb and eye movements were faster than movements with two limbs.

Table 5.2

Movement Time (ms) per Effector Pair

	(+ eyes)	(+ hand)	(+ foot)
hand	358.15 (17.72)	-	406.39 (19.77)
foot	344.67 (21.53)	362.66 (20.18)	-

Note. Standard errors are in parentheses.

5.3.1.2 Reaction Time

Average RT per condition is shown in Table 5.5 and Figure 1.1. There was a main effect of effector pair, $\chi^2(5) = 3916.8$, $p < .001$. Accordingly, RT was fastest for eye movements that were accompanied by a hand movement and slowest for foot movements that were accompanied by a hand movement. Post-hoc comparisons revealed all conditions to differ significantly from one another (all $p < .001$, except for “hand (+ eyes)” vs. “hand (+ foot)”, $p = .017$).

Table 5.3

Reaction Time (ms) per Effector Pair

	(+ eyes)	(+ hand)	(+ foot)
eyes	-	262.25 (18.52)	277.98 (21.97)
hand	328.07 (17.18)	-	334.92 (16.71)
foot	362.66 (21.83)	378.55 (18.62)	-

Note. Standard errors are in parentheses.

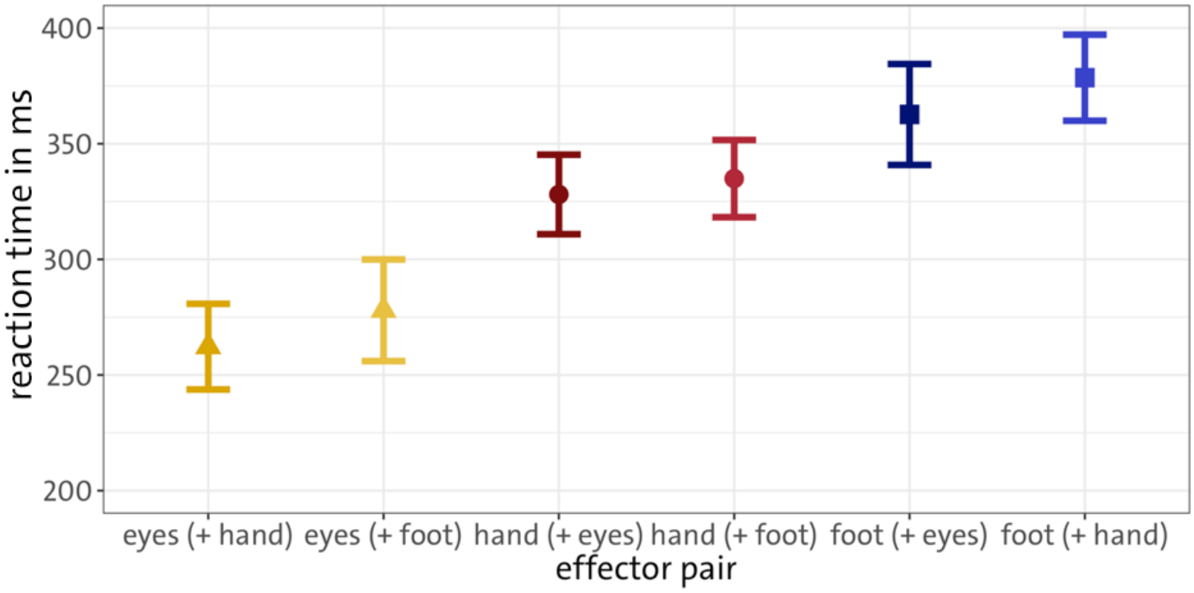

Figure 5.4. Reaction times of eye (yellow triangles), hand (red circles), and foot (blue squares) movement. In parentheses, the effector that accompanied the movement is indicated. Whiskers represent the standard error of the mean.

5.3.2 EEG

5.3.2.1 Event-Related Potentials

The ERPs locked to the onset of the cue showed an increase in negativity over medial fronto-central electrodes (C1, Cz, C2, FC1, FCz, FC2, F1, Fz, F2) approximately 500 ms post-cue in all conditions. Cluster-based permutation tests revealed a significant difference between effector pairs about 600 ms after the cue, being most pronounced preceding “hand + foot” and “foot + eyes” movements. The signal further diverged until the end of the trial.

Post-hoc comparisons (Figure 5.5) revealed a significant difference between the “hand + eyes” and “hand + foot” condition 500 ms after the cue at centro-parietal electrode sites. The conditions “hand + eyes” and “foot + eyes” differed significantly 600 ms after the cue. The comparison between the “hand + foot” and “foot + eyes” condition was only significant after 1200 ms. That is, simultaneous movements including the foot were preceded by more negative amplitudes than simultaneous eye and hand movements. These differences were most pronounced at electrodes Cz, C1, and C2 for all effector pairs. Thus, our results are in line with previous work (Miller & Gerstner, 2013), showing that participants successfully prepared movement with two different effectors at the same time.

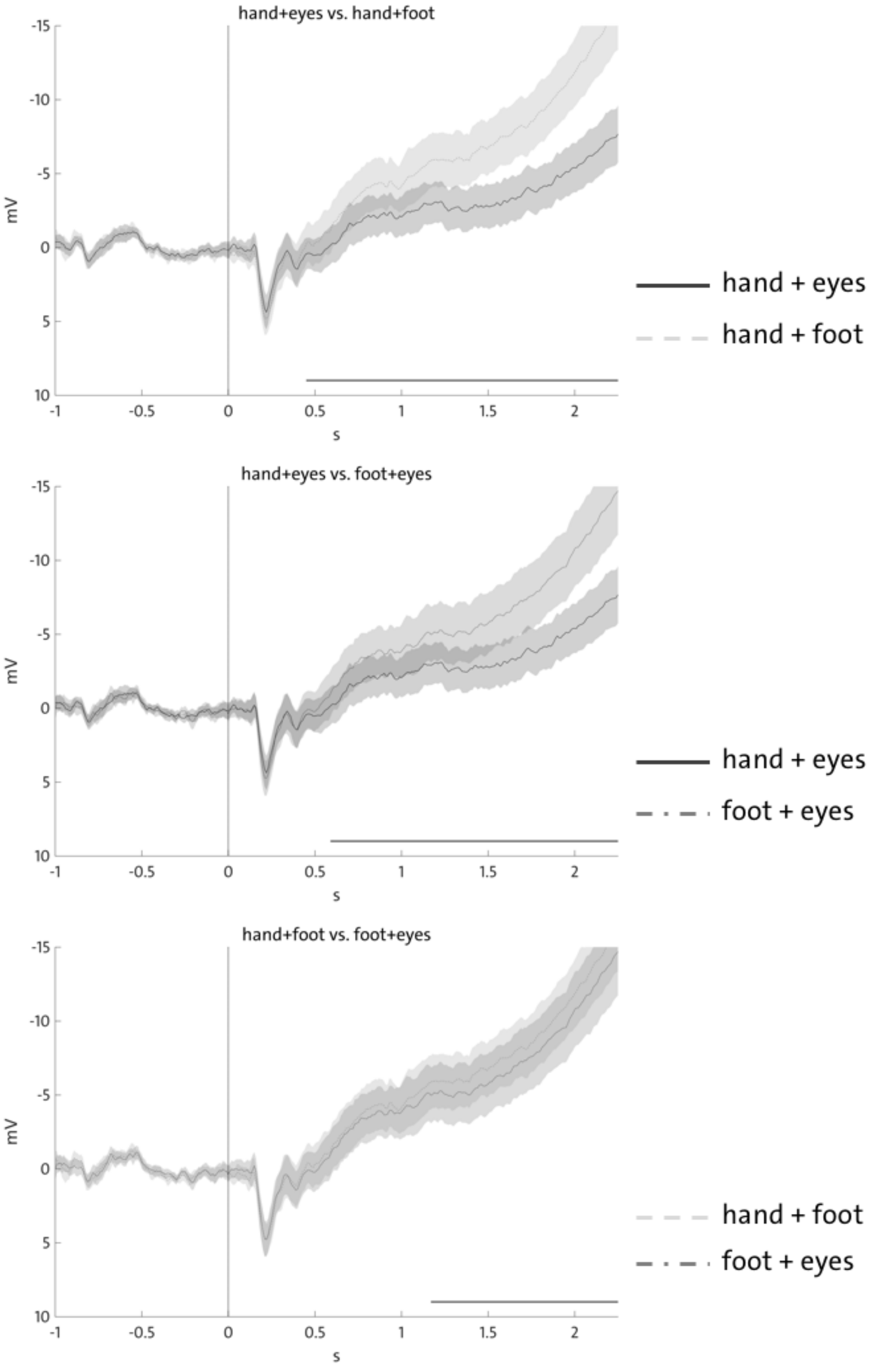

Figure 5.5. Post-hoc comparisons of the ERPs at Cz. Shaded areas represent the standard error. Vertical lines depict the presentation of stimuli. Gray horizontal lines mark significant differences between the conditions.

5.3.2.2 Time-Frequency Representations

Low Frequencies

In the range from 20-30 Hz, we observed a desynchronization over central electrodes in all conditions. There were no significant differences between the planning signal of movements to the left and movements to the right target. Thus, data were collapsed across both target sides.

