The effects of walking on peripheral visual information processing in a MoBI dual-task setting: An ERP study

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Abstract

Processing visual information while walking makes up a large part of our everyday life. Impairments in one or both tasks could lead to negative consequences such as collision, falls or errors in the cognitive task. However the exact nature of this cognitive-motor dual-task is not yet fully understood. The goal of the current research was therefore, to investigate whether recently proposed assumptions of an walking-induced visual information processing of peripheral input were replicable, and whether this had an impact on task difficulty. A dual-task MoBI approach utilizing a cognitive-motor task was employed. 24 participants executed a visual discrimination task while concurrently executing varying motor tasks on a treadmill in a Gait Real Time Analysis Interactive Lab (GRAIL). Stimuli were presented on a screen at varying levels of eccentricities. The obtained results did not indicate a clear interaction effect between walking and peripheral vision. Significant results of an interaction between eccentricities and movement were only obtained in the ERP component P2 at parietal-occipital recording sites, while the components N1 and P3, as well as behavioural data remained insignificant. However, for these measures a significant effect of Visual Angle was found. Treadmill walking and the simple detection might not have induced realistic real-life demands which consequently made it difficult to examine the interaction of walking and peripheral visual information processing. Nonetheless, the positive modulation for the interaction of walking and peripheral angle found in the P2 component, calls for further investigations under a modified task setting.

keywords: Dual-task walking, peripheral vision, information processing**,** EEG, ERP.

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1 Introduction

When navigating through the grocery aisle, we might push our shopping cart, have our gaze fixed at the grocery list in our hands and simultaneously also scan the shelves for the items we have to buy. This requires cognitive processes that both focus our attention in a goal-oriented and endogenous (i.e., internally driven, top-down), way to complete our task, as well as exogenous (i.e., involuntary, bottom-up) mechanisms, that are caused by sudden sensory occurrences in the environment catching our attention (Hopfinger & West, 2006). While walking through our environment, we are therefore focused on our main goal, however, we also have to ensure a stable gait and remain attentive to our environment to avoid falling or collision. Situations like the supermarket example, in which individuals perform a visual-cognitive task while being in motion, are examples of dual-tasking and make up a large part of our everyday life (Beurskens, Steinberg, Antoniewicz, Wolff, & Granacher, 2016; De Sanctis, Butler, Malcolm, & Foxe, 2014).

Walking in complex and fast-changing situations requires our attention to be divided over a wide area of the visual field, namely from the central to the peripheral visual field, in order to integrate crucial information and navigate successfully (Staugaard, Petersen, & Vangkilde, 2016). Especially informational input from the visual periphery plays a key role in monitoring information and detection of objects, particularly when information tracking occurs in multiple locations simultaneously (Klostermann, Vater, Kredel, & Hossner, 2020). Peripheral vision is associated with low acuity (Strasburger, Rentschler, & Jüttner, 2011; Wolfe, O'Neill, & Bennett, 1998) and therefore, diminished accuracy in detection and discriminability of visual information (Carrasco, Evert, Chang, & Katz, 1995; Staugaard et al., 2016). However, sudden changes in the surrounding are registered via the periphery. It allows us to see the "whole picture" without moving our eyes or head and adapt to surprising events.

Even though there is evidence that locomotion has an impact on peripheral vision, the assumed outcome differs significantly. On the one hand, insights into the cognitive mechanisms of dual-task walking suggested that increasing task demands due to walking might even worsen peripheral vision's low acuity (Nenna, Do, Protzak, & Gramann, 2020; Staugaard et al., 2016). On the other hand, studies reported an enhancement of peripheral vision induced by walking (Benjamin, Wailes-Newson, Ma-Wyatt, Baker, & Wade, 2018; Cao & Händel, 2019).

Considering these contrasting findings and the relevance of visual information processing while being in motion in everyday life, an understanding of the underlying mechanisms of dual-task paradigms is thus crucial as performance deterioration in one or both tasks could lead to negative outcomes regarding safety and successful task completion

(Beurskens et al., 2016; Liebherr, Weiland-Breckle, Grewe, & Schumacher, 2018; Mirelman et al., 2014; Reiser, Wascher, & Arnau, 2019). Therefore, in the following sections, the interplay of walking and peripheral vision will be discussed utilizing a dual-task setting. To obtain a more detailed understanding beyond solely behavioural factors, relevant electrophysiological correlates of the key concepts will be examined. Lastly, the main assumptions of this research will be presented in the form of a research question and corresponding hypotheses.

1.1 Dual-task interference on walking and peripheral vision

Theories on mental workload and capacity sharing (Wickens, 1984) propose that performing more than one task could lead to a mismatch in available and needed cognitive resources – depending on the task demand – and might thereby cause too much demand on mental workload. Attentional and cognitive resources in dual-task situations have to be distributed over the tasks at hand by a limited-capacity parallel processor, resulting in dual-task interference to some extent (Wickens, 1984). More specifically, the extension of this limited-capacity theory – the multiple resource model (Wickens, 2002) – proposed that both processing and execution of a task depends on a variety of resource types, as opposed to just a singular information processing source. Henceforth, dual-task performance is determined by whether the to-be-performed tasks share a common resource pool and the degree of task demand that taps into the processing source (Wickens, 1984, 2002). Tasks dependent on the same limited cognitive resources are consequently impacted by a scarcity of attentional resources, with performance decrements as a function of increasing workload and task demand.

Furthermore, according to Kahneman's (1973) theory of selective attention, the allocation of attentional resources can be directed by the individual and thereby focused on prioritized tasks or objects, when faced with a scarcity of attentional resources. Characteristic for dual-task situations is that one of the tasks will be prioritized when task demands increase and therefore will receive more attentional resources (Yogev-Seligmann, Hausdorff, & Giladi, 2012). Studies investigating the concurrent performance of a visual-cognitive and motor task reported that performance in one or both task domains decreased when task demands became too complex and therefore demanding (Malcolm, Foxe, Butler, Molholm, & De Sanctis, 2018; Nenna et al., 2020; Protzak, Wiczorek, & Gramann, 2020). In line with the "posture first" strategy in which the motor task would be prioritized in order to avoid injuries (Shumway-Cook, Woollacott, Kerns, & Baldwin, 1997), cognitive-motor dual-task settings elicited diminished cognitive performance as reflected by increased reaction times, omission errors and missed targets (Beauchet, Dubost, Herrmann, & Kressig, 2005; Chong et al., 2010; De Sanctis et al., 2014; Reiser et al., 2019). Yogev-Seligmann, Hausdorff, and Giladi (2008) stated that

walking under demanding dual-task conditions will lead to deteriorating task performance because walking is not purely automated, but indeed requires higher-level executive functions and attentional resources to control and produce gait. Moreover, deficits in dual-task walking compared to single-task walking performance was mirrored in indicators of less stable and secure gait behaviour and postural stability (Al-Yahya et al., 2011; Beauchet et al., 2005; Beurskens et al., 2016; Pizzamiglio, Abdalla, Naeem, & Turner, 2018). When imposed with an interference task while walking individuals' walking speed and stride length was reduced (Beauchet et al., 2005; Beurskens et al., 2016; Pizzamiglio et al., 2018), and the time to make a stride increased with complexity (De Sanctis et al., 2014). Relating this to the framework of limited capacity (Wickens, 1984, 2002) and attentional resource allocation theories (Kahneman, 1973) the observed performance deterioration of cognitive-motor dual-task scenarios could be explained by a scarcity of attentional resources. In other words, within this theoretical framework, it can be concluded that concurrent processing of visual information and walking is likely to result in a dual-task interference with performance decrements in one or both tasks.

1.2 Walking-induced enhancement of peripheral visual information processing

Emboldened by animal studies that showed enhanced visual information processing in the periphery during locomotion (Dadarlat & Stryker, 2017), recent studies demonstrated that this observation could be partly translated to human cognition as they replicated the effects of enhanced vision during human treadmill walking in comparison to standing (Benjamin et al., 2018). Cao and Händel (2019) conducted a follow-up study and demonstrated that similar results could be obtained during natural walking. Participants were briefly exposed to a target stimulus – a disk with certain contrasts – appearing at different eccentricity levels and were instructed to press a button as soon as they detected the object (Cao & Händel, 2019). While walking, relevant electrophysiological and behavioural factors were strongly modulated by the surrounding contras and indicated a significantly stronger surround-centre interaction during walking compared to standing (Cao & Händel, 2019). Since contrast sensitivity in the periphery was increased in comparison to the centre field, the authors assumed that an altered peripheral vision processing could have shifted the surround-centre interaction when walking, leading to visual processing enhancement (Cao & Händel, 2019).

The studies by Cao and Händel (2019) and Benjamin et al. (2018) concluded that this enhancement was caused by a surround suppression effect due to locomotion, and stand in contrast to dual-task studies which reported performance decrements. Relating to the arousal theory which proposed that cognitive performance can be positively impacted by the right amount of arousal, it could be argued that dual-task walking trials elicited exactly optimal levels

of excitation that focused attention to the task at hand (Shumway-Cook et al., 1997). Shumway-Cook et al. (1997) explained that with optimal arousal of the central nervous system irrelevant or distracting events can be dismissed thereby allowing for executive capacities to focus on the necessary processes. Additionally, previous studies proposed that during locomotion, it seemed that the motion of surface elements from the surrounding – the optic flow – is slowed down which enhanced visual information processing (Pelah, Barbur, Thurrell, & Hock, 2015; Thurrell, Pelah, & Distler, 1998). Information of the peripheral field plays a crucial role for factors associated with navigation and motion perception, and holds important information about sudden changes in the environment (Stoffregen, Schmuckler, & Gibson, 1987; Strasburger et al., 2011; Warren, Kay, Zosh, Duchon, & Sahuc, 2001). Therefore, study findings indicating a walking-induced could be explained by the fact that locomotion could elicit optimal levels of arousal that could simultaneously filter out irrelevant information and enhance peripheral visual input.

1.3 Electrophysiological measures of walking and peripheral vision in dual-tasking

Notwithstanding the essential role of vision for human motor tasks, the current understanding of human visual information processing during locomotion is limited (Cao & Händel, 2019; Matos et al., 2020). Brain research over the past decades has substantiated that all forms of behaviour are generated in and controlled by the nervous system, and as a result are the product of brain activity (Van Leeuwen, 1976). Hence, all overt and covert behaviour will be reflected as electrical phenomena in the brain (Rubin et al., 2019; Van Leeuwen, 1976). Investigating overt behaviour with neuroimaging tools such as electroencephalography (EEG), therefore, provides valuable insights into the underlying mechanisms (Kasper, Cecotti, Touryan, Eckstein, & Giesbrecht, 2014).

