Effects of whole body vibration on cognition

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Preface

This thesis presents five studies that explore the effects of whole-body vibration on different cognitive functions including attention, mental rotation, memory and inhibition. These studies received ethical approval by the University of Regensburg Ethics Committee. The author is grateful to Novotec Medical GmbH (Pforzheim, Germany) for providing the vibration platform.

Contents

1 Introduction

1.1 Health effects of whole body vibration

Whole body vibration (WBV) exercise uses an oscillating platform as a stimulus, transmitting forced mechanical oscillation through the legs of an individual standing on the platform (Rittweger, 2010) and stimulating subcutaneous proprioceptors, muscle spindles and Golgi tendon organs (Rogan et al., 2011; Sonza et al., 2013). It has been suggested that WBV exercise can have beneficial effects on skeletal muscle strength and cardiovascular health, especially in elderly people and individuals with medical conditions (Park et al., 2015). In recent years, the utility of WBV in promoting physical fitness and managing various chronic conditions has been assessed.

1.1.1 Physical fitness and motor functions

Research has increasingly explored the potential value of WBV in improving athletic performance not only in elite athletes (Bullock et al., 2008), but also in recreational athletes, untrained adults, children with disabilities and older people (Bullock et al., 2008; Cochrane et al., 2004; Colson et al., 2010; Ebben et al., 2010; Fernandez-Rio et al., 2010; Matute-Llorente et al., 2014; Merriman & Jackson, 2009; Ritzmann et al., 2014; Wyon et al., 2010). The evidence in regard to the effects of WBV on various performance parameters, such as vertical jump height, power, balance and agility is contradictory. While numerous studies have shown improvements in performance following exposure to WBV, others have found no positive effects (Wallmann et al., 2019). The differences in results may be due to the use of different protocols in respect to frequency (with a range of 20–50 Hz), amplitude (2–10 mm) and duration (30 s–10 min) of WBV. Middle age is associated with physiological decline of, among other parameters, muscle power (Metter et al., 1997; Reid & Fielding, 2012). While physical exercise is known to be effective in improving muscle power and performance (Booth et al., 2011), adherence to exercise training routines tends to be low (Kowal & Fortier, 2007). WBV may be a tool capable of overcoming barriers to regular physical exercise (Wallmann et al., 2019). In comparison to a control group, a 5-week progressive WBV training in 45–55-year old women was demonstrated to improve vertical countermovement jump and range of motion performance (Hawkey et al., 2016). These findings suggest that WBV training can reduce age-related performance deterioration in middle age.

WBV training may be a useful exercise modality, especially in elderly people, since it does not require conventional dynamic exercise such as free weight or dynamic movement. In a randomised controlled trial, for example, short training sessions using WBV three times weekly for 6 weeks improved gait, motor capacity, body balance and quality of life in elderly nursing home residents (Bruyere et al., 2005). Various benefits have been reported following WBV training (Sitjà-Rabert et al., 2012), including increased muscle strength (Bogaerts et al., 2007) and bone density (Verschueren et al., 2004) as well as improved cardiorespiratory fitness (Bogaerts et al., 2009), body balance (Bautmans et al., 2005; Cheung et al., 2007; Torvinen et al., 2002) and quality of life (Runge et al., 2000). WBV exercise in older people also appears to produce beneficial effects on walking ability and postural control (C.-H. Chen et al., 2014; Osugi et al., 2014; Silva & Schneider, 2011). A systematic review and meta-analysis, combining the evidence from randomised controlled trials of resistance training, endurance training and WBV exercise in older people, examined the comparative effects of these different approaches (Lai et al., 2018). WBV appeared to have a small beneficial effect on physical performance. However, resistance training of a minimum 6 weeks duration was found to be the most effective intervention, achieving a substantial increase in muscle strength and a moderate improvement in physical performance when compared with people following their normal routine (Lai et al., 2018). Furthermore, WBV provided no additional benefit in regard to muscle strength, balance or mobility when added to a comprehensive exercise programme attended regularly by institutionalised older adults (Lam et al., 2018).

1.1.2 WBV in the management of chronic conditions

WBV has been proposed to be of potential use in a variety of chronic medical conditions, such as lower back pain, fibromyalgia, osteoporosis, obesity and diabetes. Exercise treatment is widely recommended and used in people with non-specific lower back pain (Searle et al., 2015). Vibration has been suggested to be of value when used as an exercise modality rather than in an occupational context, and to be able to alleviate rather than aggravate chronic back pain (Iwamoto et al., 2005; Rittweger et al., 2002). WBV has also been used as a complementary treatment to relieve pain intensity and improve back function (Boucher et al., 2013; B. Chen et al., 2019; del Pozo-Cruz et al., 2011; Wang et al., 2014; Zheng et al., 2019). It has been further hypothesised that WBV exercise may be more helpful than general exercise, since vibratory stimulation may increase muscle strength and joint stability by improving neuromuscular activation (Maeda et al., 2016; Ye et al., 2014). A systematic literature review concluded that there is no clear evidence of therapeutic efficacy of WBV exercise in individuals with nonspecific chronic lower back pain (Perraton et al., 2011). However, this conclusion was based on randomised controlled trials with small sample sizes. A recent randomised controlled trial comprising 89 participants with non-specific chronic low back pain showed that WBV exercise was more effective than general exercise in relieving pain and improving functional disability (Wang et al., 2019). Further studies should include different subgroups exposed to different WBV frequencies.

Fibromyalgia is a chronic disorder of unknown aetiology, which is characterised by chronic, widespread, non-inflammatory body pain, fatigue, insomnia, and poor physical fitness (Bennett et al., 2007; Bennett, 2009). Exercise training is commonly recommended for adults with fibromyalgia. WBV may be helpful in the management of this disorder, since it could offer benefits in regard to balance, fatigue, pain, disability and health-related quality of life. A systematic literature review surmised that WBV could be an effective treatment for fibromyalgia as a main therapy or in addition to physical exercise programmes (Collado-Mateo et al., 2015). However, the comparison of the small number of available trials was limited by significant differences in intervention, protocol and assessment. A Cochrane study analysed whether WBV alone or in addition to mixed exercise is superior to a control condition or another intervention in women with fibromyalgia (Bidonde et al., 2017). The findings of this study indicated that the small number of participants and wide confidence intervals yielded very low quality evidence. Furthermore, the few studies included in the Cochrane analysis failed to measure major outcomes such as pain intensity, stiffness, fatigue or physical function.