Figure 5.6 depicts the topography of this desynchronization in all conditions. When “hand + eyes” movements were prepared, the power decrease was lateralized to the left hemisphere, resembling the typical somatotopic effect that occurs when right (i.e., contralateral) hand movements are prepared alone (top panel). When “foot + eyes” movements were prepared, the power decrease was localized over central cortex, resembling the typical somatotopy of foot movement preparation (middle panel). When “hand + foot” movements were prepared, these somatotopic effects seemed to be combined, reflected by a left lateralized and a central locus of desynchronization (bottom panel).

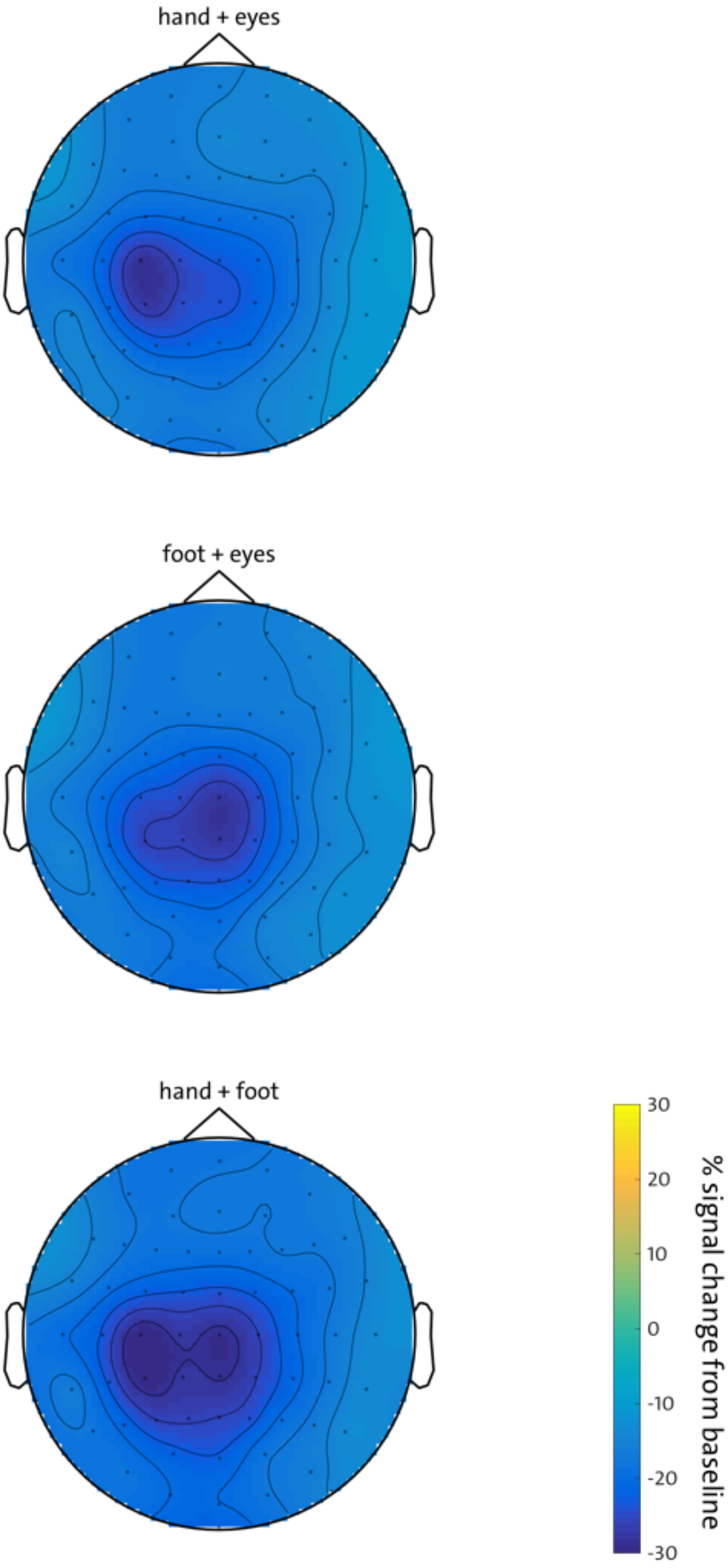

Figure 5.6. Topographies of oscillatory activity from 20-30 Hz during the delay (1.75 – 2.25 s). When hand + eye movements (top) were prepared, desynchronization lateralized the contralateral hemisphere. When foot + eye movements (middle) were prepared, desynchronization was medial. When hand+ foot movements (bottom) were prepared, two foci of desynchronization emerged.

High Frequencies

In the range from 60 to 80 Hz, we observed an increase in synchronization over central electrodes during movement planning for effector pairs including the foot, that is, in the “hand + foot” and the “foot + eyes” condition. The enhancement was most visible during the last 250 ms of the delay period (Figure 5.7). Figure 5.8 shows the average power increase from 60 to 80 Hz in all conditions at Cz for the entire delay period. Furthermore, synchronization increased bilaterally over posterior electrodes in all conditions, being strongest preceding “hand + foot” movements and weakest preceding “hand + eyes” movements (Figure 5.7).

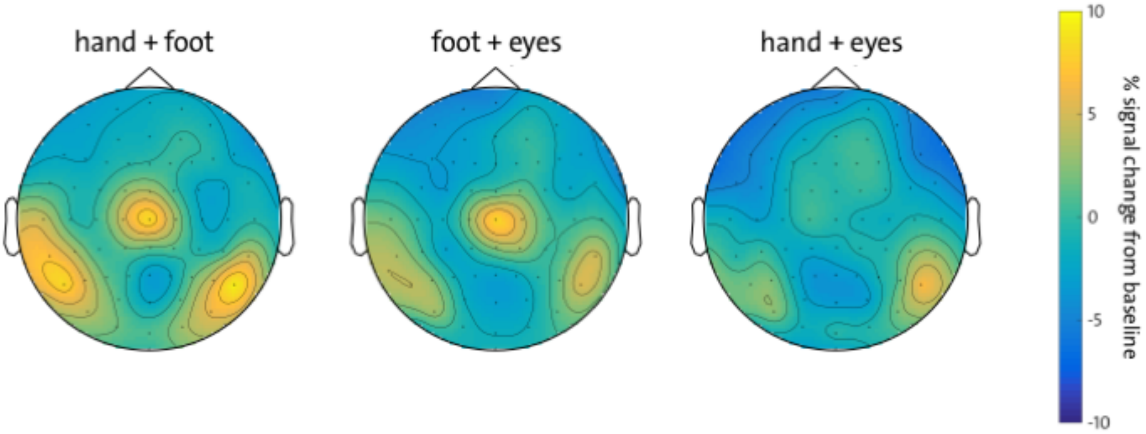

Figure 5.7. Topography of increased synchronization from 60-80 Hz at the end of the delay (2 – 2.25 s) for all effector pairs.

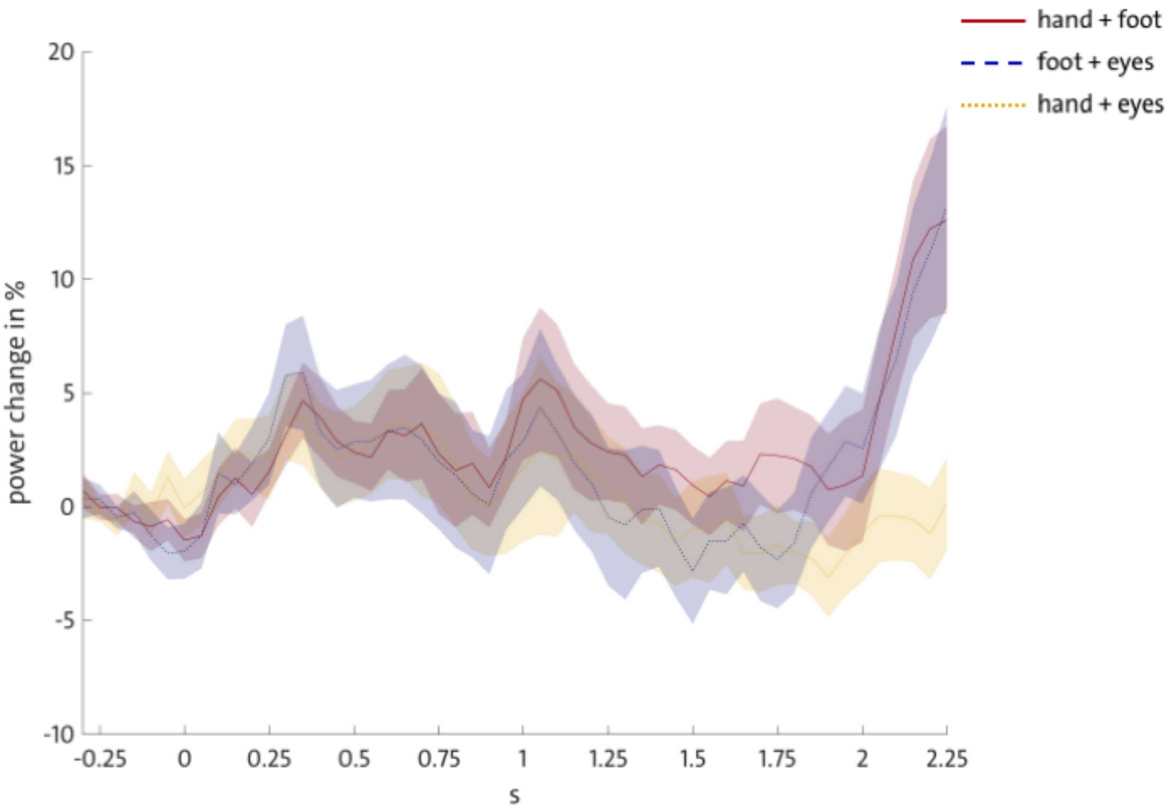

Figure 5.8. Average power change from 60-80 Hz at Cz throughout the entire trial for hand + foot (red, solid line), foot + eye (blue, dashed line), and hand + eye (yellow, dotted line) movements. Shaded areas indicate the standard error of the mean. Average power for effector pairs including the foot increases significantly at the end of the delay.