Technological advancement of the past years has made it possible to record and examine neural states and changes in actively moving individuals using mobile brain or body imaging (MoBI) approaches (Gramann, Ferris, Gwin, & Makeig, 2014; Gramann et al., 2011; Gwin, Gramann, Makeig, & Ferris, 2010; Makeig, Gramann, Jung, Sejnowski, & Poizner, 2009). In the most recent of these approaches, a small, wireless and, portable EEG system was combined with tools to monitor bodily behaviour (Debener, Minow, Emkes, Gandras, & de Vos, 2012; Reiser et al., 2019). EEG is considered a reliable measurement tool as it has ample temporal resolution, is unobtrusive and non-invasive (2010). In their dual-task walking study, Nenna and colleagues (2020) presented visual stimuli via virtual reality and were able to show differences in performance and workload in varying natural walking motor tasks in an indoor setting. In other dual-task studies participants executed the cognitive-motor dual-task in a stationary motor

setting, such as on a treadmill or stationary cycle (De Sanctis, Butler, Green, Snyder, & Foxe, 2012; Malcolm et al., 2018; Pizzamiglio et al., 2018; Scanlon, Sieben, Holyk, & Mathewson, 2017) or outdoors during free walking (Reiser et al., 2019). MoBI, therefore, allows investigating the neural basis of resource allocation and cognitive information processing in complex and realistic dual-task situations, as opposed to traditional stationary EEG study conditions (Cao & Händel, 2019; De Sanctis et al., 2014; Malcolm et al., 2018; Reiser et al., 2019). Therefore, the current research employed a MoBI approach with the focus on three ERP components, that were considered relevant to assess visual information, mental workload, and attentional resource allocation capacities, namely visual N1, P2 and P3, in order to evaluate whether walking enhanced peripheral visual information processing.

1.3.2 The visual N1 component

The N1 is the first negative visually evoked potential that peaks first over anterior and then posterior scalp areas around 150ms – 200ms post-stimulus (Vogel & Luck, 2000). This component is elicited by visual stimuli and therefore serves as a neurophysiological marker to assess early visual information processing (Vogel & Luck, 2000). Findings obtained by Haider, Spong, and Lindsley (1964), suggested that the amplitude of N1 is negatively correlated with degrees of accuracy and attention. Investigating the exact nature of N1 amplitude, Vogel and Luck (2000) discovered that the visual N1 is the product of generalised discrimination processes within the area of attention and therefore, reflects visual information processing. Furthermore, early research into N1 has demonstrated that shifts in its latency visualize processing efforts associated with the stimuli at hand (Callaway & Halliday, 1982; Luck, Heinze, Mangun, & Hillyard, 1990). With increasing effort to process the visual perception, N1 onset, peak and offset occur significantly later (de Tommaso et al., 2008; Gazzaley et al., 2008; Nunez, Vandekerckhove, & Srinivasan, 2017). In dual-task studies, N1 amplitude has been shown to decrease when the cognitive and postural modalities of the tasks were competing for attentional resources, such as in the case of perturbation (Little & Woollacott, 2015; Quant, Adkin, Staines, Maki, & McIlroy, 2004). The authors inferred that individuals needed to simultaneously process visual input related to the cognitive and the complex motor task, creating an imbalance of available attentional resources (Little & Woollacott, 2015; Quant et al., 2004). Therefore, the N1 might well be a reliable neural marker to indicate whether the motor task was too demanding and therefore interfered with the visual information capacities or in fact enhanced it.

1.3.4 The visual P2 component

The visual P2 component is the second positive deflection in the ERP wave evoked by visual input, typically peaking between 200ms – 300ms at the fronto-central and parietal-

occipital regions of the scalp (Liebherr et al., 2018). P2 has been regarded an indicator of information processing of somatosensory (Maeno, Gjini, Iramina, Eto, & Ueno, 2004) and which impacted the ease of resource allocation (Allison & Polich, 2008; Johannes, Münte, Heinze, & Mangun, 1995; Maeno et al., 2004; Sugimoto & Katayama, 2013). The P2 latency decreased when stimuli enhancing factors, for instance luminance, were positively modulated, confirming the notion that the P2 is evoked by visual input and reflects an early attentional and perceptual processing ability (Johannes et al., 1995). Further, P2 amplitude was shown to be connected to the amount and ease with which participants allocated attention to the stimuli (Johannes et al., 1995). This is something that is modulated by stimulus intensity (Crowley & Colrain, 2004) and task difficulty (Allison & Polich, 2008; Sugimoto & Katayama, 2013). Both simple visual detection single-task studies (Maeno et al., 2004), as well as complex dual-task examinations (Allison & Polich, 2008; Huang & Hwang, 2013; Sugimoto & Katayama, 2013) have shown that P2 amplitude decreased when task difficulty increased. Existing findings, therefore, indicated that the P2 component is a sufficient neurophysiological marker to assess early perceptual and attentional processing.

1.3.5 The P3 component

The P3b component (referred to as the P3 in the following) is a large positive ERP component peaking around 300ms - 500ms after stimulus onset predominantly over the parietal areas of the scalp (Kok, 2001; Van Dinteren, Arns, Jongsma, & Kessels, 2014). In general, the P3 component is regarded as a reflection of central processing stages, reflecting experienced task difficulty, resource allocation (Sirevaag, Kramer, Coles, & Donchin, 1989), and stimulus perception, evaluation and categorization (Kok, 2001; Polich, 2004). A short latency and high amplitude have been validated as a reflection of superior and successful information processing capabilities (Kok, 2001; Polich, 2004; Van Dinteren et al., 2014). When individuals were exposed to resource competing, complex situations, such as dual-tasking, the P3 amplitude of the secondary task decreased with increasing task difficulty in the primary task (Kelly & O'Connell, 2013; Malcolm et al., 2018; Nenna et al., 2020; O'Connell, Dockree, & Kelly, 2012; Protzak et al., 2020; Reiser et al., 2019). Furthermore, with increasing task difficulty or difficulty in categorization processes resulting in increased information processing time, P3 latency is shown to increase as well (Kok, 2001; Sirevaag et al., 1989). Opposing the stimulus evaluating and context updating theory, a different interpretation proposed that P3 is rather the product of higher-order functioning signalling the made decision based on the stimulus evaluation and not the evaluation itself (Verleger, Jaśkowski, & Wascher, 2005). More specifically, P3 is viewed as a monitoring process coordinating perceptual information

processing, decision making and the appropriate responding (Verleger, 1988; Verleger et al., 2005). However, study results remain inconclusive about the processing indications of P3 (Verleger et al., 2005), and rather imply that P3 might be a cumulation of different cognitive operations (Van Dinteren et al., 2014). Nonetheless, existing research has shown that a decreased P3 amplitude and prolonged latency are sufficient neurophysiological markers to assess experienced task difficulty and resource allocation.

1.4 The aim of this Study

This research aimed to quantify the relationship between walking and peripheral information processing using a MoBI dual-task approach, thereby allowing for a real-time-assessment of visual information processing and mental effort during locomotion. The goal was to investigate if recently proposed assumptions of an walking-induced visual information processing of peripheral input were replicable (Benjamin et al., 2018; Cao & Händel, 2019). Further, demands on mental workload were also investigated to examine whether the visual information processing enhancement also eased task difficulty in the dual-task setting and consequently improved cognitive task performance.

Therefore, the study focused on the following research question: *To what extent can dual-task walking enhance early perceptual and attentional processes in the peripheral visual field and thereby ease task difficulty and mental workload in active dual-task situations?*
In order to test this, participants executed a visual cognitive task with stimuli presented on a screen at varying levels of eccentricities, categorized as central and peripheral angles (*central* and *peripheral* condition) while parallelly executing a motor task with differing levels of locomotion. Based on previous research findings following hypothesis and predictions were derived:

H1: Processing of peripheral visual information from the periphery should be enhanced due to walking.

P1: The walking-induced enhancement should be reflected in behavioural indexes of performance in the cognitive visual task, namely as decreased reaction times and increased response accuracy.

P2: If walking enhanced peripheral visual information processing, this should be reflected in increased early perceptual processing and attentional capacities, namely as increased amplitudes of the ERPs N1 and P2.

P3: If walking trials facilitated early perceptual processing and attentional capacities of peripheral visual targets, then this should support successful resource allocation and decrease mental workload, reflected as an increased amplitude of P3.

2 Methods

The study was approved by the Ethics Committee of the Leibniz Research Centre for Working and Human Factors and all procedures were executed following the Declaration of Helsinki. Prior to entering the study all participants read and signed a written informed consent (see Appendix I). They were assured about their anonymity and informed that participation is on a voluntary base.

Due to the special circumstances of the Covid-19 outbreak, all participants were required to sign a Covid-19 information sheet and declaration about their physical health state. Moreover, a contact traceback document and information sheet to report infections with Covid-19 initially after the experiment were handed out.

2.1 Participants

A sample of 24 right-handed healthy participants (12 female, 12 male) in the age range of 18 to 33 years *(M = 24.5, SD = 3.09)* took part in this study. The study was published on social media groups for study participant acquisition and to the study listing of two local universities to recruit participants. Potential participants were also sampled by approaching known participants from IfADo's data bank and by referral from staff and individuals who already participated in previous studies. All participants had normal to corrected vision and reported no prior or present neurological or psychiatric conditions. Further, as the experiment was conducted with instructions given in German, all participants had to be native German speakers or at least excel at a fluent level. In order to assure qualitatively good EEG recordings individuals with hairstyles or skin conditions on the scalp that might prevent good signal quality, were excluded from participation. For this study, participants received either monetary compensation of 10€ per hour or were credited subject hours for their university course.

The study also had exclusion criteria restricting individuals to participate in the study that were not related to the study's subject or design at hand but with safety measurements, thereby excluding individuals who have been in contact with Covid-19 patients and who either lived in or travelled to areas where Covid-19 infection rates were above a certain threshold. Even though recent studies (Scheid, Lupien, Ford, & West, 2020) have shown that face-mask do not negatively impact performance and respiration during physical activity participants were still given the choice to execute all tasks either wearing the medical face mask or to take it off.

2.2 Design

For the MoBI approach, the motor and cognitive task were performed in parallel, which meant that participants had to attend to both tasks simultaneously and equally. The cognitive task, was divided into two conditions, one with one ring and the other with five rings. The

current research focused only on the analysis of the one-ring condition. Each level of the cognitive task was combined with a level of the motor task, resulting in six condition blocks with a total duration of 10 minutes. The block sequence of the task combinations was quasi-randomised based on the Latin Square Design of Experiments using six factors. Administration of the block sequences was counterbalanced across participants. The experiment used a 3x3 within-subject design. The independent variables were Movement Complexity of the motor task and eccentricity levels of Visual Angle at which the visual stimuli was presented on the screen. Of particular interest for this study was the interaction effect between these two independent variables. As behavioural dependent measures, reaction time (RT) and accuracy rate (AR) were assessed and analysed. For the electrophysiological markers, the dependent variables were the ERP components N1, P2 and P3.

2.3 The Cognitive-Motor-Task

The cognitive task was a visual discrimination task in which participants had to carefully monitor a sequence of stimuli and respond as quickly and accurately as possible. Participants were presented with one Landolt-C and had to discriminate the orientation of the opening. When presented with the Landolt-C, participants determined the location of the ring first and then distinguished whether the opening of the ring was oriented either to the bottom or the top, without moving their head or taking their eyes off the centre of the screen. The sequence started with the presentation of a fixation cross, then followed by the stimulus. After each stimulus presentation, participants were shown the fixation cross again. As one object of this study was to investigate whether information presented in the peripheral visual field will be processed better while in motion, 300 stimuli randomly appeared either in the central visual field at 0° or the peripheral one, and divided into slightly peripheral 18° and peripheral 40° angles relative to the fixation cross at the screen centre. Once the stimulus was detected and processed, participants responded via button press of the custom-made controller (see Figure 1a for visualisation of the custom-made controller). As a means to control for bias towards one hand, the responses were given in two-button conditions. In one condition, the right button needed to be pressed for Landolt C openings on top, and the left button for openings on the bottom. In the second condition, this process was reversed. These two conditions were counterbalanced across participants, with participants being quasi-randomly assigned to one of either.