Low bone mineral density and associated osteoporosis are major risk factors for fragility fractures (Gregg et al., 1997; Kanis et al., 2000). Mechanical stimulation is necessary for the maintenance of bone health (Frost, 1994), and physical exercise is an effective treatment for osteoporosis (Pollock et al., 1998). WBV training has been employed as an alternative exercise intervention and has been demonstrated to increase bone density via mechanical load (Prioreschi et al., 2012). A recent systematic review and meta-analysis evaluated the results of published randomised controlled trials assessing the effects of WBV on bone mineral density in postmenopausal women (Marín-Cascales et al., 2018). Statistically significant differences in lumbar spine and femoral neck bone mineral density between WBV intervention and control groups were found (Marín-Cascales et al., 2018). However, the number of published studies was small and the WBV protocols used were highly heterogeneous.

Two major health risk factors today are high body mass index and high fasting plasma glucose, both of which are increasing in prevalence at an alarming rate (Lange, 2017). The majority of obese people maintain a sedentary lifestyle and show little inclination to enroll and persist in conventional exercise programs due to physical limitations, musculoskeletal discomfort or lack of self motivation. WBV may therefore offer a low-threshold training option. Factors that may contribute to a reduction in fat mass after WBV exercise include: (1) triggering of lipolysis through activation of the central sympathetic nervous system innervating white adipose tissue, (2) improved insulin action and glucose regulation leading to enhanced glycaemic control, and (3) an increase in the release of growth hormone, which stimulates metabolism and is usually decreased in obese people (Zago et al., 2018).

The findings of a systematic review of the scientific literature showed that WBV training is a promising adjuvant intervention in the treatment of obese women (Zago et al., 2018). WBV training may be particularly useful in deconditioned obese individuals with poor motivation (Figueroa et al., 2012). When WBV exercise is combined with dietary intervention or used as an alternative to traditional exercise training, it may be as effective as aerobic and resistance exercise in reducing fat mass (Nam et al., 2016; Vissers et al., 2010). Improved cardiac autonomic function (Severino et al., 2017; Wong et al., 2016) and a decrease in central and peripheral arterial stiffness (Alvarez-Alvarado et al., 2017; Wong et al., 2016) have been observed following at least 6 weeks of WBV exercise, and a significant reduction in body weight and an improvement in muscle strength have been seen after 10 or more weeks of training (Alvarez-Alvarado et al., 2017; Figueroa et al., 2014; Milanese et al., 2013; Severino et al., 2017). Further long-term studies, with male as well as female participants, are needed to further evaluate the health benefits of WBV exercise in obese people.

WBV exercise has been shown to reduce blood glucose levels (Di Loreto et al., 2004) but not to affect insulin or glucagon concentrations. The most likely explanation for this is elevated glucose uptake into contracting skeletal muscles. A pilot study examined the effect of WBV on blood glucose levels in elderly people and found a significant decrease following a single 10-minute WBV session (Licurci et al., 2017). These beneficial effects on glucose levels need to be confirmed in studies using larger samples and control groups. An acute session of WBV training has been shown to reduce glucose levels in elderly women with diabetes (Pessoa et al., 2018). The findings of a systematic review and meta-analysis of randomised controlled trials suggest that a 12-week progressive intervention with WBV combined with exercise has a slight, statistically significant effect on glycaemic control in patients with type 2 diabetes (Robinson et al., 2016). High-quality trials need to establish the efficacy of WBV in diabetes and to clarify whether the effects are due to vibration, exercise or a combination of both. WBV training in addition to a hypocaloric diet may further enhance insulin sensitivity and glucose regulation (Bellia et al., 2014).

WBV has often been promoted in recent years as a useful intervention and has shown favourable outcomes in the rehabilitation of various populations with chronic conditions that normally diminish quality of life. A systematic review of the available literature attempted to identify the effects of WBV on health-related quality of life in individuals with chronic conditions, such as respiratory, musculoskeletal and neurological diseases (G. Li et al., 2019). Based on the findings of randomised controlled trials comparing WBV with non-intervention or alternative intervention groups, it was found that WBV may improve health-related quality of life in patients with chronic conditions. However, the evidence provided is insufficient to warrant the recommendation of WBV as an intervention (G. Li et al., 2019).

1.1.3 Conclusion and future perspectives

Despite many promising findings, it is currently far from clear whether WBV can play a role in the promotion of physical fitness and the management of chronic medical conditions. While many studies have shown improvements after exposure to WBV, others found no positive effects on performance. Major problems hampering the evaluation of the available evidence involve a wide range of methodological issues, including a lack of standardised procedures. The value of comparisons between the available studies is limited by varying interventions, vibration protocols and measurements. In order to ensure the reproducibility of WBV interventions, the information provided in research reports should include the type of vibration, frequency, amplitude, peak acceleration and duration of vibration, assessment of accuracy of vibration parameters, type of footwear, potential slipping of the feet and use of support devices during vibration exposure (e.g. in frail people) (Rauch et al., 2010).

1.2 Effects of whole-body vibration on cognition

Evidence regarding the effects of physical activity (PA) on cognition has shown beneficial effects of an acute bout of PA on cognitive performance (Y. K. Chang et al., 2012; J. L. Etnier et al., 1997; Pontifex et al., 2019; Tomporowski, 2003). However, only a few studies to date have examined the effects of whole-body vibration (WBV) on subsequent cognitive performance (see Table 1.1).

Furthermore, other previous studies have either shown performance deterioration (Sandover & Champion, 1984; Sherwood & Griffin, 1990, 1992) or no effects (J. Ljungberg et al., 2004; J. K. Ljungberg & Neely, 2007b) during WBV exposure.