In the first analysis, we subtracted the signal of one target side from that of the other target side per effector pair (e.g., “hand to right + foot to left” minus “hand to left + foot to right”) and contrasted the resulting activity between hemispheres (Target X Hemisphere). By doing so, we aimed at unveiling distinct effector-specific frequency bands, which should initially be represented in the hemisphere contralateral to the reach target, within one comparison. However, none of the analyses revealed distinct modulations at any frequency. Figure 5.9 shows an example histogram of the permutation distributions for the Target X Hemisphere analysis in the “hand + foot” condition (two-sided tests; top row: largest negative cluster, bottom row: largest positive cluster). The dot indicates the cluster statistic (summed t-value) before permutation. If the summed *t*-values of the permuted data exceeded that of the original data, the comparison would be considered significant. However, the original cluster statistics lie well within the permutation distribution in all comparisons, that is, they likely resulted by chance (*p*-values of the largest negative and positive cluster, respectively: “hand + foot”, *p* = .99, *p* = .12; "foot + eyes", *p* = .99, *p* = .99; "hand + eyes", *p* = .99, *p* = .96). Thus, none of the statistical comparisons was significant.

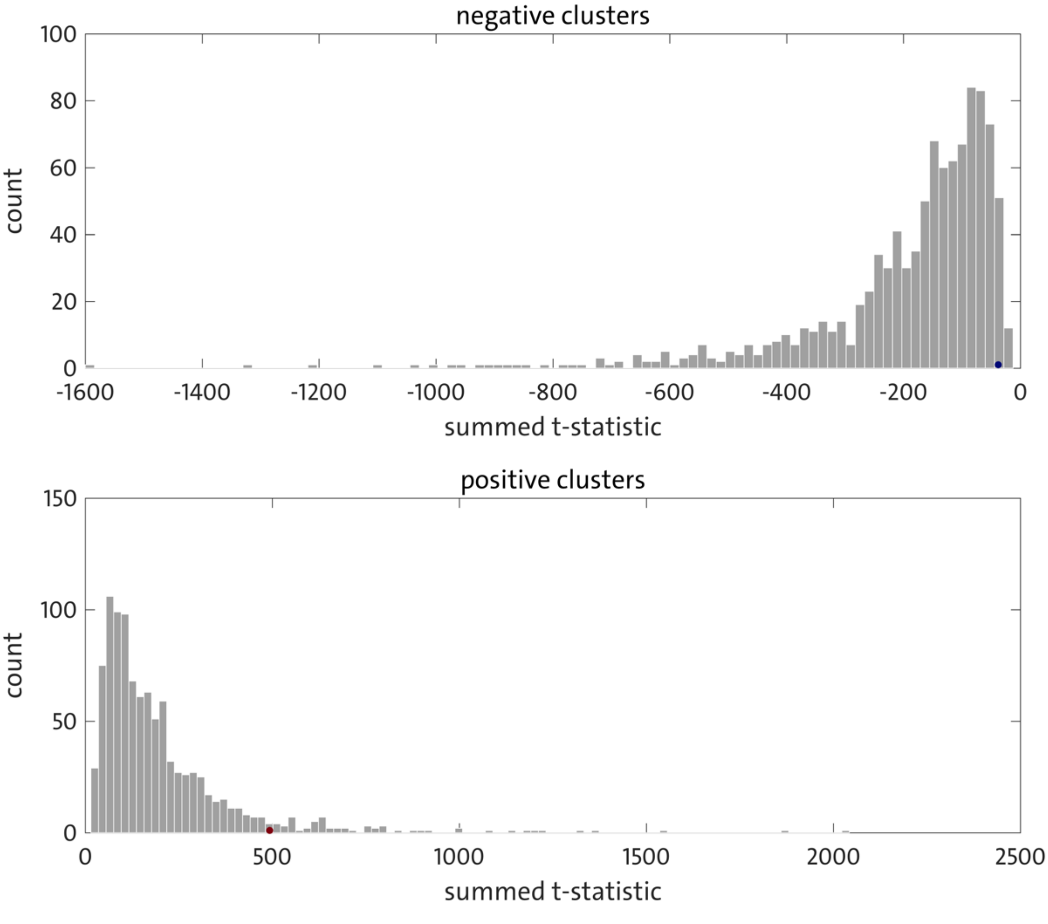

Figure 5.9. Histograms of permutation distributions of the Hemisphere x Target analysis for “hand + foot”. The top (bottom) row depicts the summed t-values of all negative (positive) clusters. The blue (red) dot indicates the original cluster statistic before permutation.

In the second analysis, we compared all effector pairs with one another, irrespective of target side. That is, activity related to the effector that was moved in both conditions, should cancel out (under the assumption that movement plans of two simultaneously moved effectors are independent). By doing so, we aimed at showing that the central synchronization from 60-80 Hz is unique to foot movement planning, and not contaminated by movement plans of uninstructed effectors.

Figure 5.10 shows the last 250 ms of the delay period for all comparisons. There was a central power increase from 60-80 Hz similar to that observed for foot movement planning only (study 3) when hand as well as eye movement planning were counterbalanced (i.e., “hand + foot” vs. “hand + eyes” and “foot + eyes” vs. “hand + eyes”). However, only the comparison of the “hand + foot” and the “hand + eyes” condition was significantly different (largest positive cluster, $p = .03$), with the former showing a larger enhancement of the gamma-band. When foot movement planning was counterbalanced by comparing activity in the “hand + foot” condition to activity in the “foot + eyes” condition, the central modulation was not evident (largest negative cluster, $p = .07$; largest positive cluster, $p = .99$). Thus, the central gamma modulation we previously observed is at least to some extent specific for foot movement planning.

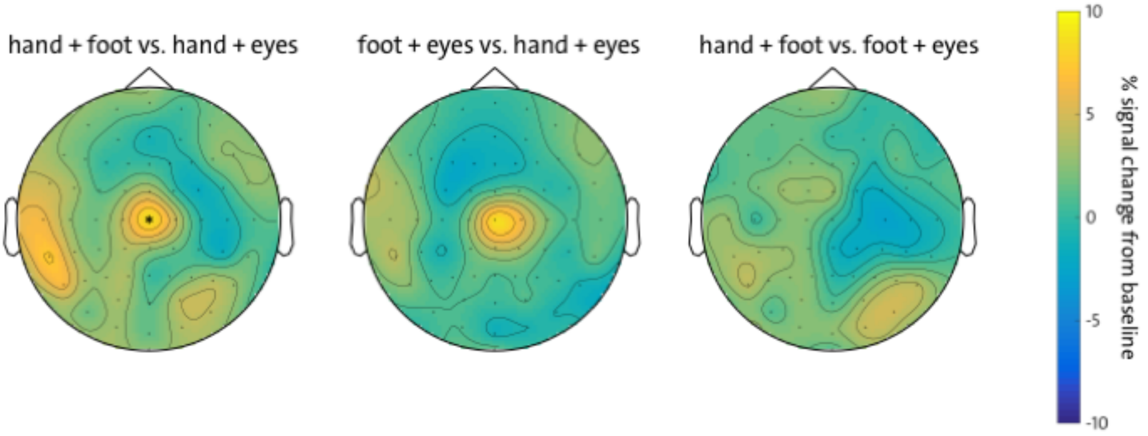

Figure 5.10 Topographies of comparisons between all conditions from 60-80 Hz at the end of the delay (2 – 2.25 s). Significant sensors are marked by asterisks.

Finally, we analyzed target-related activity in the “hand + eyes” condition in the same manner as van der Werf and colleagues (2010). Targets were recoded as ipsi- or contralateral with respect to each hemisphere, that is, movements to the left that were performed with the hand were coded as ipsilateral to the left hemisphere and as contralateral to the right hemisphere. The reverse is true for eye movements that were performed at the same time. When activity of ipsi- and contralateral targets were compared, no clear-cut modulations of the power spectrum became evident. We did not observe the specialization of frequency bands in the gamma range for one or the other effector, as reported by van der Werf and colleagues (2010). Figure 5.11 shows the permutation distribution of the cluster-based permutation test. As evident in the location of the original test statistic (marked by dot), there were no significant effects (largest negative cluster, p = .25; largest positive cluster, p = .99). Thus, their finding was not replicated in our current sample.