The motor task was executed on the treadmill and was divided in three levels of motor complexities, namely standing (ST), walking (WA) and perturbation (PE). In the WA condition the treadmill was pre-set to a speed of 1.2m/s. In PE trials participants walked at the same speed with perturbations caused by a swaying motion of the treadmill to the left or to the right

in a random sequence. These perturbations always occurred at the same time as stimulus presentation.

a)

b)

c)

Figure 1. A visualisation of the mobile set-up of the experiment and the GRAIL. **(a)** This depictions shows the participant wearing the mobile 64 active Ag/AgCI electrode system, the safety harness and 26 reflective markers placed on pre-defined positions of his body. In each hand, he held the self-made response controller which is operated by thumb pressing. **(b)** In this image the same participant can be seen, shown in profile and placed in a clearer depiction of the GRAIL. Presented on the screen, was the white fixation cross, set to the preferred height, centred across the vertical line on the screen. The participant was secured to the safety cord dangling from the ceiling via the safety harness he was wearing under the backpack. This picture also shows one of the 12 infrared cameras at the edge of the treadmill. Both pictures were taken after the successful conclusion of the experiment and were published with obtained written consent of the participant. **(c)** At the core of the GRAIL the treadmill was placed within a 180° semi-cylindrical LCD-screen. Surrounding the treadmill and screen, 12 infrared cameras were installed at the square-formed scaffold. The experiment could be monitored by the experimenter and the technician from the computer set-up in the right bottom corner.

2.4 Materials and Equipment

2.4.1 Equipment for MoBI approach

This study was carried out in the Gait Real Time Analysis Interactive Lab (GRAIL, Motek Forcelink BV, The Netherlands) on the premises of the Leibniz Research Centre for Working Environment and Human Factors at TU Dortmund (IfADo), with data being collected from August to November 2020. To successfully record brain activity whilst being in motion, the mobile experimental set-up, MoBI, was employed, as depicted in Figure 1a and Figure 1b. At the core of the GRAIL system was the dual-belt instrumental treadmill, embedded with two individual force plates. The treadmill was placed within a 180° semi-cylindrical LCD-screen (5m x 2.9m), with a distance of 1.4m to the edge and 2.4m to the centre of the treadmill. Surrounding the screen and the treadmill, 12 infrared cameras (Vicon-capture system, Oxford)

were installed in order to capture any movement of the body by the reflective movement markers as shown in Figure 1c (Motek, Forcelink BV, The Netherlands, 2020). Participants were equipped with a custom-made response handle with buttons for each hand and a backpack for the duration of the experiment. In this backpack, they carried the recording mobile EEG LiveAmp amplifier 64 paired with the Wi-Fi Receiver, LiveSensor and Trigger Extension (Brain Products GmbH, Gilching, GER) and two power banks.

2.4.3 EEG data acquisition

A mobile 64 active Ag/AgCI electrode system was used to acquire EEG using the international 10-20 system. The acticap, a tight-fitting but flexible cap with electrode holders, was made of a breathable mesh to limit sweating and fitted over the subject's head. Prior to the study participants reported their head size in circumference so that the appropriate EEG cape (sizes ranged from 54cm to 60cm in circumference) could be plugged with the electrodes beforehand. Electrodes were online referenced to FCz and grounded to AFz. All electrodes were filled with conductive gel to make sure impedances were equal to or below 10kΩ. EEG Data was recorded using two joint LiveAmp 64 amplifier (Brain Products GmbH, Gilching, GER) with a built-in gyroscope to register head movements. The amplifier recorded at a sampling rate of 500Hz and a bit depth of 24 bit. For a detailed version of the EEG data acquisition see Appendix 6.

2.4.3 Visual stimuli for cognitive task

The visual stimulus, Landolt-C, was programmed and controlled via the visual programming tool D-Flow (Motek, Forcelink BV, The Netherlands). At the start, participants were presented with a white fixation cross in the centre of the screen, followed by the stimulus, see Figure 2 for a visualisation of this sequence. The stimulus consisted of a white Landolt-C (circle line width: 3cm, opening width: 3cm, diameter: 15cm), as used in eyesight tests, with the opening of the Landolt-C either to the top or bottom. The stimulus was presented on a black coloured screen, appearing randomly on any position along the mid horizontal line of the screen. Stimulus were categorized in peripheral (angles: -40°, -18°, 40°, 18°) and central (angle: 0°) visual field targets. Participants were instructed to keep their gaze fixated at the centre, and therefore stimuli were detected peripherally without the movement of the eyes. This was crucial to compare detection and attentional differences across peripherally and centrally presented stimuli. Participants were shown both the stimulus and the fixation cross for a duration of 250ms with interstimulus intervals lasting between 1250ms to 1750ms.

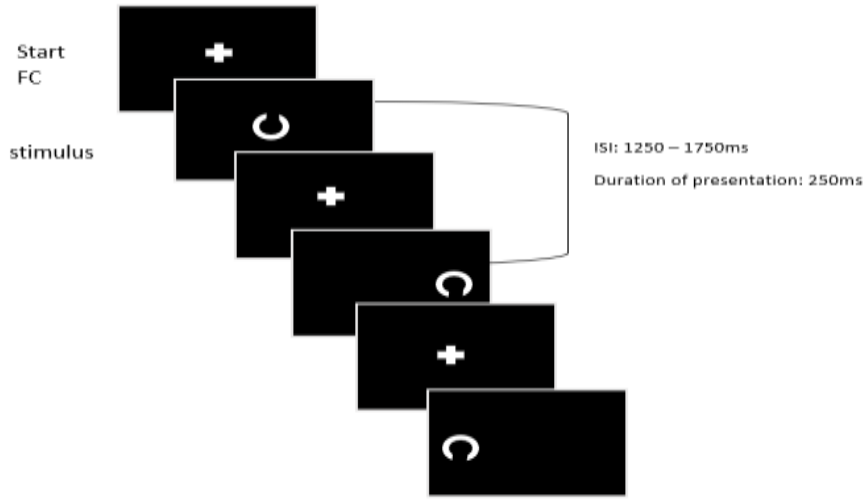

Figure 2. A schematic overview of an example sequence. At the beginning of each trial, a fixation cross (FC) was presented for 250ms at the centre of the screen. The hight of the fixation cross was set to eye-level of the participant according to his or her preference. The stimuli appeared on a random position along the horizontal centre line on eye-level with the participant. These positions were categorized in peripheral visual field and central visual field targets. The interstimulus-interval (IS) was between 1250 and 1750ms.

2.5 Procedure

All experiments were carried out in the morning to prevent bias as research has shown that performance in motor and cognitive tasks can vary depending on circadian differences and the time of day of the task execution. participants arrived at the institute by 9.00am at the day of the experiment. All measurements were obtained in one session. Upon arrival all participants were handed the study's information sheet (see Appendix 1) to read and signed the informed consent (see Appendix 2). Following that, participants filled out a questionnaire regarding demographic information (see Appendix 3) and were given the opportunity to visit the restrooms. Subjects were advised in advance to wear comfortable sports wear and shoes for their own convenience and safety. In addition, it was deemed necessary that the clothes should be a tighter fit and had no reflective portions to prevent any distortion of the 3D-model. To control for reflective properties of clothing or equipment, participants were asked to put on the safety harness and step on the treadmill. In the dimmed lab, it was now possible to check whether any part of the clothes, shoes or the equipment was reflecting light. Next, the EEG acticap (actiCAP Slim electrodes & actiCAP Snap cap, Brain Products GmbH, Gilching, GER) was put on and prepared. The two EEG amplifier were stored in the backpack and put on the participant's back. After that, 26 reflective movement markers were placed over the participant's body on specific bony landmarks in accordance with a predefined human body model (HBM, see Appendix 5). The participants were then strapped to the ceiling security cord with their safety harness. An explanatory walkthrough of the GRAIL was given to make the

participants familiar with the set-up, explaining the photoelectric barriers at the front and back of the treadmill and adjusting the safety cord to the height of the participant. A quick calibration of the system was employed which required the execution of a simple five task sequence of the participant (e.g. raising arms in front of their body, walking on the spot, walking backwards etc.). In this way, a 3D model could be generated in the GRAIL D-Flow software, created by the reflections of the body movements captured by the infrared cameras for gait measure analysis. This preparation and calibration took about 1.5 hours for each individual on average. Following this, the experiment started with a baseline measurement in each movement and cognitive complexity to make sure that participants were comfortable with the task and understood it properly. Standardized verbal instructions were given prior to the baseline measurement in regard to the testing procedure (see Appendix 4). After each block, participants were asked to fill out a NASA-TLX questionnaire to assess subjective workload and encouraged to take a rest. Once the experiment was over, the equipment was removed and participants were escorted to the bathroom, where they could change and wash their hair.

2.6 EEG Data Pre-Processing

The recorded dataset consisted of the EEG and gyroscope head movement data and was pre-processed offline with the help of custom MATLAB (version 2020b, Massachusetts, The MathWorks Inc.) and EEGlab toolboxes (Delorme & Makeig, 2004). Continuous data was low- and high pass filtered at 0.5Hz and 30Hz to reduce slow signal drifts using MATLAB's fourth-order IIR Butterworth filter with DC-offset removal. Channels were rejected based on two statistical testing grounds, namely using probability and kurtosis criteria. First, all channels with kurtosis of 8SDs or higher were excluded. Then, all channels with a probability higher than 5SDs were removed. The data was average-referenced to the accepted electrodes and segmented into epochs ranging from – 800ms to 1800ms time-locked to cue onset with a duration of 2600ms in total per epoch. In order to facilitate Independent Component Analysis (ICA) a new dataset was generated solely for the ICA by resampling the data from 500Hz to 250Hz. Individual Components (ICs) were then examined with the automated trial rejection (voltage threshold: 500 μV, probability threshold: 5SD,maximum percent of trials to reject per iteration: 10%) for signal noise caused by typical artefacts (eye and muscle movements) and noisy trials were removed from the ERP and ICA dataset. The baseline was corrected 200ms preceding the cue. Subsequently, rejected channels were spherically interpolated. Lastly, an extended ICA was performed on the ICA dataset and following that the resulting IC weights from the ICA-pruned dataset were applied to the EEG dataset.