Table 1.1 *Evidence regarding positive and negative effects of WBV exposure on subsequent cognitive performance*

Study	Cognitive Tests (Domains)	Results
(den Heijer et al., 2015)	Stroop Test (*Executive function/inhibition*)	positive
(Fuermaier, Tucha, Koerts, van den Bos et al., 2014)	Stroop Test (*Executive function/inhibition*)	positive
(Regterschot et al., 2014)	Stroop Test (*Executive function/inhibition*)	positive
(J. K. Ljungberg & Neely, 2007a)	Search And Memory Task (*Attention*)	negative
(Zamanian et al., 2014)	Selective Attention Test, Divided Attention Test (*Attention*)	negative

1.2.1 Suitable research design

Initially, the choice of a suitable research design should be considered when planning a study to explore the effect of WBV on subsequent test performance (Pontifex et al., 2019) (*see* Table 1.2 for an overview).

The studies showing beneficial effects of WBV on cognitive performance (*see* table 1.1) used a within-subject design, which means that participants in these studies were repeatedly exposed to WBV and subsequent cognitive assessment (den Heijer et al., 2015; Fuermaier, Tucha, Koerts, van Heuvelen et al., 2014; Regterschot et al., 2014). Thus, improved cognitive functioning was likely to be affected by learning and practice due to repeated exposure to vibration treatment and subsequent cognitive testing.

Table 1.2 *Categorization of experimental designs common in PA-cognition interaction studies (Pontifex et al., 2019)*

Research design	**Main characteristics**	
	Study design	*Cognitive assessment*
Between-Subjects Posttest comparison	Each subject is included in just one study condition	After cessation of the experimental condition
Between-Subjects Pretest Posttest comparison		Pre- and posttest
Within-Subjects Posttest comparison*	Each subject is included in the same study condition experiencing a particular form of PA (or a control condition)	After cessation of the experimental condition
Within-Subjects Pretest Posttest comparison		Pre- and posttest
Within-Subjects Crossover Posttest Comparison	Each subject is consecutively included in both a PA condition and a control condition (e.g., on separate days)	After each cessation of the experimental condition
Within-Subjects Crossover Pretest Posttest Comparison		Pre- and posttest

** This type of experimental design was not included in the list of Pontifex et al. (2019).*

However, an alternative between-subjects design with only post-test measurements of cognitive performance involves the difficulty that this approach only allows the assessment of differences between two or more groups, and the differences obtained are assumed to be due to the exercise treatment (Pontifex et al., 2019). Nevertheless, this experimental design may be suitable for examining the effect of WBV exposure on subsequent cognitive performance with regard to specific criteria including random assignment to experimental conditions, a sufficient sample size and appropriate covariates. Furthermore, a between-subjects design may avoid learning and practice effects in light of specific characteristics of the study sample, such as motivation, age and IQ (Bartels et al., 2010).

Thus, a within-subjects design was applied in studies 1 and 2 due to the positive results of the studies summarised above examining the effects of WBV on cognitive performance. However, as the results of studies 1 and 2 did not reveal beneficial cognitive functioning following WBV, compared to a control condition, subsequent studies used a between-subjects design to avoid learning effects and explore the effect of the study design on the relationship between WBV and subsequent cognitive performance.

1.2.2 Suitable control condition

A second question concerns the selection of an appropriate control condition to examine the effects of WBV on subsequent test performance. It may be assumed that participants will develop specific expectations about both the physiological requirements needed when they are exposed to WBV and the outcome variables assessed. Thus, as participants formulate their own assumptions regarding the presumptive outcomes of the present study when they enrol in the experiment, they will eventually behave in a way that fits the assumption (Pontifex et al., 2019). Therefore, the most suitable control condition should always be considered when designing a study about the effects of PA on cognition in general (Merriman et al., 2011).

Within the PA-cognition interaction literature, four different control conditions have typically been discussed (Pontifex et al., 2019): baseline control conditions, passive control conditions, control conditions engaging cognitive processes and control conditions engaging another form of PA. A baseline control condition means that baseline performance is captured prior to the experimental intervention but not utilised as a form of pretest. In a passive control condition, subjects do not engage in any activities other than sedentary behaviour such as sitting on a chair without cognitive engagement, and this is also known as a disengagement control condition. In a control condition engaging cognitive processes, subjects participate in cognitively endearing activities such as reading or watching a video. Recently, a control condition engaging in another form of PA has been shown to be an active form of control condition.

The comparison of different types of control conditions suggested that a suitable control condition for WBV exposure could be participants standing on the vibration platform, as this appears to be a disengagement control condition where subjects stand on a vibration platform without undergoing WBV. Moreover, standing on the vibration platform without exposure to WBV seems to constitute the most appropriate control condition when the duration remains constant in both the experimental and the control conditions, such that the only aspect that differs between the study groups is the presence or absence of WBV. Therefore, a disengagement control condition that comprised standing on the vibration platform without WBV exposure was chosen for the studies described below.

2 Studies

2.1 Effects of whole body vibration on different components of attention

2.1.1 Introduction

Numerous studies have shown that physical activity is beneficial to physical health (Warburton et al., 2006). For example, regular physical activity has been shown to reduce the risk of non-communicable diseases, such as obesity, cardiovascular disease and type-2 diabetes (Penedo & Dahn, 2005; Wahid et al., 2016). In addition to studies reporting associations of elevated physical activity levels with physical health benefits, other studies have revealed that physical activity may also increase emotional wellbeing and decrease symptoms associated with depression or anxiety (McMahon et al., 2017; Penedo & Dahn, 2005), especially in adolescents (Biddle & Asare, 2011).

Increasing evidence suggests that physical activity has beneficial effects on cognitive functions. For example, aerobic fitness training has been found to improve the performance of elderly people in cognitive tasks, irrespective of training method or task type (Colcombe & Kramer, 2003). Other studies in the elderly suggest that regular aerobic exercise can enhance various cognitive processes, such as selective attention, task switching, working memory span and inhibition (Guiney & Machado, 2013). Physical activity has been demonstrated to have beneficial effects on cognitive functions, such as concentration and working memory, and on academic performance in children and adolescents (Esteban-Cornejo et al., 2015; Haapala, 2012).