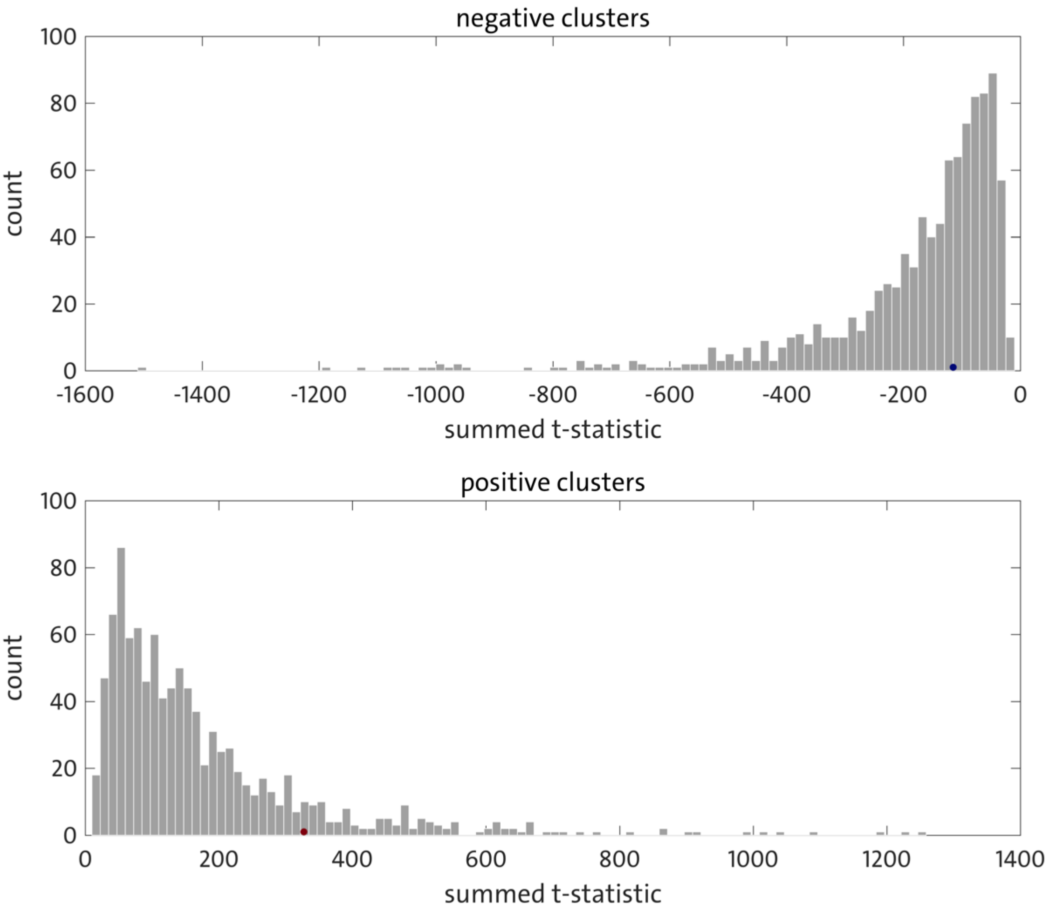

Figure 5.11. Histograms of permutation distributions of the comparison of ipsi- and contralateral targets for hand + eye movements. The top (bottom) row depicts the summed t-values of all negative (positive) clusters. The blue (red) dot indicates the original cluster statistic before permutation.

Source Reconstruction

We used adaptive spatial filtering techniques (beamforming) to estimate the sources of the oscillatory activity in the gamma-band that we observed on the sensor level. Figure 5.12 shows the results of the cluster-based permutation tests comparing the end of the delay interval (2 – 2.25 s) against baseline. The top panel depicts the reconstructed source of the increased synchronization preceding “hand + foot” movements in the range from 60-80 Hz. The peak of this activity was found in the left cerebellum (MNI coordinate with largest absolute z-value: -18, -80, -52, $z = 2.9$). The activity also spread across bilateral occipital cortex, covering extrastriate cortex.

The middle panel depicts the source of the increased synchronization preceding “foot + eyes” movements in the range from 60-80 Hz. The peak of this activity was found in the right occipital lobe, also covering extrastriate cortex (MNI coordinate with largest absolute z-value: 6, -96, 20, $z = 2.78$). The activity also spread across left extrastriate cortex.

The bottom panel depicts the sources of activity preceding “hand + eyes” movements in the range from 60-80 Hz. The peak of this activity was found in the left occipital lobe, again including extrastriate cortex (MNI coordinate with largest absolute z-value: -34, -96, -12, $z = 2.52$). This activity also spread across the right occipital lobe, though it was weaker than in the other two conditions. A second, negative peak originated from the left frontal lobe (MNI coordinate with smallest absolute z-value: -34, 32, 28, $z = 2.58$). This activity covered dorsolateral prefrontal cortex (dlPFC).

Thus, the source of activity in all conditions seems to lie in occipital or even cerebellar rather than parietal areas. This is somewhat surprising, as goal-directed movement planning has been shown repeatedly to take place in PPC. We will discuss the findings below.

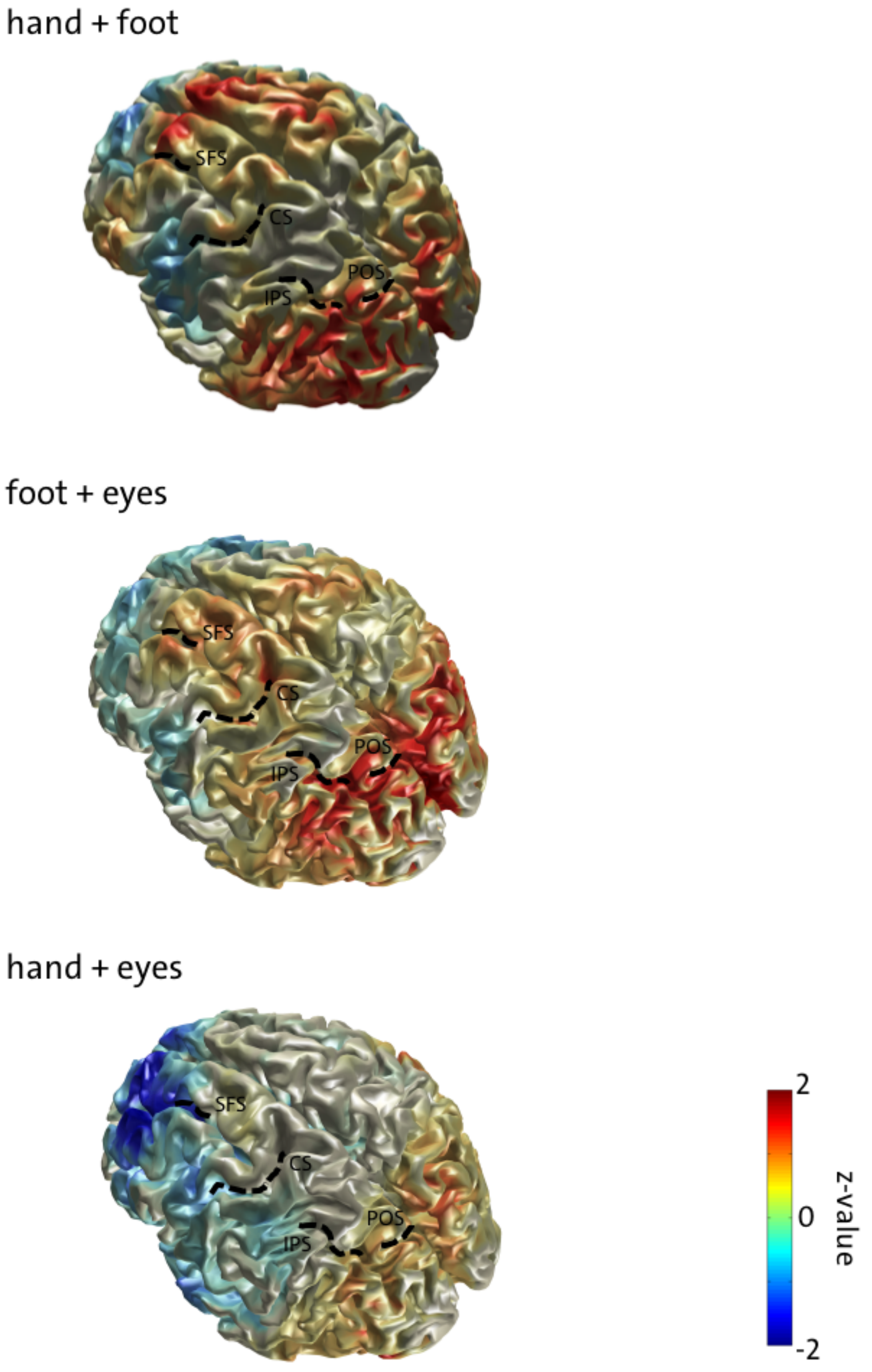

Figure 5.12 Reconstruction of the gamma-band sources from 60-80 Hz. The results of the cluster-based permutation tests (delay vs. baseline) were plotted onto the surface and masked at $z < 1$ for each effector pair. CS = central sulcus, IPS = intraparietal sulcus, POS = parieto-occipital sulcus, SFS = superior frontal sulcus.