2.7 Data Analysis

2.7.1 ERP Analysis

The ERP components N1, P2 and P3 at parietal-occipital recording sites were the focus of this study. Therefore, the data for parietal-occipital sites, was averaged across the electrodes Pz and POz. Since incorrect responses can evoke deteroriating EEG activity such as the error-related negativity (Holroyd & Coles, 2002) only correct button responses were included in the dataset for the ERP analysis. Firstly, two grand average waveform plots were derived by averaging across all condition and participants. From these plotted waveforms prominent negative and positive going deflections were assessed as grand average peaks to derive ERP component specific time-windows relative to cue onset (N1: 188ms – 288ms, P2: 250ms – 400ms, P3: 300ms – 500ms). The EEG data was analysed time-locked to the onset of the cue, namely the fixation cross and not the onset of the stimulus. Research (de Dreu, Schouwenaars, Rutten, Ramsey, & Jansma, 2019; Fan, McCandliss, Sommer, Raz, & Posner, 2002; Weinbach & Henik, 2011) has shown that neuronal activity already commences before the actual presentation of the stimulus, as participants both process the fixation cross and prepare themselves for the upcoming task. Therefore, time windows were defined by visual inspections of the grand average waveforms and not based on time windows defined by recent literature findings, as these studies analysed the data time-locked to stimulus presentation. Around these grand average peaks a smaller time window of 40ms was placed so as to obtain distinct peaks for the components (N1: 208ms, P2: 252ms). Within these small time windows each component was parametrized as the mean amplitude for all subjects and conditions. In order to quantify parietal P3 voltages it was not possible to specify temporal points of maximum deflections, as this component unfolded rather slowly. For this reason, a fixed timeframe between 400ms and 500ms based on literature review (Allison & Polich, 2008; Polich, 2004) was selected to calculate mean amplitudes for the different trial combinations across participants.

2.7.2 Behavioural performance indexes

In order to quantify behavioural responses for statistical analysis, reaction time (RT) and accuracy rate (RA) of the visual-cognitive task were assessed. Reaction time was assessed as the latency between stimulus onset and participant responses. To calculate the accuracy rate, the overall amount of presented stimuli were divided by the number of correctly given responses. Responses were credited as correct only when the correct button was pressed and the response time ranged between 150ms and 1500ms measured from visual stimulus onset. Every other response was categorized as wrong and thereby not admitted for further data

analysis. Movement data was collected and processed via the D-Flow software, however not further examined for the current study.

2.8 Statistical Analysis

The statistical analysis was carried out in MATLAB (version 2020b, Massachusetts, The MathWorks Inc.). ERP data were analysed with a 3 x 3 repeated measures analysis of variance (ANOVA) with Movement Complexity and Visual Angle as within-subject factors. In case of sphericity assumption violations the Greenhouse-Geisser (GG) corrections were applied to the ANOVAS. As the behavioural indexes of performance (RT and AR) were not normally distributed, they were set in GLME with Movement Complexity and angles set as fixed effect factors, using the participants as the grouping variable. The data was set with a random intercept and a fixed slope for all participants by the GLME formula, $DV \sim Visual\ Angle * Movement\ Complexity + (1|\ Participant)$ to test for the effects of the dependent variables. Statistically significant values for both GLME and ANOVA were taken at the p – value of 0.05 or lower. For all three test measures, the bias-corrected partial eta squared (η_p^2) was computed. This correction was calculated for all estimations of effect sizes reported. In order to evaluate whether the effect size is small, medium or large, η_p^2 was transformed to Cohen's d and interpreted accordingly (Cohen, 1992). Since the statistical analyses lack specification at which level of the different predictor variable means the significant differences lay, a Wilcoxon matched pairs test was conducted for the GLMEs. Similarly, a post-hoc test, a pairwise t-test with adjusted p – values to the methods of the Bonferroni correction (Bonferroni, 1936) was administered for all movement complexities at all factorial levels for the ANOVAs. In case of a p-value correction, adjusted critical p – values (p_{crit}) are provided. As in ANOVAs multiple comparisons are done it is prone for an accumulation of type 1 and type 2 errors, known as the family-wise accumulation. This error rate was controlled for by adjusting p – values with the Bonferroni correction.

3 Results

3.1 Behavioural performance indexes

The first hypothesis proposed that, for WA-periphery trials a decrease in reaction time (RT) and an increase in accuracy rate (AR) compared to ST-periphery is expected.

For RT, the analysis revealed no significant interaction effect between the predictor variables Visual Angle and Movement Complexity ($\beta = -6.74, p = .10, \eta p^2 = <.5$), which also indicates that walking had no impact on peripheral angles in regard to reaction time. However, a main effect of angle ($\beta = -0.02$, p < .001, $\eta p^2 = .21$) was found (Figure 4). With higher degrees of eccentricities, participants seemed to require more time to process the stimulus as reflected by the increased response times ($M_{0°} = 510.17, SD_{0°} = 88.28; M_{18°} = 554.58, SD_{18°} = 95.12$; $M_{40°} = 618.99, SD_{40°} = 108.43$). Post-hoc tests showed a significant difference in RT between perception of stimuli presented in the slightly peripheral field of 18 degrees and the peripheral visual field of 40 degrees ($Z = -3.69, p < .001$).

Analysis of the accuracy rate indicated similar results. No statistically significant effect was found for the factor movement ($\beta = 0.01, p = .10$, $\eta p^2 = .30$). For angle, a significant difference was detected again ($M_{0°} = 0.96, SD_{0°} = 0.07; M_{18°} = 0.94, SD_{18°} = 0.09; M_{40°} = 0.86, SD_{40°} = 0.14$; $\beta = -0.02, p < .001$, $\eta p^2 = .30$). When comparing the means of each eccentricity, post-hoc tests showed a slight tendency towards more accuracy in the 18° and 40° conditions (t_{71} = -1.90, p = .056), however this did not reach statistical significance.

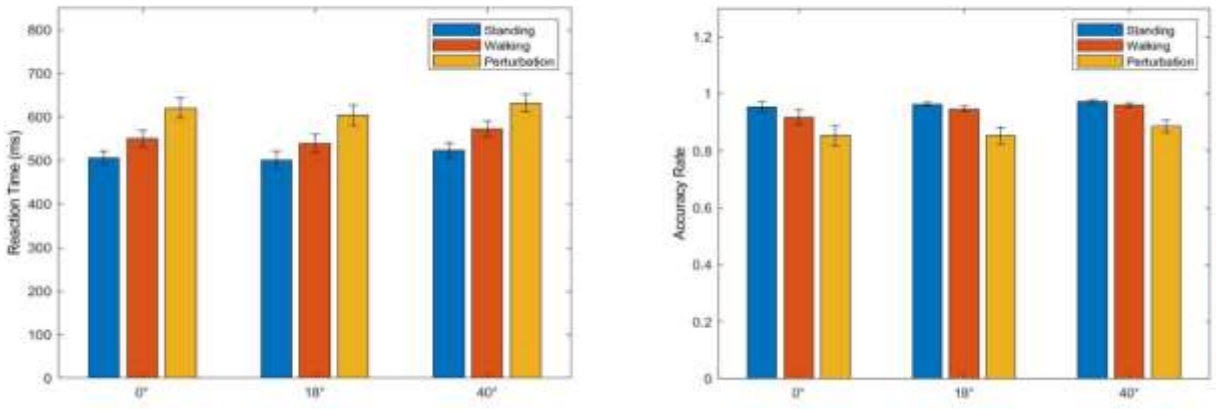

Figure 4. A visualisation of the averaged ratings of reaction time and accuracy rate for each movement complexity. Error bars depict the standard error of each movement condition.

3.2 ERPs

The second hypotheses proposed that if walking indeed enhanced visual perception in the periphery this should be reflected as a significant interaction effect in the ERP components N1 and P2, which are known to be modulated by enhanced early perceptual information processing. Further, in the last hypothesis it was theorized that if perceptual enhancement

occurred in WA-periphery trials, this should also lead to a decrease in mental workload as reflected by the components P2 and P3. In Table 2 an overview of the statistical analysis for each component is reported while significant effects will be discussed in the following section.

Table 2

This table shows the results of the repeated measures ANOVA of the ERP component at parietal-occipital recording sites for all experimental conditions and the interaction of the independent variables angle (central 0° vs slightly peripheral 18° vs peripheral 40°) and movement complexity (standing vs walking vs walking with perturbations). Reported are the test statistics (F), the P-value (p_{crit}) with Greenhouse-Geisser adjustment and the effect size (adjusted partial eta squared ηp^2).

	N1			P2			P3		
Factor	F	p	ηp^2	F	p	ηp^2	F	p	ηp^2
Angle	$F_{2,46}$ = 2.52	.02*	.02	$F_{2,46}$ = 2.78	.09	.02	$F_{2,46}$ = 19.16	<.001**	.15
Movement	$F_{2,46}$ = 14.50	.89	<.00	$F_{2,46}$ = .14	.88	.05	$F_{2,46}$ = 2.17	.14	.03
Angle*Move	$F_{2,46}$ = .49	.49	<.00	$F_{2,46}$ = 3.60	.02*	.01	$F_{2,46}$ = .57	.62	.05

Note. *p < .05. **p < .001

3.3.1 Parietal-occipital N1

The ERP component N1 at the parietal-occipital cluster did not show an interaction between Visual Angle and Movement Complexity. However, N1 amplitude ANOVA showed a main effect for Visual Angle ($F_{2,46}$ = 2.52, p = .02, p_{crit} = .02; see Table 2). Post-hoc tests with Bonferroni corrected adjustments revealed that N1 amplitude was more strongly modulated by targets presented in the central field than in the peripheral field ($M_{0°}$= -1.03, $SD_{0°} = 2.32$; $M_{40°.}$ = -.44, $SD_{40°,} = 2.58$; t_{71} = -2.77, p = .01). Likewise, a significant difference in amplitude was also found for the comparison of 18° and 40° trials ($M_{18°}$= -1.17, $SD_{18°} = 2.57$; t_{71} =.50 , p < .001). This modulation of amplitude with changing angles for the N1 component can also be seen in the grand-average waveform, as perturbations shows the largest amplitude compared to the other two conditions, see Figure 5.

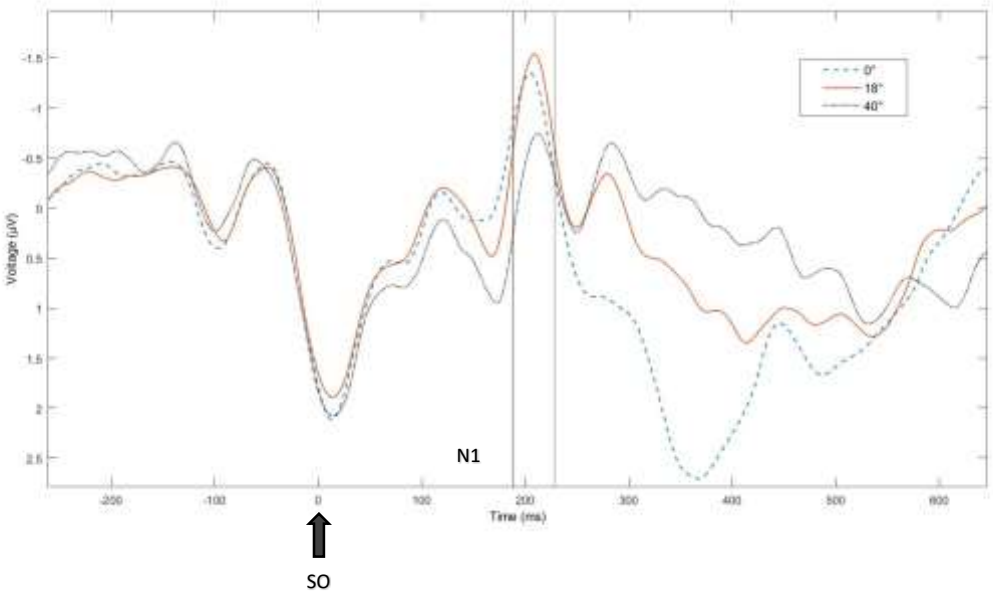

Figure 5. ERP plot of the component N1 for the main effect of movement complexity, superimposed across parietal-occipital channels Pz and Poz. Negative components are plotted upwards-going and vice versa. The waveforms are averaged over all angle trials with each line representing one motor task. Stimulus onset (SO) was at 0ms. The two rectangle bars depict the small time window of +/- 20ms around the ERP amplitude peak, which was derived from the grand-grand average waveform in order to prevent trial-biased peak-picking.