Overall, the findings of many studies in the field of sport and exercise research point to positive effects of physical exercise on cognition (Colcombe & Kramer, 2003). In particular, physical activity appears to improve performance in cognitive tasks assessing executive functions (Hillman et al., 2008). Executive functions are the mental processes underlying the regulation, management and control of other cognitive processes, such as attention, working memory, mental flexibility and inhibition (Chan et al., 2008). People unable to take physical exercise may need alternative means of attaining the benefits for cognition derived from physical activity. One such alternative is whole body vibration (WBV), which is characterised as the exposure of the whole body to mechanical vibrations produced by a vibrating platform (Regterschot et al., 2014). WBV is often used as a training method, with people performing specific exercises while standing on the platform. This active form of WBV can be distinguished from a passive form, where people undergo vibration without performing exercises. Passive WBV might play a role in the fostering of physical fitness in elderly people or the treatment of chronic diseases (Gritschmeier & Lange, 2020). Furthermore, passive WBV has been suggested to improve executive functions in individuals unable to play sports actively (Regterschot et al., 2014).

Several studies have investigated the effects of active WBV on various physiological measures in both non-clinical and clinical samples (Fuermaier, Tucha, Koerts, van Heuvelen et al., 2014). For example, whole-body oxygen uptake (VO_2) has been found to be significantly increased by vibration (Rittweger et al., 2001). Furthermore, heart rate, muscle activity and diastolic blood pressure are enhanced by active WBV compared to the same exercises performed without WBV (Cochrane et al., 2008). In older adults, WBV was shown to improve both balance ability and mobility (Lam et al., 2012).

Beneficial effects of WBV on cognitive performance have been shown primarily in murine studies examining learning processes in mice following WBV treatment (Lahr et al., 2009; Timmer et al., 2006). The findings of these studies suggest positive effects of WBV on cognition, with daily WBV treatment for five weeks significantly enhancing maze learning in aged and young mice compared to controls not exposed to WBV.

Several studies have investigated possible effects of WBV on cognition in humans. Initial studies examined changes in cognitive functioning of healthy people when performing cognitive tasks during WBV. Some studies have shown deteriorations in long-term memory, short-term memory and arithmetic reasoning skills during WBV (Sandover & Champion, 1984; Sherwood & Griffin, 1990, 1992) while others found no effects of WBV on short-term memory or reasoning skills (J. Ljungberg et al., 2004; J. K. Ljungberg & Neely, 2007b). Further studies examined possible effects of WBV on subsequent performance in tasks assessing executive functions in healthy individuals and adults with attention-deficit/hyperactivity disorder (ADHD) (Fuermaier, Tucha, Koerts, van Heuvelen et al., 2014; Regterschot et al., 2014). These studies demonstrated that short-term exposure to WBV (two minutes) elicited improvements in attention in both healthy people and those with ADHD (Fuermaier, Tucha, Koerts, van Heuvelen et al., 2014). Since both studies used the same cognitive task (Stroop Colour-Word Interference task), it is unclear whether the beneficial effects of WBV on attention performance may also be found for other tasks measuring different aspects of attention. Furthermore, the findings of another study on the effects of WBV on inhibition suggested that a positive effect on cognitive performance may rely on repetitive exposure to WBV treatment (den Heijer et al., 2015).

The aim of the present study was to examine whether WBV can affect other types of attention tasks in healthy students. Based on the available literature, the hypothesis of this study was that exposure to WBV twice for two minutes would increase attentional functions, as assessed using an attention test battery, compared to a control condition without vibration.

2.1.2 Methods

2.1.2.1 Participants

Eighty undergraduate psychology students aged 18–35 years participated voluntarily in this study. Individuals with uncorrected sensory or motor impairments were not included. The participants were randomly assigned to one of four test conditions. In each condition, 20 people were tested on one of four cognitive tests assessing different aspects of attention. The participants were rewarded with research hours required for psychology studies. The participants' age, sex and IQ (Lehrl, 1995) for each test condition are presented in Table 2.1.

Table 2.1 *Age, sex and IQ of study participants for each test used*

	Alertness	**Working memory**	**Divided attention**	**Go/nogo**
Age (years, mean ± standard deviation)	22.5 ± 4.8	22.1 ± 3.7	20.5 ± 1.9	23.8 ± 7.2
Sex (female/male)	18/2	16/4	16/4	16/4
IQ (mean ± standard deviation)	103.2 ± 10.4	107.0 ± 12.2	107.2 ± 13.4	97.0 ± 7.5

2.1.2.2 Materials

WBV

A vibrating platform (Galileo Med Advanced, Novotec Medical GmbH, Pforzheim, Germany) (Novotec Medical GmbH, 2015) was used to administer passive vibration (650 x 510 x 120 mm; 36 kg). The vibration platform generates mainly vertical sinusoidal vibrations. The vibration frequency can be adjusted with 0.5 Hz increments from 5 Hz to 30 Hz and the vertical vibration amplitude can be set from 0 to ± 4.5 mm. In addition to frequency and amplitude, duration is an adjustable parameter of the platform. The platform provides an additional setting (Wobble), with the frequency of vibration fluctuating continuously within the range of a given frequency and offers four different degrees: soft, normal, hard and custom. Two vibration conditions and a control condition were implemented. The vibration conditions were (1) WBV using a consistent frequency of 15 Hz and (2) wobble condition with a frequency of 15 Hz and the wobble degree “normal” (15 Hz ± 2.5 Hz). In both conditions, the amplitude of vibrations was 2 mm. There was no vibration in the control condition. The participants stood on the platform without shoes.

Test battery for the assessment of attention

The computerised Battery of Tests for Assessing Attention (Zimmermann & Fimm, 1993) was used to examine the effects of vibration on different components of attention. The following four TAP subtests were used: (1) alertness, (2) working memory (difficulty level 2), (3) divided attention (execution form 1) and (4) go/nogo (1 out of 2). The alertness subtest measured reaction times (RTs) under two conditions. Participants were required to respond as quickly as possible, by pressing a key, when visual stimuli appeared on a computer screen. In the tonic alertness condition, the stimuli were presented without prior warning. Phasic alertness was assessed by measuring RTs when a warning sound preceded the appearance of the visual stimulus (Zimmermann & Fimm, 1993). The working memory subtest required participants to match sequentially presented visual stimuli in terms of a 2-back task. In the test condition chosen, the participants were asked to determine whether each double-digit number presented on the screen corresponded with the previous one or the number before that. This task examined the control of information flow and the updating of information in working memory (Zimmermann & Fimm, 1993). The divided attention subtest was a dual-task paradigm, with a visual and auditory task needing to be performed simultaneously (Zimmermann & Fimm, 1993). The go/nogo subtest assessed behavioural control and required the inhibition of responses provoked by visually similar, but non-target stimuli (Zimmermann & Fimm, 1993).