5.4 Discussion

Experiments investigating effector specificity have typically compared activity preceding single goal-directed movements with one effector to that of another effector. Using such a design previously (chapter 4), we identified a unique modulation of the gamma-band during foot movement planning. In the range from 60-80 Hz, foot movements were preceded by a relatively higher synchronization than eye as well as hand movements at central electrodes. A complementary analysis of ERPs revealed a maximally negative CNV prior to foot movements, an intermediate amplitude prior to hand movements and a minimal amplitude prior to saccades at electrode Cz from about 500 ms post-cue until the end of the trial. However, this type of design bears some disadvantages. When single movements with one effector are cued, the possibility remains that movements with another, non-instructed effector are covertly planned in parallel (even though they are not being executed). The objective of the current study was, thus, to disentangle neural correlates of movement plans that are specific for one effector from those possibly related to movement plans of another. To this end, participants simultaneously performed delayed movements with two different effectors to targets in opposite hemifields while the EEG was recorded. The instructed effectors were either “hand + foot”, “foot + eyes”, or “hand + eyes”. We assessed behavioral parameters as well as ERPs and TFRs.

Overall, that is, independent of the second effector, RTs of the eyes were fastest, RTs of the hand were intermediate, and RTs of the foot were slowest. Reaction times with the hand as well as with the foot were generally slower when the effector was paired with another limb movement (i.e., with foot and hand, respectively) than when a limb movement was paired with an eye movement. Specifically, hand RTs were faster when the movement was paired with an eye movement than when it was paired with a foot movement. Similarly, foot RTs were faster when the movement was paired with an eye movement than when it was paired with a hand movement. Hence, the prolonged reaction times suggest that coordinating goal-directed movements of two limbs is more challenging than coordinating simultaneous movements of one limb and the eyes.

The coordination of movements with different effectors has been investigated in two lines of research: One investigating the coordination of limb movements (so-called inter-limb coordination) and one investigating the coordination of eye and hand movements. Although this was not our primary research interest, the dissociation task does indeed require the coordination of multiple effector movements. Most studies on inter-limb coordination have investigated bimanual coordination, that is, simultaneous movement with the left and right hand (for reviews see Oliveira & Ivry, 2008; Swinnen, 2002). Typically, movements are initiated slower, that is, reaction times are higher, when movements are performed with two hands as compared to one hand alone (Kelso, Southard, & Goodman, 1979). Furthermore, movements of the two hands are spatially coupled, as numerous studies show that symmetrical (i.e., mirrored) movements are easier to perform than asymmetrical (i.e., parallel) movements (Brandes, Rezvani, & Heed, 2017; Cohen, 1971; Heed & Röder, 2014; Kelso, 1984). Thus, simultaneous movements with two effectors are subject to spatial constraints.

Similar principles hold for the coordination of movements with non-homologous, ipsilateral limbs. Just like movements with two hands, simultaneous movements with one hand and one foot are constrained by spatial parameters. Rather than being biased to symmetry, however, the preferred movement direction is parallel in external space. That is, performance is better when hand and foot are both moving up at the same time than when one effector is moving up and the other down (Baldissera, Cavallari, & Civaschi, 1982). Thus, simultaneous movements with two different limbs are not independent from one another.

In our experiment, participants performed isolated rather than continuous movements, but the finding that RT depended on the effector combination suggests that these biases exist for isolated movements as well. RTs were substantially higher for combined movements than RTs of single limb movements, which we observed in our previous studies. Furthermore, onset of limb movement was significantly slower when paired with another limb as compared to being paired with an eye movement. Given that simultaneous hand and eye movements are tightly coupled to one another (Gielen et al., 1984), inter-limb coordination may, thus, be more effortful than eye-limb coordination.

In addition, we found a main effect of effector pair on MT. Crucially, movements with two limbs were slower than movements with one limb and the eyes. That is, MT in the “hand (+ foot)” condition was higher than in the “hand (+ eyes)” condition. Likewise, MT in the “foot (+ hand)” condition was higher than in the “foot (+ eyes)” condition. Even though MT could only be approximated in the “hand + foot” condition, these findings further support the notion that eye movements differ substantially from limb movements. One may argue that simultaneous limb movements are more difficult than simultaneous limb and eye movements. However, the results from our previous study suggest that movement difficulty does not affect the EEG measures we are primarily interested in. Rather, movement difficulty is reflected in posterior ERP components (cf. chapter 4).

Our analysis of ERPs served as a sanity check for successful movement preparation in our experimental design. ERPs in all conditions showed a pronounced negativity at central electrodes starting approximately 500 ms after the cue, that is, during the planning delay. The observed effects were strongest at electrode Cz, likely reflecting a modulated CNV (Miller & Gerstner, 2013; Walter et al., 1964). From 600 ms on, the CNV differed significantly depending on the effector pair. Post hoc-tests revealed the CNV of effector pairs involving the foot (i.e., “hand + foot” and “foot + eyes”) to be significantly more negative than the CNV in the “hand + eyes” condition. This difference became more pronounced towards the end of the delay. In addition, the CNV in the “hand + foot” condition was significantly more negative than those in the “foot + eyes” condition after about 1200 ms. In other words, foot movement planning seems to have to biggest impact on the combined CNV, as the difference between the conditions “hand + foot” and “foot + eyes” is smallest. These results are well in line with the study by Miller & Gerstner (2013), who reported ERPs preceding simultaneous hand and foot movements to closely resemble those of foot movements alone. In sum, we can conclude that participants successfully prepared simultaneous movements with different effectors.

Our second EEG analysis focused on oscillatory activity from 20-100 Hz. In a lower frequency range (20-30 Hz), we observed pronounced de-synchronization over central electrodes in all conditions throughout the planning delay. When “hand + eyes” movements were prepared, activity lateralized to the left hemisphere, that is, contralateral to the hand. When “foot + eyes” movements were prepared, activity was localized to medial electrodes, closely resembling the activity usually observed for foot movements alone (Pfurtscheller et al., 1997). Hence, when eye movements were paired with limb movements, the desynchronization matched the somatotopic representation of the limb alone. In case of “hand + foot” movements, we observed two foci of power decreases, likely reflecting a combination of the two limb representations. This supports our ERP finding that participants were preparing movements with both instructed effectors during the delay phase.

In the higher frequency range (60-80 Hz), we observed a distinct central power increase relative to baseline during the last 250 ms of the delay period for effector pairs including the foot. This modulation was not evident in the “hand + eyes” condition but was very similar in the other two conditions (i.e., “hand + foot” and “foot + eyes”). This enhancement bears a striking resemblance to the effect we observed for foot movement planning in study 3. Notably, it originated from the same electrodes as the modulated CNV. Further analysis of our data might reveal a correlation of the CNV amplitude and oscillatory power.

In addition, all conditions showed a bilateral increase in the same frequency range over posterior electrodes that was strongest in the “hand + foot” condition, intermediate in the “foot + eyes” condition, and weakest in the “hand + eyes” condition. In case of the “hand + eyes” condition activity was also localized more to the right hemisphere.

Source reconstruction suggested that the observed synchronization from 60-80

Hz originated from occipital areas. All effector pairs showed activity in bilateral extrastriate cortex. Located within extrastriate cortex is the extrastriate body area (EBA), which responds selectively to images of the human body (Downing, Jiang, Shuman, & Kanwisher, 2001). Furthermore, EBA is also activated during planning and executing movements (Astafiev, Stanley, Shulman, & Corbetta, 2004). When participants point to visual targets with their right hand or right foot, bilateral EBA shows an increased BOLD-signal. This response cannot be explained by attentional or sensory effects and even occurs when the to-be-used effectors were visually occluded (Astafiev et al., 2004). Crucially, EBA is not responsive to saccades, again supporting the notion that eye movements are fundamentally different from limb movements. In the present study, the eyes were moved simultaneously with either the right hand or the right foot. It might, thus, well be the case that EBA was activated in response to the upcoming limb movement.

Furthermore, activity in the “hand + foot” condition primarily originated from left, that is, contralateral cerebellum. The cerebellum plays a key role in motor control. One of its major functions is the coordination of multi-limb movements (Debaere et al., 2001a; Mauk, Medina, Nores, & Ohyama, 2000; Ramnani, Toni, Passingham, & Haggard, 2001; Thach, Goodkin, & Keating, 1992). Thus, it seems likely that the preparation of hand and foot movements to opposite hemifields recruited the cerebellum.

The source analysis also revealed a left frontal source in the “hand + eyes” condition, which was not evident in the other conditions. This activity likely originated from dlPFC. This structure has been associated with spatial working memory and action control (Cieslik et al., 2013; Leung, Gore, & Goldman-Rakic, 2002). More specifically, it is thought to be involved in the suppression of automatic saccade responses (for review see Munoz & Everling, 2004). Given that eye and hand movements are tightly coupled to one another (Gielen et al., 1984), it seems plausible that dlPFC was recruited during the preparation of dissociated eye and hand movements.