3.3.2 Parietal-occipital P2

In terms of the parietal P2, the analysis revealed a significant interaction between Visual Angle and Movement Complexity conditions ($F_{2,46}$ = 3.60, p = .000, p_{crit} = .02). A post-hoc pairwise comparison with Bonferroni corrections showed that P2 amplitude seemed to vary considerably for the movement task perturbation across angles. It could be seen that the amplitude for the central angle 0° was larger in comparison to the deflection of peripheral angle 40° ($M_{0°}$=.71, $SD_{0°} = 1.95$; $M_{40°.}$ = -.42, $SD_{40°,} = 2.36$; t_{23} = -1.86, p = .02; see Figure 6) Moreover, post-hoc comparison showed a statistical significant difference between 0° and 18° ($M_{18°.}$ = .10, $SD_{18°,} = 2.15$; t_{23} = 2.07, p = .048). The post-hoc comparison also revealed a significant distinction between the angles 0° and 18° for the walking complexity (t_{23} = 3.32, p = .003). As can be seen in Figure 7, trials with stimuli presented in the peripheral visual field of 40 degrees elicited the smallest P2 amplitude followed by trials with 18 degrees ($M_{0°} = .75, SD_{0°} = 2.15$; $M_{18°.}$ = -.27, $SD_{18°,} = 2.57$). It is worth highlighting that the experimental condition walking and central visual field trials did not elicit a distinguishable P2 peak, see Figure 6.

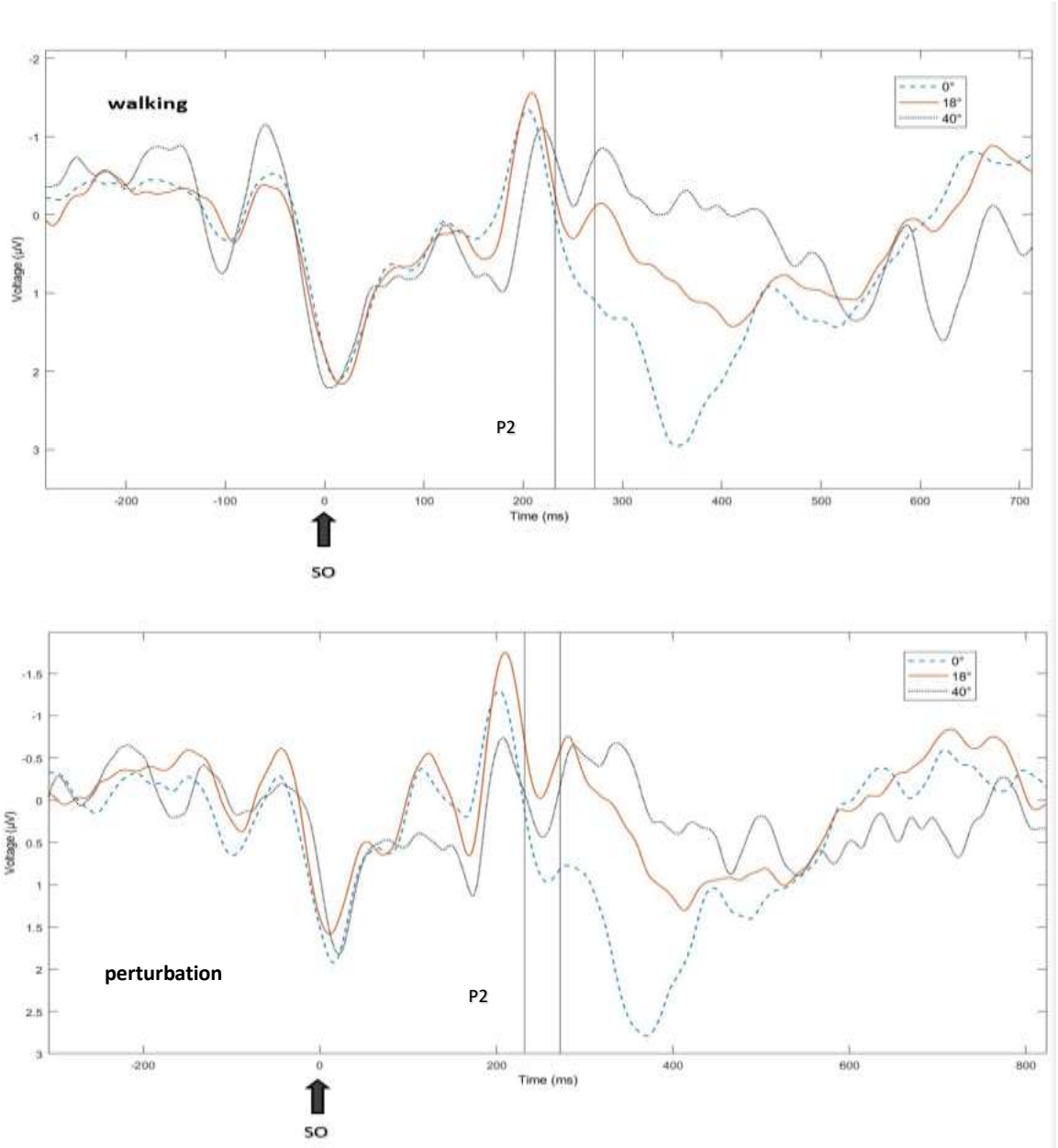

Figure 6. ERP plot of the component P2 for the interaction effect of movement complexities and angles 0° and 18° superimposed across parietal-occipital electrodes POz and Pz. Positive components are plotted downward-going and vice versa. Stimulus onset (SO) was at 0ms. The rectangle bar depicts the small time window of +/- 20ms around the ERP amplitude peak, which was derived from the grand-grand average waveform in order to prevent trial-biased peak-picking. As can be seen the component peaks around the same time post-stimulus for all angle conditions. The observed P2 amplitude difference between 0° and 18° is statistically significant. Interestingly, $\boldsymbol{WA_{central}}$ did not register a clear peak. It can be seen that all trials elicited similar peak onsets and latencies. Top: WA condition.
Bottom: PE condition.

3.3.3 Parietal-occipital P3

The analysis of the parietal-occipital P3 revealed a significant effect for the factor Visual Angle ($F_{2,46}$ = 19.16, p < .001, p_{crit} < .001, see Table 4). Post-hoc test calculations with Bonferroni corrections showed that there was a statistically significant difference in P3 amplitude between trials with 0° and trials with 18° angle ($M_{0°} = 1.58, SD_{0°} = 1.34$; $M_{18°,}$ = 1.14, $SD_{18°,} = 1.55; t_{71} = 3.37, p = .001$ d = .40). Likewise, trials with 40° and 0° yielded

statistical significance ($M_{40°.}$ = .45, $SD_{40°} = 1.55$; ; $t_{71} = 6.90, p < .001$, d = .81). Lastly, a considerable difference was found between the two peripheral angles 18° and 40° ($t_{71} = -5.423, p < .001$, d = .64). A visualisation of the ERP component also demonstrated that P3 onset was later for the trials with 18° and 40° as depicted in Figure 8. Further, this plot also shows that both peripheral angle conditions manifested a slow P3 component with an increased latency ranging from about 400ms to 550ms post-stimulus.

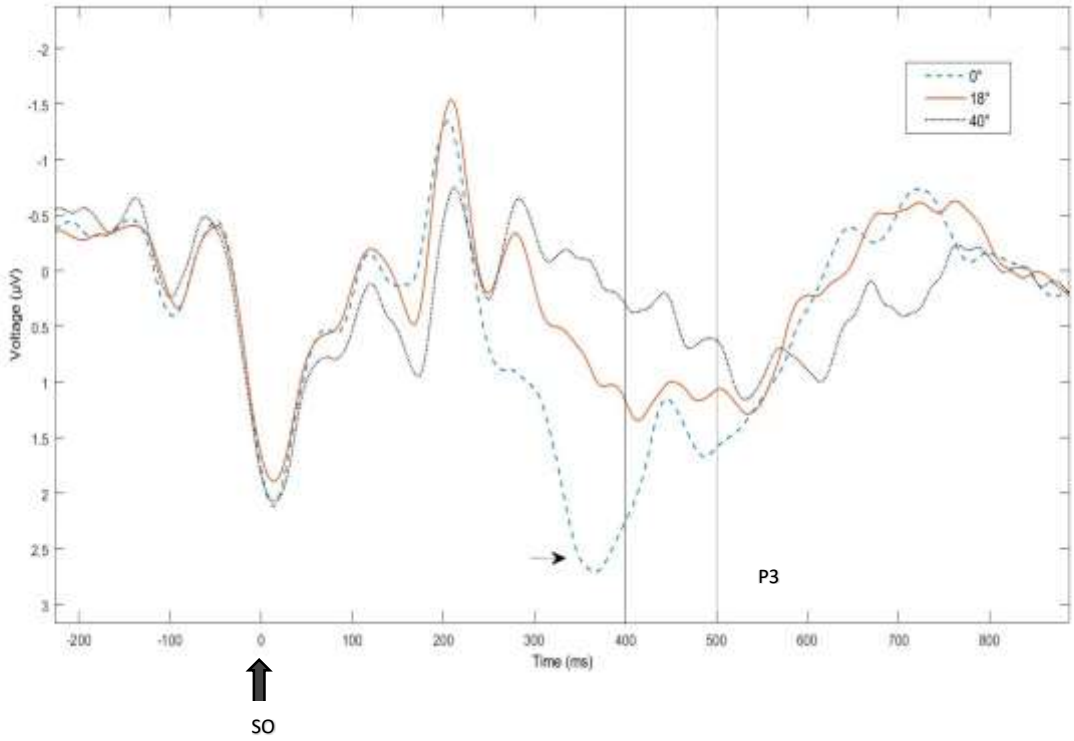

Figure 7. ERP plot of the component P3 for the interaction effect of movement complexity walking and angles superimposed across parietal-occipital electrodes POz and Pz. Positive components are plotted downward-going and vice versa. Stimulus onset (SO) was at 0ms. The rectangle bar depicts the small time window of +/- 20ms around the ERP amplitude peak, which was derived from the grand-grand average waveform in order to prevent trial-biased peak-picking. It can be seen that centrally presented targets elicited an earlier onset (marked with a right pointing arrow) and was more pronounced.