2.1.2.3 Study design and procedure

Each participant underwent three test sessions within seven days; the test sessions were separated by at least one day. Within each session, the participants were exposed to one of the three conditions (WBV, Wobble or Control) with subsequent attention testing. Each condition on the vibrating platform lasted two minutes and was immediately followed by attention testing. A further two minutes of the same condition as well as consecutive attention testing followed. The order of the attention subtests administered was alertness, working memory, divided attention and go/nogo. To avoid order effects of testing in the repeated measures design over three sessions, a counterbalanced design using six different sequences of the three vibration conditions was used.

2.1.2.4 Statistical analysis

The outcome measures used for the TAP subtest “alertness” were median of RTs and phasic alertness; for “working memory”, the number of correct reactions, number of errors, number of omissions and median of RTs; for “divided attention”, the number of errors and number of omissions; for “go/nogo”, the number of errors and median of RTs. A two-way analysis of variance (ANOVA) with repeated measures was performed for each of the four TAP subtests. One factor was “test condition” (WBV, Wobble and Control) and the other was “assessment stage” (first or second testing of attention within a session). P-values of less than 0.05 were considered statistically significant. No multiple testing correction was performed. All statistical analyses were performed using the Statistical Package for Social Sciences 22.0 (SPSS, IBM 2015).

2.1.3 Results

Means and standard deviations for the parameters analysed in the four test groups (alertness, working memory, divided attention and go/nogo tests) are presented in Table 2.2. No statistically significant main effects of the factors *test condition* or *assessment stage* or interaction effects were found for any of the parameters.

Table 2.2 *Mean values of the parameters analyzed in the four test groups (alertness, working memory, divided attention and go/nogo tests)*

	Test condition	**WBV**				**Wobble**				**Control**			
	Assessment stage	1		2		1		2		1		2	
TAP subtest	*Outcome measures*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Alertness	*Median of response times*	219.8	22.3	221.8	24.2	218.7	21.0	216.0	24.6	215.5	23.4	211.0	22.2
	Phasic alertness	.01	.05	.03	.05	.02	.06	.01	.05	.03	.06	.01	.04
Working memory	*Median of response times*	554.7	154.2	555.7	190.3	553.2	160.1	580.9	185.9	521.7	141.2	553.5	128.9
	Number of correct reactions	12.6	4.0	12.6	3.5	12.6	3.7	12.5	3.5	11.5	4.0	12.7	3.7
	Number of errors	2.1	3.3	1.4	2.3	2.5	4.6	2.1	3.4	1.5	3.0	1.2	2.8
	Number of omissions	2.5	4.0	2.5	3.5	2.4	3.7	2.5	3.5	3.5	4.0	2.3	3.7
Divided attention	*Number of errors*	5.6	7.1	3.9	6.4	6.9	9.5	5.0	8.5	5.6	7.1	5.7	8.9
	Number of omissions	1.8	1.8	1.0	1.1	1.1	1.4	1.3	1.9	.9	1.0	.8	.9
Go/Nogo	*Median of response times*	354.1	42.6	358.3	44.9	341.9	41.8	356.4	40.6	362.5	46.2	367.6	60.1
	Number of errors	1.4	.9	.7	.9	1.8	1.6	1.1	1.4	1.7	1.9	.8	.9

**M* = mean; *SD* = standard deviation

2.1.4 Discussion

The aim of the present study was to investigate possible effects of WBV in healthy university students on different attentional functions using the TAP (alertness, working memory, divided attention, go/nogo). The results of the study did not reveal any statistically significant effects between the two vibration conditions used (WBV, Wobble) and the control condition on the attentional components assessed. Individuals exposed to a vibration condition immediately before attention testing did not perform better than those not exposed to vibration. The significant reduction of errors in the test go/nogo from the first to the second assessment stage may be due to a practice effect.

In the present study, participants in the vibration conditions produced neither quicker responses nor fewer mistakes than controls; neither did they work more carefully, as shown in the numbers of omissions or false reactions. Our results could not confirm the findings of other studies showing positive effects of WBV on some cognitive abilities when the respective tests were performed immediately after WBV (Fuermaier, Tucha, Koerts, van Heuvelen et al., 2014; Zamanian et al., 2014). While other studies found that physical activity and WBV improved working memory performance (Smith et al., 2010) the present study, in accord with the results of J. K. Ljungberg und Neely (2007a), showed no positive effects of WBV exposure on subsequent test performance. In view of the absence of studies investigating the influence of WBV treatment on tests of alertness or divided attention, future studies should examine in more detail whether these attentional components may benefit from WBV.

Previous studies examining cognitive abilities after exposure to vibration (den Heijer et al., 2015; Fuermaier, Tucha, Koerts, van Heuvelen et al., 2014; J. K. Ljungberg & Neely, 2007a; Regterschot et al., 2014) revealed shorter RTs, while, in accordance with other studies investigating cognitive abilities during WBV (Costa et al., 2012; Sherwood & Griffin, 1992), the present study found longer RTs. In studies investigating WBV effects while participants are standing on the vibrating platform, distraction caused by the vibration may explain increased RTs (McLeod & Griffin, 1995). Taken together, the present results do not support the hypothesis that WBV produces beneficial effects on the attentional functions tested.