In order to disentangle frequencies representing movement plans for each single effector, we used three different approaches: First, we subtracted activity preceding movements to one target side from that of movements to the other target side per effector pair and compared the left to the right hemisphere. If targets are processed in the hemisphere contralateral to an effector and if a frequency-band specifically codes for that effector, power in the left hemisphere should increase for that frequency when movements to the right are being prepared and vice versa for movements to the left (i.e., power in the right hemisphere should increase). Because movements with two effectors were prepared and executed simultaneously, we expected to observe two effector-specific frequency bands evolving at the same time, one in each hemisphere. When subtracting target-related activity from one another for each effector pair (e.g. “hand to the right + foot to the left” – “hand to the left + foot to the right”), power in the frequency-band related to each effector should be decreased in one hemisphere, respectively. By then comparing left and right hemisphere to one another, effector-specific frequencies can be displayed within one comparison (now being relatively increased for one effector while being relatively decreased for the other). Contrary to our hypothesis, this first analysis revealed no effector-specific frequency bands.

Second, we compared activity preceding simultaneous effector movements irrespective of target side. By contrasting two different effector pairs, activity related to the effector that was part of both pairs is counterbalanced, under the assumption that the effector plans are independent from one another. For instance, when comparing “foot + eyes” to “hand + eyes” movements, activity specific for eye movement planning should cancel out, leaving a comparison of hand and foot movement planning (similar to study 3). Here, we observed the same foot-specific central increase from 60 to 80 Hz when hand as well as eye movement planning was counterbalanced (i.e., when comparing “foot + eyes” vs. “hand + eyes” and “foot + hand” vs. “hand + eyes”). Even though this finding was only significant when “foot + hand” and “hand + eyes” movements were contrasted, it corroborates our results from study 3 (chapter 4). The power enhancement between 60 and 80 Hz might, thus, be specifically involved in foot movement planning.

Conversely, the bilateral posterior increase we observed for all effector pairs was diminished when contrasting the conditions to one another. As suggested by the source reconstruction, this power modulation might reflect activity in the EBA, which is similarly strong for hand as well as foot movements.

Finally, we used an analysis approach suggested by van der Werf and colleagues (2010) for the analysis of the “hand + eyes” condition to make our data comparable to that previous study. Targets for hand movements were re-coded as ipsi- and contralateral with respect to each hemisphere (i.e., vice versa for eye movements) and the activity was compared (contra- vs. ipsilateral). However, our findings failed to confirm the previously suggested division of the power spectrum into hand- and eye-specific frequency bands.

One fMRI study identified a network that is involved in simultaneous hand and foot movements (Debaere et al., 2001a). Participants were asked to perform cyclical up- and down-movements with the hand, the foot, or both at the same time. Simultaneous movements were either made in the same or opposite direction. Simultaneous movements led to increased activation in a distributed network including the supplementary motor area, cingulate motor cortex, premotor cortex, primary sensorimotor cortex, and the cerebellum that exceed the sum of single effector activations. One possibility to further understand our data could be to assess connectivity between cortical areas in the frequency domain (Aru et al., 2015; Hipp, Hawellek, Corbetta, Siegel, & Engel, 2012; Nolte et al., 2004). Additional analyses of our data could reveal a similar network, possibly linking the effector-specific beta-desynchronization, which likely stems from M1, to the posterior increase in the gamma-band that originated from the cerebellum.

A drawback of the current study is the rather complex experimental setup. The task was very challenging for participants as evident in the low number of trials that entered the final analysis. In addition, the EEG showed a high number of artifacts, so that further trials had to be excluded. This resulted in low statistical power in most of our analyses and could thus explain the lack of significant effects in some cases. Nonetheless, we were able to pinpoint many interesting effects, both behavioral and in the EEG.

To conclude, we set out to identify neurophysiological correlates of movement plans that are specific for one effector while controlling for possible covert movements plans for another. In case of foot movements, we could corroborate the notion from our previous study that the central 60-80 Hz modulation is truly specific for this effector. In case of simultaneous eye and hand movements, however, movement plans are not as easy to decode in the frequency domain, presumably due to the close coupling of eye and hand movements.

6 General Discussion

We interact with our environment using different effectors with ease. The neural correlates of movement planning have been studied intensively by comparing eye and hand movements in non-human and human primates (e.g., Cui & Andersen, 2007; Gallivan et al., 2011; Snyder et al., 1997; van der Werf et al., 2010; Vesia et al., 2010). The majority of these studies suggest an effector-specific organization of PPC, with distinct sub-regions each serving the preparation of movements with a different body-part (Astafiev et al., 2003; Connolly et al., 2003; Fernandez-Ruiz et al., 2007; Filimon et al., 2009; Hinkley et al., 2009; Medendorp et al., 2005). However, a comparison of eye and hand movements is insufficient to draw conclusions about whether the effector of an action is a relevant organizational principle of movement planning in PPC, given that we cannot manipulate objects with our eyes. That is, most actions we typically perform with a hand can also be performed with another limb, but not with the eyes. Crucially, fMRI studies revealed overlapping parietal activity for hand and foot movement planning, raising the question of whether and, if so, how similar effectors, such as these limbs, are discriminated in PPC (Heed et al., 2011; Leoné et al., 2014). Thus, the objective of the current dissertation project was to scrutinize the presumed effector specificity of PPC by investigating foot movements in addition to eye and hand movements. Using motion tracking and EEG, we assessed delayed movements in four different studies.

6.1 Overview of our studies

The first study (chapter 2) aimed at identifying motoric principles that are common for both hand and foot. We assessed behavioral and kinematic parameters of movements with either effector. To control for physical differences between the limbs, we developed a delayed Fitts paradigm that manipulated the difficulty of a movement.

The second study (chapter 3) aimed at identifying electrophysiological signatures that specifically code for hand and foot movement planning. To this end we adopted our delayed Fitts task for an EEG setting.

In the third study (chapter 4), we used an optimized version of our delayed Fitts paradigm to identify effector-specific coding in both ERPs and oscillatory activity. In addition to hand and foot movements, we investigated whether saccades indeed show an electrophysiological signature that differs from the limbs, as would be expected from functional differences.

In the final study (chapter 5), we used a dissociation task to control for the following confound: When goal-directed movements are performed with a single effector, a movement with an uninstructed effector might be covertly prepared nonetheless, corrupting the observed signal. From a different perspective, the observed signal might also reflect attentional processes of where in space the movement is planned to. Hence, we asked participants to perform simultaneous movements with two effectors to visual targets in opposite hemifields. All combinations of the right hand, right foot, and eyes were possible. For instance, the hand reached and touched a target in the left hemifield while the foot moved and touched a target in the left. Our key findings and suggestions for further research will be presented in the following.

6.1.1 Behavioral principles of hand and foot movements

In all our studies employing the delayed Fitts paradigm, both hand and foot movements followed Fitts' law. That is, they were slower when directed at difficult as compared to easy targets. At the same time, the kinematic profile of both limbs was affected by target difficulty in a similar manner. We observed higher peak velocities and a shorter deceleration phase for movements to easy targets as compared to movements to difficult targets for hand as well as foot movements. Behavioral principles, such as Fitts' law, are viewed as an important characterization of how the brain controls hand movements. Indeed, this typical computational phenomenon can already be observed before movement onset, that is, during movement planning (Bertucco et al., 2013). Thus, our finding that the hand and foot share this basic processing principle suggests that movement planning for both effectors might also rely on common cortical mechanisms.

Another behavioral measure that could be used to further probe common motoric principles of hand and foot movements are so-called switching costs. Switching costs, which are typically defined as increased RTs, occur when participants have to switch effectors between consecutive movements (Rabbitt, 1968; Rosenbaum & Kornblum, 1982). In a previous study, participants were instructed to make sequential tapping movements with the index and the middle finger of the left and right hand (Trapp, Lepsien, Sehm, Villringer, & Ragert, 2012). Here, switching costs between fingers of different hands were higher than switching costs between fingers of the same hand. The authors argued that there might be a response conflict between fingers of both hands that is related to interhemispheric inhibition (IHI) between primary motor cortices. IHI is reflected in suppressed activity of ipsilateral M1 and is considered to facilitate movements with the contralateral effector (Ferbert et al., 1992). IHI decreases when sequential movements are overlearned (Perez, Wise, Willingham, & Cohen, 2007). Accordingly, switching costs between hands decreased after participants had practiced the motor sequence in the study by Trapp and colleagues (2012). There was still an advantage for consecutive finger movements of the same hand, however, suggesting that switching between effectors (here, fingers) of the same body side is easier than switching between effectors of different body sides.

Similarly, switching between two different effector systems results in increased RTs (Philipp & Koch, 2011). When participants had to switch between responses with hand, foot, or mouth (i.e., respond vocally) on a trial-by-trial basis in a simple numerical judgement task, RT increased when a different rather than the same effector was used in the trial before. The effect was independent of which other effector was used previously. For instance, switching between hand and foot responses had the same cost as switching between foot and hand responses (Philipp & Koch, 2011). Even though participants made responses with the limbs of either body side in that study, the potential cost for switching between left or right hand and left or right foot was not examined. Such an investigation would be interesting, however, because it could tell us more about the flexible use of different limbs in everyday actions.