4 Discussion

In this study, a MoBI approach was applied to allow for a real-time assessment of visual information processing and mental effort during locomotion. A total of 24 participants executed a simple visual discrimination task while concurrently performing a motor task on an indoor treadmill in the GRAIL of the research institute IfADo. The motor task was divided into three levels of complexity, namely standing, walking and walking with perturbations of the treadmill to disrupt balance. In contrast to the majority of cognitive-motor dual-task studies, the current research manipulated target location into central and peripheral visual field in order to assess the impact of walking on peripheral perceptual capacities. Based on recent research findings (Benjamin et al., 2018; Cao & Händel, 2019) it was hypothesised that walking should have an enhancing impact on the perception of the peripheral visual field as compared to stimulus processing of the periphery during standing. Accordingly, three predictions were formulated. The first two predictions were formulated to examine the early perceptual and attentional properties of visual information processing and were expected to be reflected in reaction time and accuracy rate, as well as in the visual ERP components N1 and P2. Further, the third prediction proposed that if an walking-induced enhancement of peripheral information processing occurred, this should also have a positive impact on reducing task difficulty and mental workload, reflected in the ERP component P3.

Against expectations, the theorized significant interaction between peripheral visual information and walking was not replicated in the current study. In fact, with the exception of one ERP component, namely the P2, all electrophysiological measures and behavioural indexes demonstrated that there was no interaction between stimulus Visual Angle and Movement Complexity that would cause either an enhancement or a trade-off in visual encoding. Instead, only the factor Visual Angle was significantly modulated across these measures. Consequently, the majority of the proposed predictions were rejected.

Existing research has shown that the parietal-occipital P2 component is evoked by visual input and therefore reflects an early attentional and perceptual processing ability (Allison & Polich, 2008; Johannes et al., 1995; Maeno et al., 2004; Sugimoto & Katayama, 2013). Indeed, in the current study it was observed that within the Movement Complexity perturbation, increasing eccentricities elicited a smaller P2 amplitude. This observation is in line with previous research showing that complex motor complexities paired with a cognitive task are manifested as an attenuated P2 amplitude (Huang & Hwang, 2013). The second interaction of Movement Complexity and Visual Angle observed for this component showed somewhat surprising manifestations. Due to the dual-task cost impacting overall cognitive and motor

performance, it was not expected that walking conditions would yield better performance per se. Instead, the modulation was expected in the form of a smaller threshold difference between peripheral input in walking and standing trials compared to the difference of central visual field input. For the Movement Complexity walking, this was indeed the case. The analysis showed that perception of the peripheral vision was slightly improved compared to standing still. Further, it was observed that between an eccentricity at 18 and 40 degrees, P2 amplitude was smaller for 40 degrees. This is in line with general assumptions that with increasing eccentricity visual acuity will be attenuated (Carrasco et al., 1995; Strasburger et al., 2011; Wolfe et al., 1998). The fact, that perceptual processing at 18 degrees was enhanced during walking as compared to standing but not at 40 degrees, indicates that there is a limit to the walking-induced enhancement for peripheral visual input.

Interestingly, no clear P2 amplitude peak was detected in the wave plot for walking and central visual field trials which raised the question of a different operational process P2 might be reflecting. When looking at trials with centrally presented targets and comparing them across motor complexities, a generally small and less pronounced P2 amplitude was observed. According to the traditional assumption regarding P2, successful and enhanced perceptual encoding and little task difficulty, as associated with centrally presented targets, should be reflected as a large amplitude (Allison & Polich, 2008; Sugimoto & Katayama, 2013). One explanation for this observation might be related to the absence of a significant main effect of Movement Complexity in the current study. More specifically, in a dual-task paradigm where both motor and cognitive tasks were quite easy, this might have elicited habituation and automatization effects. In other words, participants may have experienced too little stimulation due to quite automated motor tasks of walking, that they responded to the stimuli automatically and unconsciously, which in turn signalled facilitated task execution induced by walking, however manifested itself differently than proposed by the initial hypothesis. To sum it up, for the component P2 positive modulations of enhancements were found for the impact of walking on peripheral visual information processing, thereby partly confirming the second hypothesis.

Noteworthy is that, for both behavioural indexes and the ERP components N1 and P3, a significant main effect of the factor Visual Angle but not for Movement Complexity was found and this lack of significant differences of the varying Movement Complexities might be able to explain the absence of an interaction. With increasing levels of eccentricities, behavioural performance decreased as signalled by higher reaction times and lower accuracy rate. Likewise, N1 and P3 amplitudes decreased as Visual Angle properties increased. The N1 component at posterior sites has been demonstrated to vary as a function of visual information

processing with larger amplitudes for successfully processed targets (Vogel & Luck, 2000). When attentional resources are scarce, such as in demanding dual-task situations, N1 amplitude has been shown to decrease (Little & Woollacott, 2015; Quant et al., 2004). In the current study, the participants were asked to keep their eyes fixated at the centre as identified by the fixation cross independent of where the stimuli appeared on the screen. This might have caused focused attention on the central field and when stimuli appeared at a central angle this could have significantly facilitated central perception compared to peripheral processing. In addition to the already low acuity that is inherent to the biological and functional nature of peripheral vision this need to reorientate perceptual attention and information processing might have decreased perceptual information processing in comparison to central processing (Carrasco et al., 1995; Strasburger et al., 2011; Wolfe et al., 1998). This was also reflected in P3 amplitude and latency. A high amplitude of P3 is thought to index successful information processing and low levels of task difficulty (Kok, 2001; Polich, 2004). In line with this assumption, targets presented in the central field of the screen and during standing trials engendered the largest P3 deflection. Moreover, for peripheral trials, it was shown that the latency was increased and had a later onset. Relating this to the theory that P3 latency is a monitoring and coordination process capacity (Verleger, 1988; Verleger et al., 2005), it can be assumed that prolonged P3 latencies were caused by the delayed response initiation that was associated with increased eccentricities. For both components, however, previous studies showed a significant interaction of Movement Complexity when participants simultaneously engaged in a cognitive and motor (Liebherr et al., 2018; Little & Woollacott, 2015; Nenna et al., 2020; Reiser et al., 2019). The decisive difference between previous studies and this current one seemed to lay in the nature of the dual-task task setting. First case in point would be the absence of a movement task main effect in the current study. This could indicate that the Movement Complexities were not ecological enough to elicit the assumed dual-task cost of heightened focus and task demands, especially in a stationary setting. In the same way, the potential benefits of locomotion, such as optimal arousal (Shumway-Cook et al., 1997) and decrease of optic flow (Pelah et al., 2015; Thurrell et al., 1998), that would enhance perceptual and executive functioning were not elicited. Similar to the present study, P3 amplitudinal differences between motor tasks were also absent in studies utilizing treadmill walking as opposed to standing (Gramann et al., 2010) or sitting (De Vos, Gandras, & Debener, 2014). Further, Scanlon et al. (2017) showed that indoors stationary cycling did not elicit differences in P3 amplitude compared to simple motor tasks. Contrary to this, Liebherr et al. (2018) employed one-stance balance task as opposed to bipedal standing and in the study by Reiser et al. (2019) participants mastered an obstacle course or walked freely

on their own pace in an outdoor setting as opposed to standing, in order to increase motor task complexity, and elicited significant P3 amplitudes. Therefore, it could be concluded that the modulation of the N1 and P3 amplitudes in the present study was a function of increasing angle degrees and the relative difficulty of encoding the incoming visual information from the peripheral visual field.

To summarize the findings of the present study, it was shown that P2 showed a positive modulation of walking-induced enhancement of peripheral input processing. For the rest of the measures the results remained insignificant. It is important to note that the lack of a significant Movement Complexity due to the artificial nature of treadmill walking, seemed to have played a considerable role in the absence of significant interaction effects between walking and the perception of targets presented in the peripheral visual field. Consequently, as only the factor Visual Angle reached significance for the measures, targets presented at central eccentricities were processed earlier and easier compared to targets appearing in the peripheral visual field.

4.1 Limitations

The observed absence of a clear interaction effect could be explained by some limitations of the study itself. Firstly, no statistically significant differences in the motor task were found which could make the case that indoor treadmill walking with a pre-set speed differs considerably from natural free walking. In natural free walking, visual scanning of the environment is crucial and, therefore, requires different attentional resources related to future movement planning and vigilance behaviours (Staugaard et al., 2016). Another critical point is that natural walking is impacted by integration of continuous information from the periphery and vice versa, namely that optical flow is impacted by walking as a function of decreased visual speed (Warren et al., 2001). Thus, walking on a treadmill could have diminished the need to assemble required attentional resources that would induce realistic task demands and arousal. Similarly, the advantages of free and ecological walking were not elicited. Furthermore, the current research only analysed and interpreted the results of the simple one-ring condition. However, participants also executed a more complex five-one visual task. Possible impacts of task alternating between these two conditions might have induced other processes, such as fatigue. Moreover, the complex five-ring condition might reflect a more real-life setting in regard to visual information processing and target detection. Lastly, no analysis of gait measures was executed that might provide more insight into coping and counteracting behaviours of participants.

4.2 Practical implications and future research

The results obtained in the present study did not show a clear impact of walking-induced modulations for the processing of visual information from the periphery. Therefore, practical implications were difficult to formulate and are to be treated with caution. Contrary to the expectations, no significant interaction effects between the Movement Complexities and Visual Angle were found, except in one ERP component, namely the visual P2. Here, it was shown that walking indeed positively modulated the perception of targets at peripheral angles compared to other trial combinations. However, future researchers attempting to investigate walking-induced perceptual performance should design a more ecological valid motor and visual task setting, such as applied by Nenna et al. (2020). In their study, the authors created an authentic virtual reality in which the participants walked around in their own speed and gait behaviour, which replicated the actual need to navigate and integrate visual information at different eccentricities in ongoing cognitive processes (Nenna et al., 2020). Furthermore, gait measures, such as lengthened strides or stride variability are imperative to take into account as well, as absent dual-task interference in the observed ERP correlates could be caused by adaptive gait behaviour to counteract the task demand (De Sanctis et al., 2014).

In conclusion, a positive modulation of peripheral visual information processing for the ERP component P2 was observed during walking. Nonetheless, the current study was not able to collect sufficient evidence to confirm the hypothesised significant effect of walking on peripheral information processing. Future research intending to investigate the relationship between walking and peripheral information processing should employ a motor task that allows for natural free walking as this would more authentically represent underlying cognitive mechanisms involved in dual-task visual information processing while walking.

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Appendices

Appendix I – Information Sheet

INFORMATIONSBLATT

zum Forschungsvorhaben

„Validierung und Evaluation mobiler neurophysiologischer Maße in Bezug auf reale und simulierte Umwelten“

Sehr geehrte Versuchsteilnehmerin, sehr geehrter Versuchsteilnehmer,

wir danken Ihnen für Ihr Interesse an unserer Studie! In diesem Projekt sollen Kenntnisse über die Nutzbarkeit neuer Messmethoden zur mobilen Erfassung von physiologischen Daten gewonnen werden. In einem Vergleich zwischen konventionellen Messmethoden und neuen Aufnahmetechnologien soll überprüft werden, ob eine mobile und flexible Erfassung von Prozessen im Gehirn im Zusammenspiel mit anderen physiologischen Maßen wie dem Herzkreislauf oder der Bewegung möglich ist. Zu diesem Zweck sollen Sie in kontrollierten Umgebungen Alltagsaufgaben ausführen. Hierfür sollen Sie mentale Aufgaben bearbeiten, während Sie auf dem Laufband stehen oder in verschiedenen Schwierigkeitsstufen laufen.