Available literature reviews have addressed several factors that should be considered when discussing the absence of positive effects of WBV on attention in the present study (Conway et al., 2007; J. K. Ljungberg, 2008; J. K. Ljungberg & Parmentier, 2010). First, the frequency of vibration may influence the subjective sensitivity of an individual to vibration (J. K. Ljungberg & Parmentier, 2010). A model has been proposed assuming three main effects of vibration, namely a physical reaction to the proliferation of vibration over the whole body as well as physiological and psychological functions (Kubo et al., 2001). From a physiological perspective, vibration in the range of 2 to 5 Hz leads to an increase of blood pressure and heart rate, which may be psychologically associated with a subjective exacerbation of exhaustion, possibly causing the failure of vibration to produce positive effects on cognition (Jiao et al., 2004). Most of the studies revealing negative effects of vibration used relatively low frequencies (Costa et al., 2012; J. K. Ljungberg & Neely, 2007a), while other studies showing primarily positive effects of vibration on cognition applied higher frequencies (den Heijer et al., 2015; Fuermaier, Tucha, Koerts, van Heuvelen et al., 2014; Regterschot et al., 2014). Although the present study used vibration similar to those studies reporting positive results, no positive effects were found.

Second, the exposure time to WBV may be a decisive factor in the outcome. It has been suggested that discomfort of participants increases with exposure time (Kjellberg, 1990), potentially leading to deteriorating results. At present, the optimal duration of exposure to WBV is unclear, and it is also possible that longer exposure times could lead to improved performance following WBV (Regterschot et al., 2014).

Third, when discussing factors accounting for the different effects of WBV on cognition, characteristics of the tasks used should also be considered, particularly task type and task complexity (T. McMorris, 2017). In a meta-analysis of the effects of exercise on cognition, the effect sizes regarding alertness and attention tasks were overall smaller than for central executive tasks, which suggests a pronounced effect of acute exercise on the mediating of executive functioning by the prefrontal cortex (T. McMorris & Hale, 2012). In addition, a ceiling effect of more simple tasks, as used in the present study, should be considered (T. McMorris & Hale, 2012). In general, several authors have stated that simple tasks may be less likely to be affected by physical activity than more complex tasks (T. McMorris & Hale, 2012).

Fourth, another potentially important factor that needs to be considered is the timing of test administration (during versus post-exercise). A meta-regression analysis found that exercise improved cognitive performance when the test was administered immediately after physical activity, regardless of the kind of exercise undertaken (Lambourne & Tomporowski, 2010). Thus, metabolic changes and elevated levels of arousal during physical activity may promote cognitive performance (Audiffren et al., 2008; Tomporowski, 2003). However, significant differences in performance following exercise were not found in tasks with a speed component, in which participants were required to react as quickly as possible (T. McMorris & Hale, 2012). This may also explain the negative results of the present study. Future studies should aim to investigate which task characteristics are essential to obtain positive effects of acute exercise on subsequent cognitive performance.

In summary, in comparison with no vibration, WBV immediately before assessment of attentional functions was not found to be associated with better performance in tests examining tonic and phasic alertness, working memory, divided attention and response inhibition. Future studies should examine the influence of WBV on other cognitive functions, such as executive functions or memory and learning. Such studies should vary both the WBV parameters described above and the task characteristics in order to obtain a better understanding of the way in which improvements of cognitive functioning through WBV could be effected. Since little is known about the potential processes generating positive effects of WBV on cognition, psychophysiological or neuroimaging studies may shed light on the biological processes underlying possible WBV effects on cognition.

2.2 Effects of whole body vibration on attention: Role of vibration duration and task complexity

2.2.1 Introduction

Physical activity (PA) has been identified in numerous studies to play an important role in the primary and secondary prevention of various chronic medical conditions and premature mortality (Warburton & Bredin, 2017). A decreased risk of chronic diseases, increased emotional well-being and reduced stress and depression are known benefits of regular PA. In contrast, physical inactivity is associated with substantial economic costs, including direct health care costs as well as indirect costs, such as work loss due to disability (Humphreys et al., 2014). A growing body of literature confirms the health benefits resulting from the incorporation of PA into the daily routine (Shook et al., 2015; Soares-Miranda et al., 2016). Other studies have revealed associations of regular PA with well-being and better mental health in adolescents (McMahon et al., 2017).

In addition to the reported beneficial effects of PA on physical and mental health, there is mounting evidence that cognitive abilities may also be improved by PA. A meta-analytic study has shown that aerobic fitness training significantly increases the cognitive performance of older adults, irrespective of training method or task type (Colcombe & Kramer, 2003). In addition, regular aerobic exercise can improve various cognitive processes in older adults, such as inhibition, selective attention, working memory span and task switching (Guiney & Machado, 2013). Positive associations of PA and academic and cognitive performance have also been found in adolescents (Esteban-Cornejo et al., 2015). PA also appears to be linked to better mental health in young people (Biddle & Asare, 2011). A literature review has reported that PA may aid concentration and working memory and increase academic performance in both children and adolescents (Haapala, 2012).

Furthermore, in sport and exercise research, abundant evidence points to positive effects of PA on cognition (Colcombe & Kramer, 2003). Cognitive abilities, especially attentional processes, are affected by physiological factors, such as blood pressure (Elias et al., 1997) oxygen uptake (Scholey et al., 1999), nutrition (Pönicke et al., 2005) and sports (Hillman et al., 2008). While acute coordinative exercise fosters enhanced attention and concentration performance in healthy adolescents (Budde et al., 2008), aerobic exercise training leads to modest improvements in attention, executive function, processing speed and memory (Smith et al., 2010). People unable to perform physical exercise may benefit from alternatives to exercise, such as whole body vibration (WBV), which is the exposure of the whole body to mechanical vibrations produced by a vibrating platform (Regterschot et al., 2014). When used as a training method, specific exercises are performed while standing on the platform. This active form of WBV can be distinguished from a passive form in which people undergo vibration without performing exercises. Passive WBV might play a role in the fostering of physical fitness in elderly people or the treatment of chronic diseases (Gritschmeier & Lange, 2020) It has also been suggested as an alternative means of improving executive functions in people unable to undertake active sports (Regterschot et al., 2014).