Specifically, participants could be instructed to perform a movement sequence involving hands and feet of both body sides. Effectors could be cued by displaying lower and upper case letters (cf. Trapp et al., 2012). Ideally, cued movements would recruit homologous muscles in either limb, regardless of the effector system. This could be achieved by lifting the fingers and toes (dorsiflexion) or the palm and heels (plantar or palmar flexion) from a resting position. Following the rationale of Trapp and colleagues (2012), we would expect higher IHI and thus higher switching costs between movements with the left and right body side, irrespective of the effector. Crucially, switching costs between limbs on the same body side should be smaller than switching costs between the same limb across body sides. For instance, switching between the left and right hand should be more difficult than switching between the left hand and left foot. This hypothesis is supported by the finding that IHI also occurs across limb systems, that is, hand movements inhibit ipsilateral M1 representations of the foot and vice versa (Volz, Eickhoff, Pool, Fink, & Grefkes, 2015). Hence, this experimental setup could reveal a flexible use of hand and foot movements that might be facilitated by differences in IHI evident in switching costs. In other words, it would corroborate the notion that movements with different limbs are interchangeable to some extent.

6.1.2 Event-related potentials reflecting different parameters of a movement plan

In study 2 and 3, hand as well as foot movements were preceded by effector-specific modulations of central ERPs. In line with previous work, we found a more negative CNV for foot than hand movements (Jentzsch & Leuthold, 2002; Miller, 2012). In study 3, ERPs preceding eye movements were also marked by a negative deflection at Cz, which likely reflects the so-called pre-saccadic negativity. This effect is frequently observed prior to eye movements and is also considered to reflect movement preparation (Everling et al., 1997; Klostermann et al., 1994). Crucially, these central deflections coding for the to-be-used effector were unaffected by movement difficulty or side (i.e., movement direction). Rather, movement difficulty was reflected in ERPs over left parietal cortex preceding hand, foot, and eye movements. In line with an earlier study of hand movements, we found a more positive P3 over left parietal cortex in response to difficult as compared to easy targets for 400 ms post-cue (Kourtis et al., 2012). This modulation did not differ between effector conditions, suggesting common processing principles of movement difficulty for all effectors. In study 4, we found that the CNV was more negative when foot movements were performed together with an eye or hand movement than when eye and hand movements were combined. This suggests that movement plans for two effectors are coupled when simultaneous movements have to be coordinated. Taken together, our ERP results suggest that different parameters of a movement, such as the to-be-used effector(s) and movement difficulty, are specified at different temporal and spatial stages of movement planning. While central ERPs reflect which effector is going to perform a movement, parietal ERPs seem to reflect processes that encode effector-independent, visuospatial aspects of the movement, such as difficulty.

Even though our studies provide valuable insight into ERPs reflecting instructed movement planning with different effectors, they cannot inform us about the processes underlying freely chosen movements. However, actions in everyday behavior are typically selected autonomously. By using a paradigm that encourages choosing different effectors, we could assess ERPs reflecting the preparation of movements independently from external cues. This could be achieved with the matching pennies paradigm, which encourages choosing different effectors without following a strategy (Barraclough et al., 2004). More specifically, this paradigm only rewards choices that were not predicted by a specific algorithm. By associating effector choices with a reward or, in other words, higher value, a potential bias to preferentially use hand movements could be reduced. In such a scenario, we would expect to find ERPs reflecting the effector choice before the movement is executed. Whereas the CNV depends on the presence of cues, the so-called lateralized readiness potential (LRP) can be observed before movement execution independently from external stimuli (Frost, Neill, & Fenelon, 1988; Ruchkin, Sutton, Mahaffey, & Glaser, 1986). The LRP occurs at lateral central electrodes and distinguishes between hand and foot movements. Owing to the somatotopy of M1, the LRP preceding foot movements shows a reversed polarity (Böcker, Brunia, & Cluitmans, 1994a, 1994b; Brunia, 1980). Crucially, the LRP was shown to reflect the likelihood of choosing one hand over the other when the effectors were associated with a certain value (Gluth, Rieskamp, & Büchel, 2013). Hence, we could utilize the matching pennies paradigm to assign different values to hand and foot movements on a trial-by-trial basis in order to investigate processes reflecting effector choices.

6.1.3 Movement plans for different effectors in the beta- and gamma-band

In study 3, activity in the beta-band was marked by increased de-synchronization over central cortex preceding movements with either limb. This modulation was localized contralaterally preceding hand movements and medially preceding foot movements, reflecting the somatotopic organization of M1. When two effectors had to be moved simultaneously in study 4, this somatotopic de-synchronization was modulated depending on the to-be-used effectors. In case of simultaneous hand and foot movements, we observed two foci of central power decreases, which likely reflected a combination of the two limb representations.

Furthermore, the to-be-used effectors were discriminable in the gamma-band. In study 3, we found a relatively higher synchronization from 60-80 Hz over central electrodes when foot movements as compared to both hand and eye movements were prepared. The latter two differed in the range from 40-60 Hz, with a stronger desynchronization preceding hand as opposed to eye movements. Thus, each effector was marked by a unique modulation of the gamma-band. When foot movements were combined with hand or eye movements in study 4, we observed a central power increase from 60-80 Hz that bore a striking resemblance to the foot-specific effect preceding single effector movements. By contrasting the effector pairs with one another we were able to counterbalance activity related to the effector that was part of both pairs theoretically. This analysis revealed the same foot-specific power increase from 60-80 Hz when both hand and eye movement planning were counterbalanced. Thus, our results demonstrate a characteristic central enhancement of the gamma-band during foot movement planning across task contexts.

A central aim of these studies was to identify a frequency band that potentially dissociates foot from hand movement planning, based on fMRI studies that revealed overlapping activity for these limbs in PPC (Heed et al., 2011; Leoné et al., 2014). However, source reconstruction of the 60-80 Hz enhancement relative to baseline that preceded simultaneous movements did not project to parietal areas. Instead, bilateral occipital areas, most likely the EBA, were recruited during movement planning for all effector pairs. In case of simultaneous hand and foot movements, the cerebellum was additionally activated. Even though these findings are in line with work from others (Astafiev et al., 2004; Debaere et al., 2001b), the missing activation of PPC is puzzling. PPC has consistently been shown to be involved in movement planning for different effectors in the past (Astafiev et al., 2003; Fernandez-Ruiz et al., 2007; Filimon et al., 2009; Medendorp et al., 2005; van der Werf et al., 2010). Rather than concluding that PPC did not contribute to the effects observed here, we need to keep in mind that the analysis was based on a relatively low number of trials. Owing to the complex experimental settings, both the delayed Fitts task and the dissociation task were quite challenging for participants to complete. Many trials had to be excluded from the analysis because saccades were made in the same direction as limb movements. Another reason for a high number of trial losses were artifacts in the EEG. These were caused by general muscle tension that likely stemmed from the somewhat unusual seating position participants had to maintain. Thus, it might be the case that a potential source in PPC was too weak to be reflected in our studies, due to limited power of the analysis. Future EEG studies could use predefined regions-of-interest to unveil possible sources in PPC that contribute to movement planning with different limbs. In the following, further implications of our findings will be discussed.

6.2 fMRI reveals flexibility of movement planning with different effectors

More evidence for an effector-independent organization of PPC comes from a recent fMRI study that used repetition suppression (RS) to assess neuronal activity preceding movements with different effectors (Heed, Leoné, Toni, & Medendorp, 2016). RS is based on the finding that the BOLD response of an area is attenuated when a feature that neurons in this area are responsive to is repeated (Grill-Spector & Malach, 2001; Sawamura, Orban, & Vogels, 2006). It allows to infer the properties of different neurons in putative effector-independent areas. In this context, RS is quantified as the difference between activity in trials that were preceded by the same effector and trials that were preceded by a different effector. If neurons specialized for different effectors were intermingled in the area, RS should occur, given that trials with a repeated effector will show attenuation of the signal whereas trials with a new effector will not. If, however, neurons in the area responded equally well to all effectors, no RS should occur, as neurons would always be repeatedly active and the contrasted trial types would thus not differ. Following this rationale, Heed and colleagues (2016) identified a region in SPL, which likely contains neurons that contribute to hand as well as foot movement planning. Conversely, no region seemed to contain intermingled effector-specific neurons. Thus, SPL (which forms the superior part of PPC) seems to code movements indeed effector-independently.

On a related note, Beurze and colleagues (2009) found that effector-specific activity for eye and hand movements strongly depended on the current status of a movement plan. In their study, the visual target and the to-be-used effector were instructed sequentially, that is, one was cued before the other, and vice versa. When only the spatial goal of a movement was known, activity for eye and hand movement planning largely overlapped in a parieto-frontal network, including IPS. Crucially, virtually the same network was recruited when the effector was known first, regardless of which effector was to be used. Only when both parameters of the movement plan were specified, some areas showed a preference for one effector over the other, but none was exclusively active for eye or hand movements only (Beurze et al., 2009). Hence, IPS seems to encode a range of possible movement parameters before an explicit motor command is formed in M1.