Wir möchten Sie auf folgende Punkte hinweisen:

1. Die Teilnahme an dieser Untersuchung ist freiwillig. Die Teilnahme kann jederzeit ohne Angabe von Gründen widerrufen werden, ohne dass Ihnen daraus Nachteile entstehen. Auch eine laufende Untersuchung wird auf Ihren Wunsch hin jederzeit abgebrochen.
2. Die Untersuchung wird ausschließlich zu wissenschaftlichen Zwecken durchgeführt und dient nicht der medizinischen Diagnostik. Die Ergebnisse sollen uns helfen, verstärkt mobil forschen zu können.
3. Ihre Daten werden anonymisiert gespeichert. Sie unterliegen dem Datenschutz, der eine unbefugte Weitergabe an Dritte verhindert.

Bei wissenschaftlichen Studien werden persönliche Daten und medizinische Befunde über Sie erhoben. Die Weitergabe, Speicherung und Auswertung dieser studienbezogenen Daten erfolgt nach gesetzlichen Bestimmungen ohne Namensnennung.

4. Es folgen nun einige Hinweise zum Ablauf und zu den bei dieser Studie eingesetzten Untersuchungsmethoden. Wenn weitere Fragen bestehen, werden diese gerne vom jeweiligen Untersuchungsleiter beantwortet.

Ziel der Studie

Durch technische Neuerungen auf dem Feld der physiologischen Messgeräte ist es zunehmend möglich, Messungen sowohl der Hirn- und Herzaktivität als auch der Bewegungsparameter in der Bewegung vorzunehmen. Ziel dieser Studie ist es, die kognitive Prozesse besser während alltäglicher Bewegungen zu verstehen. Hierzu sollen Sie eine kognitive Nebenaufgabe bearbeiten während Sie auf dem Laufband ruhig stehen, ganz normal oder mit Störungen des Gangs laufen.

Ablauf

Nach dem Ausfüllen der vorbereiteten psychologischen Fragebögen und dem darauffolgenden Anbringen der physiologischen Messgeräte und Bewegungsmarker werden Sie auf das Laufband begleitet und mit einer Fallleine abgesichert. Ihre Aufgabe ist es, gleichzeitig eine Bewegungs- und eine kognitive Aufgabe auszuführen.

Die Bewegungsaufgabe besteht aus folgenden Bedingungen: Stehen, einfaches Laufen, Laufen mit Störung des Gangs. Bei der Stehbedingung sollen Sie still an einer Stelle stehen. Beim einfachen Laufen sollen in normalem Gehtempo laufen. In der Laufbedingung mit Störung macht das Laufband abrupte Bewegungen nach links oder rechts während Sie laufen um Ihren Gang zu stören.

Es gibt zwei kognitive Aufgaben: Bei der ersten kognitiven Aufgabe werden Ihnen ca. alle zwei Sekunden nebeneinander fünf weiße Kreise auf schwarzem Grund präsentiert. Einer dieser Kreise hat eine Öffnung, die nach oben oder unten zeigt, ganz wie bei einem Sehtest. Ihre Aufgabe ist es, mit einem Tastendruck anzugeben, in welche Richtung diese Öffnung zeigt. Bei der zweiten kognitiven Aufgabe wird Ihnen nur ca. alle zwei Sekunden ein nach oben oder unten geöffneter Kreis angezeigt, der sich jedoch an keiner festen Stelle befindet, sondern zufällig auf der horizontalen Achse der Leinwand auftaucht. Auch hier sollen Sie mit einem Tastendruck der linken oder rechten Taste (je nach Zuweisungsgruppe) zurückmelden, in welche Richtung der Kreis geöffnet war.

Ein Durchgang dauert ca. 10 Minuten und es gibt jeweils drei Durchgänge pro kognitiver Aufgabenstellung. Nach allen Versuchsdurchgängen werden Sie wieder vom Laufband herunter begleitet, die Messinstrumente werden entfernt und Sie erhalten Ihre Versuchsvergütung.

Im Folgenden werden die Messungen im Einzelnen erklärt:

Fragebögen

Im Rahmen der Studie sollen Sie eine Auswahl an Fragebögen bearbeiten, die Ihre demographischen Daten und Ihren Gesundheitszustand betreffen. Seien Sie bitte bei der Beantwortung der Fragen ehrlich, denn nur dann geben die Fragebögen Auskunft über Ihren

tatsächlichen Status. Bitte füllen Sie diese Fragebögen in Ruhe aus und versuchen Sie, die Fragen spontan zu beantworten.

Messung der elektrischen Hirnaktivität

Die EEG-Methode (Elektroenzephalografie) misst schmerzfrei die elektrische Aktivität des Gehirns an der Kopfoberfläche. Die Verbindung zwischen Kopfoberfläche und Messgerät wird sowohl mittels kleiner, hinter den Ohren geklebten Elektroden als auch einer herkömmlichen EEG-Ableitung über 64 Elektroden, die auf einer Kappe angebracht sind, hergestellt. Die vom Gehirn ausgehende elektrische Aktivität wird abgeleitet, während Sie stehend oder laufend die Aufgaben bearbeiten. Die EEG-Ableitung ist eine oberflächliche (nicht-invasive) und erprobte Messmethode. Sie ist keine diagnostische Untersuchung, das heißt, die Daten werden nicht auf das Vorliegen von Erkrankungen, sondern ausschließlich für wissenschaftliche Zwecke analysiert. Nach der Nutzung der EEG-Kappe ist das Waschen der Haare angeraten, da sich Rückstände der Leitpaste an den Haaren bilden.

Messung der Bewegungsparameter

Um Bewegungen zu erfassen, werden kleine Bewegungssensoren mit Klebeband an Ihren Gelenken und Ihren Extremitäten angebracht. Diese können die einzelnen Bewegungen der Hände, Arme, Füße und Beine separat registrieren und aufzeichnen.

Freiwilligkeit der Teilnahme

Selbstverständlich ist die Teilnahme an der Studie freiwillig. Sie können die Untersuchung jederzeit abbrechen, ohne dass Ihnen hieraus Nachteile entstehen oder Sie dies begründen müssen. Der von Ihnen geleistete Zeitaufwand wird anteilig entschädigt. Sie erhalten bei diesem Versuch als Vergütung 10 € oder 1 Versuchspersonenstunde pro Versuchsstunde. Bei vorzeitigem Abbruch der Studie werden die Versuchspersonenstunden / das Geld anteilig gutgeschrieben / ausgezahlt.

Gibt es eine besondere Gefährdung oder Belastung?

Besondere Belastungen oder Gefährdungen treten bei der Untersuchung nicht auf.

Was passiert mit meinen Daten?

Bei wissenschaftlichen Studien werden Daten erhoben. Die Weitergabe, Speicherung und Auswertung dieser studienbezogenen Daten erfolgt nach gesetzlichen Bestimmungen und setzt

vor der Teilnahme an der Studie Ihre freiwillige Einwilligung voraus. Die erhobenen Forschungsdaten werden ohne Namensnennung verschlüsselt (Anonymisierung). Ein Rückschluss auf Ihre Person ist nicht möglich.

Im Rahmen dieser Untersuchung werden Daten elektronisch und ohne Namensnennung gespeichert. Die Ergebnisse werden ausschließlich für wissenschaftliche Veröffentlichungen genutzt. Die Bestimmungen der ärztlichen Schweigepflicht und des Bundesdatenschutzgesetzes sind gewährleistet.

Vielen Dank!

Prof. Dr. Edmund Wascher

Appendix II– Informed Consent

EINVERSTÄNDNISERKLÄRUNG

Im Rahmen der Studie „Validierung und Evaluation mobiler neurophysiologischer Maße in Bezug auf reale und simulierte Umwelten“ werden verschiedene Fragebögen, psychologische Tests, Elektroenzephalografie- (EEG) und Motion-Tracking-Messungen durchgeführt.

Die Details und Ziele der gesamten Studie wurden mir erklärt und alle meine Fragen sind zu meiner Zufriedenheit beantwortet worden. Ich bin sicher, dass ich bezüglich meiner Teilnahme an der Studie alles verstanden habe. Das Merkblatt für Teilnehmer/innen habe ich gelesen. Ich weiß, dass ich meine Teilnahme an dieser Studie jederzeit widerrufen kann.

Ich,

.....

(Name) (Vorname)

erkläre hiermit mein Einverständnis, an der Studie freiwillig teilzunehmen.

Alle meine personenbezogenen identifizierenden Daten werden vertraulich behandelt. Meine separat erhobenen Kontoinformationen werden ausschließlich zum Zwecke der Probandengeld-Überweisung verarbeitet und nach Ende der gesetzlichen Aufbewahrungsfrist gelöscht. Die Weitergabe meiner Studien-Daten für statistische Auswertungen erfolgt in jedem Falle pseudonymisiert und ausschließlich zu wissenschaftlichen Zwecken.

Ich bin damit einverstanden, dass meine Daten vom IfADo (Prof. Dr. Edmund Wascher und Mitarbeitern) ausgewertet werden. Diese Auswertung umfasst alle Fragebögen und psychometrischen Tests, sowie die EEG- und Motion-Tracking-Messungen. Ich habe zur Kenntnis genommen, dass meine Daten ohne Namensnennung so verschlüsselt werden (Anonymisierung), dass niemand auf meine Person zurückschließen kann.

☐ Ja ☐ Nein

Es werden ausschließlich die anonymisierten Daten, die aus den Erhebungsinstrumenten (Fragebögen, psychometrische Daten, EEG-, EKG- und Motion-Tracking-Daten) resultieren, digitalisiert und am IfADo auf gesicherten Datenträgern abgespeichert. Die Auswertung erfolgt erst nach der Anonymisierung. Ich kann meine Zustimmung jederzeit widerrufen.

Eine Kopie dieser Einverständniserklärung und das Informationsblatt habe ich erhalten.

☐ Ja ☐ Nein, ich will keine eigene Kopie

Dortmund, den ..... Unterschrift .....

Appendix III – Participant Demographic Information

Nr.: _ _ _

Demographiefragebogen

1) **Geschlecht**: Bitte geben Sie Ihr Geschlecht an.

.....

☐ 2) **Alter**: Geben Sie bitte den Monat und das Jahr Ihrer Geburt an.

Monat: _ _ Jahr: _ _ _ _ Alter (Jahre): _ _

☐ 3) **Körpergröße**: Bitte geben Sie Ihre Körpergröße in Centimetern an.

☐ _ _ _ cm

☐ 4) **Staatsangehörigkeit**: Bitte geben Sie Ihre Staatsangehörigkeit an.

.....

5) **Familienstand**: Bitte geben Sie Ihren Familienstand an.

.....

6) **Beruf**: Bitte geben Sie Ihren derzeitigen Beruf an.

.....

7) **Bildungsabschluss**: Bitte geben Sie Ihren höchsten Bildungsabschluss an.

☐ Hauptschulabschluss

☐ Mittlere Reife

☐ Abitur / Fachhochschulreife

☐ Universitäts- / Fachhochschulabschluss

☐ Promotion

Nr.: _ _ _

Fragebogen zum Forschungsvorhaben

☐ ☐

"Validierung und Evaluation mobiler neurophysiologischer Maße in Bezug auf reale und simulierte Umwelten"

Zur Teilnahme an unserer Studie benötigen wir noch folgende Angaben von Ihnen:

☐ ☐ Händigkeit: .....