Both in clinical and non-clinical samples, potential effects of active WBV on different physiological measures have been investigated (Fuermaier, Tucha, Koerts, van Heuvelen et al., 2014). Diastolic blood pressure, heart rate and muscle activity have been shown to be improved through active WBV to a similar extent to exercises performed without WBV (Cochrane et al., 2008). Whole-body oxygen uptake (VO_2) has also been demonstrated to be significantly increased following passive vibration (Rittweger et al., 2001). Other studies have revealed that WBV may improve balance and mobility in older adults (Lam et al., 2012).

The available research on the effects of WBV on cognitive abilities is sparse and inconsistent (Kjellberg, 1990; J. K. Ljungberg, 2008). In addition to different performance tests, previous studies have used various frequencies, amplitudes and durations of WBV. In rodent studies examining learning processes, subsequent WBV treatment produced beneficial effects on cognitive performance (Lahr et al., 2009; Timmer et al., 2006). Both old and young mice have shown enhanced maze learning performance when undergoing WBV treatment compared to control mice. Human studies have examined cognitive functioning of healthy people performing cognitive tasks during WBV. In a study investigating the effects of WBV on short-term memory (memory scanning), different intensities of WBV were used (0, 1.0, 1.6 und 2.5 m/s^2) (Sherwood & Griffin, 1990). This study found a detrimental effect of vibration on performance. In another study, participants performed a memory task during WBV of 16 Hz (2.0 m/s^2). Participants in the experimental condition performed worse than controls without WBV (Sherwood & Griffin, 1992). Negative effects of WBV on performance have also been reported in other studies (Conway et al., 2007 ; Costa et al., 2012). Simulation of automotive vibration has been shown to impair attentional processes (J. K. Ljungberg & Neely, 2007a; Zamanian et al., 2014). Further studies found no evidence of a connection between WBV and cognitive performance (J. Ljungberg et al., 2004; J. K. Ljungberg & Neely, 2007b).

Since the results of studies showing possible effects of concurrent WBV on cognitive performance can be distorted by distraction effects, additional studies have assessed prolonged effects of WBV on cognitive functioning after exposure to WBV. For example, improved performance in a computerised Stroop task has been reported following two minutes of WBV (30 Hz) (Fuermaier, Tucha, Koerts, van Heuvelen et al. (2014). This effect could be observed both in healthy people and in those with a diagnosis of ADHD. Similar results revealing positive effects on executive functions in healthy individuals after WBV exposure have been found (Regterschot et al., 2014). As both of the above studies used the same cognitive task (Stroop Colour-Word Interference task), it remains unclear whether the beneficial effects of WBV on attention may also be found for tasks measuring other aspects of attention.

In the research field of exercise and cognition, two factors should be taken into account: parameters related to exercise (mode, intensity, duration) and task characteristics (difficulty, complexity). Several variables moderating the link between PA and cognition include counterbalancing/randomization, timing of testing (during exercise versus post-exercise) and task complexity (T. McMorris & Hale, 2012). Many studies have suggested that simple tasks are less likely to be influenced by PA than more complex tasks (Dietrich, 2003; Terry McMorris & Graydon, 2000). The established interaction between brain function, stress and central executive tasks would presuppose that complex tasks will be more sensitive to both positive and negative effects of acute PA (T. McMorris & Hale, 2012).

The aim of the current study was to investigate whether WBV results in differences in task performance in participants performing an attentional test of high task complexity following WBV exposure. The study is predicated on the contention that more basic tasks (e.g. simple reaction tasks) may elicit ceiling effects compared to more complex tasks (T. McMorris & Hale, 2012).

2.2.2 Methods

2.2.2.1 Participants

This study was conducted at a laboratory of the University of Regensburg, Germany. A sample of 40 undergraduate psychology students (34 females and 6 males; mean age ±

standard deviation: 21.5 ± 3.6) voluntarily participated in the study. Each participant underwent each of three vibration conditions (WBV with constant vibration frequency, WBV with fluctuating vibration frequency, no vibration) in a within-subject design. Exclusion criteria were: age below 18 years and above 35 years, uncorrected sensory or locomotor impairments, pregnancy and first language other than German. The participants received course credits for their participation. Each participant underwent three test sessions within seven days.

2.2.2.2 Materials

Demographic Variables

At the beginning of the first test session, participants completed a questionnaire including the demographic variables: age, gender, handedness, native language, graduation, study path (or possibly job) and semester.

Primary Appraisal Secondary Appraisal (PASA)

The PASA serves as a self-report questionnaire assessing anticipatory cognitive appraisals based on the transactional model of stress by Lazarus und Folkman (1984). This model posits the existence of two different evaluation processes in stress-related situations, operationalised with two subscales. Firstly, the relevance of the situation should be assessed relative to the extent of potential costs and benefits (primary appraisal). Subsequently, the perceived coping resources, the degree to which an individual feels able to change the difficult interaction of person and environment, should be assessed (secondary appraisal). As the self-concept of the individual’s own abilities and the locus of control play an important role, these two concepts constitute the subscales of the secondary appraisal (Gaab, 2009; Lazarus & Folkman, 1984). A person’s total load is described by the stress index as the difference between the primary and secondary appraisal. Cronbach’s α ranges from 0.61 to 0.83, representing good homogeneity of the questionnaire. The factor structure has been validated in a non-clinical sample of 81 healthy male students (Gaab, 2009).

WBV

For all settings of the device used, we refer to section 2.1.2.2 ("WBV"). In the present study, a control condition without vibration and two different vibration conditions were implemented: a WBV condition with a constant frequency of 15 Hz (WBV-C) and another with a frequency of 15 Hz and the Wobble degree normal (15 Hz ± 2.5 Hz; WBV-W). In the control condition, the vibration platform was switched on, but no vibration took place. The participants stood on the platform without shoes.

Wiener Testsystem: Cognitrone

The Cognitrone is a subtest of the Wiener Testsystem, which assesses attention and concentration (Schellig et al., 2009). This test is based on the model of Reulecke W. (1991), which describes concentration as a condition defined by three distinctive requirements: energy, function and precision. This implies that concentration represents an exhausting state ("energy") serving a specific task accomplishment or plot ("function") performed as accurately as possible ("precision"). Attention and concentration are known to influence an individual's performance in both challenging and everyday activities. The Cognitrone test is used in investigations in the fields of traffic psychology, sports psychology, clinical neuropsychology and safety assessments. In the present study, the test form S4 with a fixed presentation time of 1.8 sec per item was used. Subjects were required to compare a geometric figure with four other geometric figures arranged above it and to decide whether the test figure was identical to one of the other figures. In the test forms with fixed working time, participants were given a short time window in which to perform the task. After every input the figure changed, and after several trials, a different test figure was used. Prior to the start of the task, instructions and exercise items appeared on the computer screen. The entire processing time amounted to eight minutes.