This notion is supported by earlier work that assessed the influence of response probability on the BOLD signal during movement planning by means of a Go/No Go paradigm (Thoenissen, Zilles, & Toni, 2002). Participants were visually instructed to either flex their index or middle finger. The color of the cue predicted the response type (Go vs. No Go) with 75% validity. After a variable delay, a tone informed the participants whether they should execute (Go) or withhold (No Go) the response. Whereas precentral activity depended on the probability of executing a movement (Go > No Go), activity in IPS and SPL did not (Go = No Go). In other words, frontal activity seemed to reflect actual motor preparation while parietal activity seemed to reflect motor intention rather than the preparation of a specific response. Thus, PPC might encode a range of potential responses (here, execution vs. inhibition) before a movement plan is fully specified. On a similar note, it might encode different effectors that are potentially involved in the upcoming movement.

To sum up, different fMRI studies investigating movement planning support the idea that PPC flexibly codes different parameters of a movement plan, such as the effector, before the motor response is ultimately specified in frontal areas.

6.3 Connectivity between parietal and frontal motor areas

If PPC is indeed not organized according to effectors, the question arises of how parietal movement plans are translated into explicit motor commands in M1. If the same portion of PPC codes for hand and foot movements, the signal needs to be routed to effector-specific areas in M1 in order to successfully execute the movement. In their fMRI studies, Heed and colleagues (2011, 2016) found effector-independent areas in PPC to be connected with lateral, hand-specific M1 during hand trials, and with medial, foot-specific M1 during foot trials, suggesting a task-dependent routing of signals from PPC to M1. Thus, communication between parietal and frontal cortex seems to take place depending on the to-be-used effector.

A potential means of communication between effector-independent PPC and effector-specific M1 is connectivity in the frequency domain (Engel, Gerloff, Hilgetag, & Nolte, 2013; Schoffelen & Gross, 2009; Siegel, Donner, & Engel, 2012). For instance, the phases of a specific frequency can be correlated across different brain areas, which can be assessed using coherence measures (Fries, 2005, 2015). There can also be a correlation of different frequencies, so-called cross-frequency coupling (Canolty & Knight, 2010). Here, the phase of a low-frequency oscillation and the amplitude of a high-frequency oscillations in different regions are statistically dependent, suggesting a transfer of information between the two. Similarly, both phases or both amplitudes of different frequencies within or across regions can be coupled. Further analyses of our data could possibly reveal cross-frequency coupling between the gamma- and the beta-band. In this scenario, gamma-activity possibly originating from PPC could be coupled with effector-specific beta-decrease in M1, depending on which limb is going to be moved. In case of foot movement planning, activity from 60-80 Hz could be connected to medial sources of the beta-band. In case of hand movement planning, activity from 40-60 Hz could be connected to lateral sources of the beta-band. Thus, an assessment of cross-frequency coupling in our data could possibly reveal communication between the beta- and gamma-band coding for the to-be-used effector.

Putative functional connections between parietal and frontal areas can be probed by means of paired-pulse TMS (Koch et al., 2007; Rothwell, 2011). By stimulating PPC prior to ipsilateral M1, excitability of the latter is modulated both at rest and in a task-specific manner, as measured by MEPs (Koch et al., 2007, 2008). When Koch and colleagues (2008) applied paired-pulse TMS before hand movements to targets in either visual hemifield, only MEPs before movements to contralateral targets were affected. Similar results were obtained for reaching with limited vision but not for saccades, suggesting that the functional interplay between PPC and M1 truly reflects reaching and not just general spatial movement planning. This method provides an excellent opportunity to investigate whether PPC indeed flexibly contributes to movement plans of hands as well as feet. For instance, we could apply a first pulse to the effector-independent region in SPL identified by Heed and colleagues (2011, 2016), while participants prepare either hand or foot movements. A second pulse would be applied to hand-specific M1 in half of the trials and to foot-specific M1 in the other half. During M1 hand stimulation, MEPs at hand muscles should be increased by PPC stimulation only in case of hand movement instruction but not in case of foot movement instruction. During M1 foot stimulation, the opposite pattern should emerge: MEPs at foot muscles should be increased by PPC stimulation only when foot movements are instructed but not when hand movements are. If this was the case, we could assume that the functional interplay between PPC and M1 does indeed vary with the current effector.

In sum, different methods can be used to further investigate task-dependent connectivity between parietal and frontal motor areas. Whereas EEG can provide insight into the time course of communication, TMS can be used to causally infer connectivity between putative effector-independent areas within PPC and effector-specific M1.

6.4 Motor imagery and action observation as measures of movement planning

As aforementioned, a drawback of our studies was the high complexity of the instructed movements, which resulted in considerable trial loss. Even though we think that studies of action planning should try to make the assessed movements as realistic as possible, there are experimental workarounds avoiding movement execution that are worth to be considered. The most prominent accounts are motor imagery and action observation. During motor imagery, participants are asked to imagine themselves performing a movement. During action observation, participants typically watch movies of others performing movements.

Both imagined and observed movements seem to follow the same behavioral principles as executed movements. In an early study, Decety and Michel (1989) reported that participants took the same time for writing a sentence or drawing a cube, regardless of whether they imagined or executed the movement. Crucially, numerous studies have shown that Fitts' law (1954) is evident in motor imagery (Decety & Jeannerod, 1995; Maruff et al., 1999; Maruff & Velakoulis, 2000; Sirigu et al., 1996). In the classic tapping paradigm, imagined hand movement times were highly correlated with actual movement times (Sirigu et al., 1996). Similarly, imagined walking movements can be described by Fitts' law (Decety & Jeannerod, 1995). The same holds for observing more or less difficult movements of others. For instance, participants were asked to judge if a videotaped person could accurately perform movements to targets of varying size at different speeds. Indeed, movement times that were judged to be just possible scaled linearly with difficulty, that is, they followed Fitts' law (Grosjean et al., 2007). This finding was corroborated by a study with a patient suffering from a frontal lesion, who showed the same violation of Fitts' law when executing and observing movements (Eskenazi, Grosjean, Humphreys, & Knoblich, 2009). Thus, motor imagery and action observation appear to be governed by the same motoric principles as movement execution. It seems straightforward to suggest that an imagined version of our delayed Fitts paradigm could yield parallel results for foot movements.

Furthermore, motor imagery and action observation show modulations in the EEG that are similar to movement execution. For instance, one study investigated ERPs preceding executed and imagined hand and foot responses (Carrillo-de-la-Peña, Lastra-Barreira, & Galdo-Álvarez, 2006). Participants had to respond or imagine the response with either effector of the left or right body side in a flanker task (Eriksen & Eriksen, 1974). Here, an arrow indicating the response side was flanked with either congruent or incongruent stimuli, pointing in the same or opposite direction, respectively. In both congruency conditions, LRPs reflecting the to-be-used effector were observed. In case of incongruent flankers, however, LRPs first reflected the preparation of a response with the incorrect body side but reversed back to the expected polarity prior to movement execution. This held for hand as well as foot movements. Crucially, the same effect was evident for both imagined and executed movements. Though it was more pronounced in the execution condition, the LRP in the imagery condition reliably reflected whether stimuli were congruent or incongruent and which effector the movement was imagined with. That is, different parameters of a movement plan were encoded in ERPs during imagined movements that closely resembled those of executed movements. Likewise, observing actions was shown to result in similar motor-related ERPs as movement execution (Bozzacchi, Spinelli, Pitzalis, Giusti, & Russo, 2014). Thus, ERPs during motor imagery and action observation reliably represent processes related to actual movements. It might be interesting to assess whether imagined movements show the same ERP modulations reflecting movement difficulty that we observed preceding actual movements.

By means of functional imaging, both motor imagery and action observation have consistently been shown to result in cortical activation overlapping that of actual movement execution (Buccino et al., 2001; Ehrsson, Geyer, & Naito, 2003; Filimon et al., 2007; Lotze et al., 1999). This holds for hand as well as foot movements (e.g., Gerardin et al., 2000; Lafleur et al., 2002). In one fMRI study, activation during both imagined and observed hand movements were compared to that during executed movements (Filimon et al., 2007). All conditions showed substantial overlap in regions associated with movement control, including IPS and SPL, that is, key structures in the debate around effector specificity. Both executed and observed reaching movements recruited EBA. Recall that EBA contributed to movement planning of different effectors in our and other studies (Astafiev et al., 2004). Thus, these findings suggest that motor imagery and action observation recruit areas that are crucially involved in movement planning beyond primary motor cortex.

In sum, both motor imagery and action observation might be suitable accounts to scrutinize effector specificity in future studies. Rather than imposing a challenge on participants by instructing them to perform complex movements, one could ask them to imagine or observe movements with different effectors in varying task settings. By doing so, more trials could be included in the analysis, which might, for instance, reveal more subtle modulations of the EEG.

6.5 Conclusion

The research presented in this thesis demonstrates that movement plans for different effectors are more flexible than previously thought based on studies of reaches and saccades. Our comparison of hand and foot movements reveals a wealth of commonalities between these two effectors. These limbs share both behavioral and electrophysiological characteristics, underlining their ability to perform analogous goal-directed movements. At the same time, movement planning of different effectors can reliably be distinguished using both ERPs and frequency representations. Whereas the former likely originate from M1, the source of the latter remains to be determined.

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