Sehhilfe (Brille, Kontaktlinsen): .....

Bitte beantworten Sie noch folgende Fragen:

Hatten Sie in der Vergangenheit neurologische Krankheiten (z.B. Hirnerkrankung,

☐ ☐ Hirnverletzung, Epilepsie, Schlaganfall)?

Ja Nein

Haben Sie bekannte Hörschäden?

Ja Nein

Falls ☐ ja, ☐ welche:

.....

☐ Haben ☐ Sie aktuelle Beeinträchtigungen des Gehörs (z.B. durch Erkältung)?

Ja Nein

Falls ja, welche: ....

☐ Haben ☐ Sie bekannte Sehschwierigkeiten?

Ja Nein

Falls ja, welche: .....

Haben Sie aktuelle Beeinträchtigungen des Sehens?

Ja ☐ Nein ☐

Falls ja, welche: .....

Haben Sie bekannte motorische Schwierigkeiten?

Ja ☐ ☐ Nein

Falls ja, welche: .....

Haben Sie aktuelle Beeinträchtigungen der Motorik?

Ja ☐ Nein ☐

Falls ja, welche: .....

Leiden Sie unter einer Beeinträchtigung des Gleichgewichtssinns (vestibuläres System)?

Ja Nein

Falls ja, welche: .....

Leiden Sie unter Beeinträchtigungen des Herz-Kreislauf-Systems?

Ja Nein

Falls ja, welche: .....

Besteht eine Hautallergie (z.B. auch bei Pflastern)?

Ja Nein

Nehmen Sie zurzeit Medikamente ein?

☐ Ja ☐ Nein

Falls ja, welche: .....

Appendix IV – Standardized Verbal Instructions

Liebe Teilnehmerin, lieber Teilnehmer,

vielen Dank für die Teilnahme an diesem Versuch. Bevor die Messung startet, werde ich Ihnen die kognitive und die motorische Aufgabe erklären.

Es wird zwei kognitive Aufgabentypen geben. Der erste Typ besteht darin, dass Ihnen fünf horizontal angeordnete Ringe präsentiert werden, von denen einer nach oben oder unten geöffnet ist (ähnlich wie bei einem Sehtest). Ihre Aufgabe ist es, per Tastendruck zu entscheiden, ob der Ring nach oben oder unten geöffnet ist. Sollte der Ring die Öffnung oben haben, drücken Sie die linke Antworttaste, sollte der Ring die Öffnung unten haben, drücken Sie die rechte Antworttaste. Bevor Sie die Ringe sehen, wird ein Fixationskreuz in der Mitte der Leinwand dargeboten. Bitte fixieren Sie dieses Kreuz und versuchen Sie, auch während der Präsentation der Ringe mit dem Blick nicht vom Mittelpunkt der Leinwand abzuweichen. Der zweite Aufgabentyp ist sehr ähnlich. Hier wird nur ein Ring präsentiert, der nach oben oder unten geöffnet ist. Dieser Ring erscheint jedoch an einem zufälligen Punkt auf der horizontalen Achse. Hier sollen sie wieder angeben, ob der Ring nach oben oder unten geöffnet ist, wobei Sie links bei einer Öffnung nach oben drücken sollen, und rechts, wenn der Kreis nach unten geöffnet ist.

Der kognitive Aufgabentyp wird blockweise gewechselt, sodass Sie innerhalb eines Blocks immer dieselbe Aufgabe bearbeiten sollen. Sollten Sie sich bei einer Antwort unsicher sein, drücken Sie keine Taste.

Zusätzlich sollen Sie eine motorische Aufgabe ausführen. Entweder stehen Sie während der Präsentation der Ringe oder haben die Aufgabe langsam mit oder ohne Gangstörung zu gehen (1,2 m/s). Die Gangstörung besteht darin, dass das Laufband bei Stimuluspräsentation abrupt nach links oder rechts auslenkt. Diese motorische Aufgabe wechselt blockweise, also ob Sie stehen, ohne Störung laufen oder mit Störung laufen. Die Bedingung wird Ihnen vor jedem Block mitgeteilt.

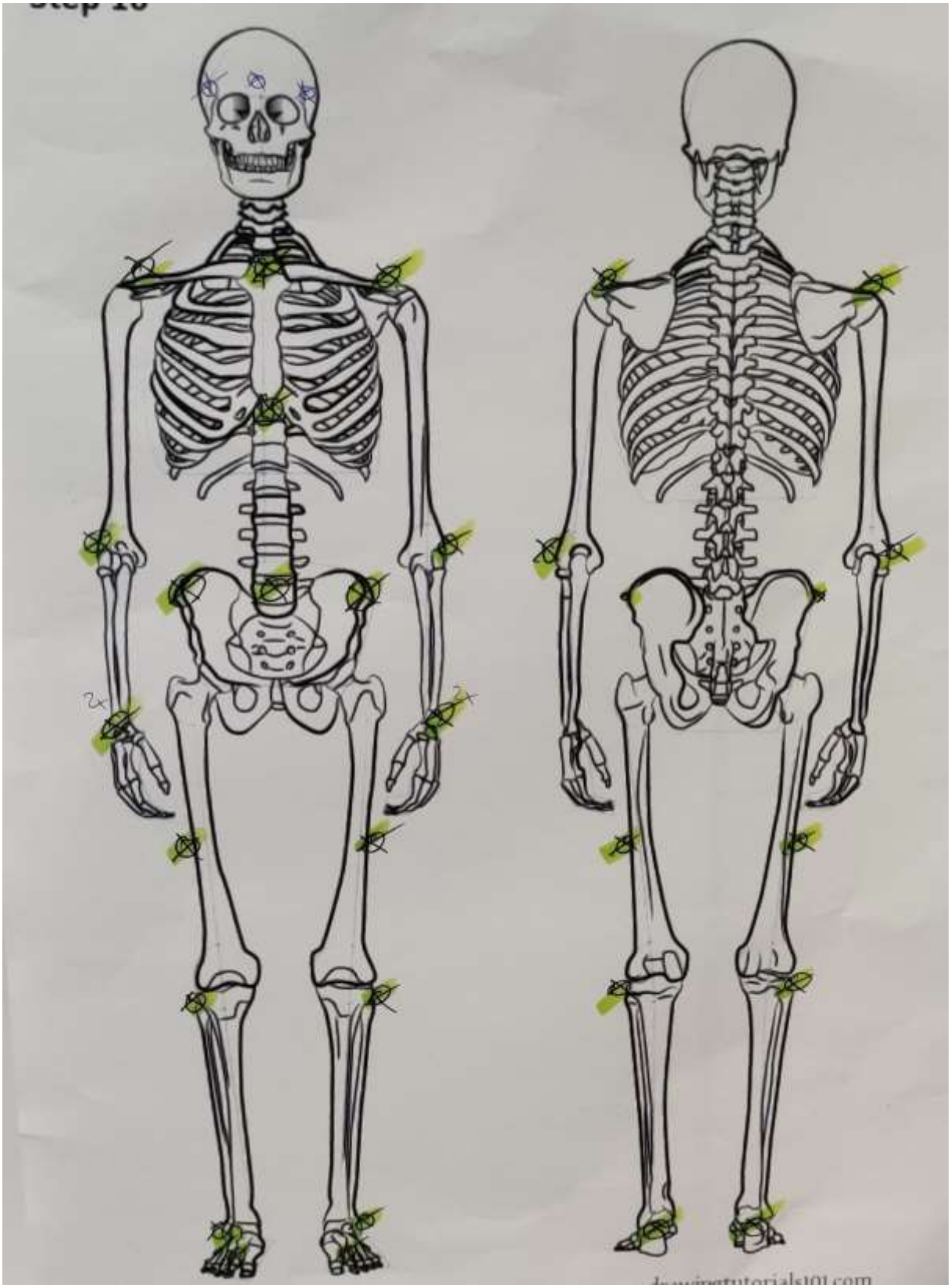
Jeder Block dauert 10 Minuten.

Nach jedem Block wird Ihnen ein Fragebogen zur subjektiven Einschätzung Ihres Workloads während des letzten Blocks hereingereicht. Bitte füllen Sie diesen nach Ihrem eigenen Empfinden aus; hier gibt es keine falschen Antworten.

Sollten Sie noch Fragen haben, können Sie diese jetzt oder zwischen den Blöcken stellen.

Zuerst gibt es zwei Proberunden mit jeweils einer kognitiven Aufgabe, damit Sie sich mit den Aufgabenstellungen vertraut machen können. Danach wird es für jede Laufbedingung eine Baselinemessung von 3 Minuten geben. Danach beginnt dann die Experimentalphase mit der gleichzeitigen Bearbeitung von motorischer und kognitiver Aufgabe. Ganz am Ende sollen Sie noch ein Segelbootspiel absolvieren, zu dem ich später noch eine Instruktion geben werde.

Appendix V - Predefined Human Body Model (HBM)



Appendix VI - EEG Data Acquisition

A mobile 64 active Ag/AgCI electrode system was used to acquire EEG using the international 10-20 system. The acticap, a tight-fitting but flexible cap with electrode holders, was made of a breathable mesh to limit sweating and fitted over the subject's head. Prior to the study participants reported their head size in circumference so that the appropriate EEG cape (sizes ranged from 54cm to 60cm in circumference) could be plugged with the electrodes beforehand. Electrodes were online referenced to FCz and grounded to AFz. To keep impedance at or below 10kΩ, all electrodes were filled with conductive gel. Data was recorded using a LiveAmp amplifier (Brain Products GmbH, Gilching, GER) with a built-in gyroscope to register head movements. The amplifier recorded at a sampling rate of 500Hz with a sampling interval of 1000ms and a bit depth of 24 bit. The amplifier was connected with a LiveAmp Sensor, Trigger Extension and Wireless Adapter (Brain Products GmbH, Gilching, GER) where participants' responses, as well as the trigger signal of the GRAIL and the photodiode at stimulus onset, were registered and marked into the EEG signal. The implementation of the photodiode into the EEG signal is important in order to check whether the stimulus generated by the computer software has also been presented to the participant on screen. Recorded data was stored on the SD-card embedded in the amplifier and transferred to a laptop's hard drive via the LiveAmp File converter software after each experiment. During the experiment, the online EEG signal was transmitted to a computer set-up and could be viewed with the Brainvision recorder software. As this study entailed a mobile set-up and movement was a major part of the task some extra precautions had to be taken to prevent EEG data distortion caused by cable motion or entanglement, for instance. All electrode wires were equally split into four sections across the scalp and mounted through velcro-fastened cable mounts on the cap next to the participant's ears. The electrode wires were then securely taped in those four bundles, making sure that enough tension was on the wires without pulling on them too much either, and attached to the mobile amplifier. To protect the EEG system, it was stored in a small impact-protected case within the backpack. Further, all wires were securely taped together and put in an upright position to prevent induction currents and cable breaks. Moreover, the lab chamber was airconditioned to prevent sweating. Additionally, participants were informed to limit behaviours and facial expressions to a minimum to avoid EEG artefacts (e.g. eye blinking, head movements, laughing, jaw clenching, swallowing etc.)