Heart rate

Heart rate was assessed as a control variable in order to quantify the possible effect of different vibrations on cognitive performance. Heart rate (beats per minute [bpm]) was recorded using the smartwatch Fitbit Surge (Fitbit, San Francisco, USA) which measures the heart rate at the wrist through photoplethysmography. Within each test session, the mean heart rate was recorded for four sequences. Sequence 1 lasted from the beginning of the test session to the beginning of the vibration, sequence 2 from the beginning of the vibration to the beginning of the test, sequence 3 from the beginning to the end of the test and sequence 4 from the end of the test to the end of the test session.

2.2.2.3 *Study design and procedure*

Each participant underwent three test sessions. Within each session, participants were exposed to one of the three vibration conditions (WBV-C, WBV-W, Control) and subsequent testing. The sequence of the conditions was counterbalanced over the participants to avoid order effects. Each vibration condition lasted four minutes. Before and after each test session the participants completed a version of the PASA. At the beginning of test session one, the subjects were required to fill in the self-report demographic survey, and at the start of each test session a smartwatch was placed on the non-dominant hand. Mean heart rate was measured over each test session. Figure 1.1 shows a schematic representation of the study procedure.

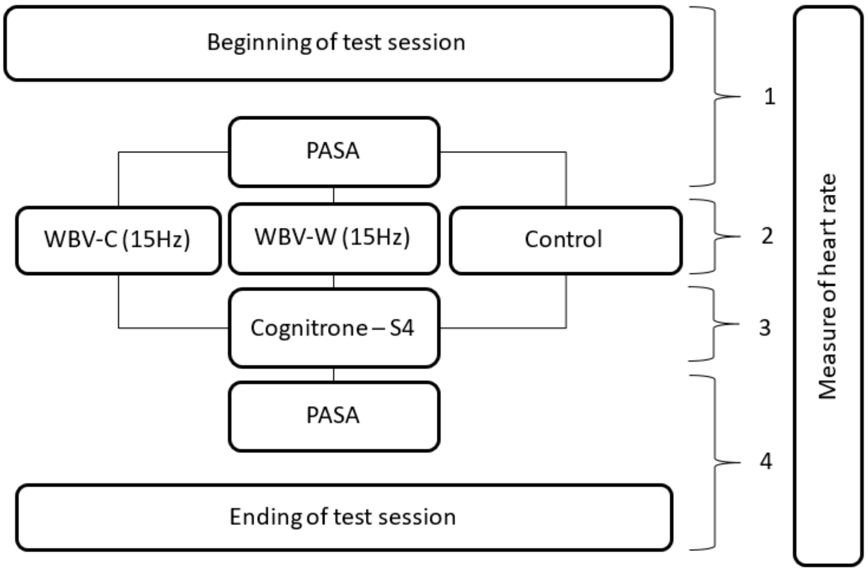

Figure 1.1 *Study procedure: curved brackets define the four periods of heart rate measurement.*

2.2.2.4 *Statistical analysis*

Table 2.3 shows the outcome measures of the test form S4 of the Cognitrone test. A one-factorial, univariate ANOVA with repeated-measures was conducted for each test variable of the Cognitrone. The factor was defined as *vibration condition* (WBV-C, WBV-W, Control). P-values of less than 0.05 were considered statistically significant.

All statistical analyses were performed using the Statistical Package for Social Sciences 22.0 (SPSS, IBM 2015).

Table 2.3 *Parameters of the test form S4 of the Cognitrone test*

Test form	Critical parameters	Explanation
Cognitrone – S4	Total "correct reactions”	Measure of working accuracy under time pressure
	Total "incorrect reactions” (errors)	Measure of working accuracy under time pressure
	Total "incorrect non-reactions” (omissions)	Measure of working accuracy under time pressure
	Mean time of correct reactions	
	Mean time of incorrect reactions	

2.2.3 *Results*

2.2.3.1 Cognitive performance after passive WBV-C, passive WBV-W and in the control session

The descriptive values of the Cognitrone test parameters for each vibration condition are presented in Table 2.4.

Table 2.4 *Mean values of cognitrone test results for the three vibration conditions*

	WBV-C		**WBV-W**		**Control**	
	M	*SD*	*M*	*SD*	*M*	*SD*
Correct reactions	62.85	5.78	68.03	5.19	70.83	4.41
Incorrect reactions	12.85	5.03	10.33	3.93	9.33	3.42
Incorrect non-reactions	17.15	5.78	11.98	5.19	9.18	4.41
Mean time of correct reactions	1.07	0.06	1.04	0.06	1.01	0.07
Mean time of incorrect reactions	1.05	0.15	1.08	0.13	1.06	0.14

**M* = mean; *SD* = standard deviation

Total correct reactions. The results of a one-way repeated-measures ANOVA revealed a statistically significant main effect of the factor *vibration condition* ($F(2, 78) = 56.60$, $\eta^2 = .592$, $p < .001$). The control group performed better than the WBV-C ($t(39) = 10.39$, $p < .001$) and WBV-W ($t(39) = 4.17$, $p < .001$) groups, while the WBV-W group performed better than the WBV-C group ($t(39) = 6.21$, $p < .001$) (*see* Figure 1.2).

Total incorrect reactions. The results revealed a statistically significant main effect of the factor *vibration condition* ($F(2, 78) = 18.45$, $\eta^2 = .321$, $p < .001$). The control group made fewer mistakes than the WBV-C ($t(39) = 5.17$, $p < .001$) and WBV-W ($t(39) = 2.06$, $p < .05$) groups. Moreover, the WBV-W group made fewer mistakes than the WBV-C group ($t(39) = 2.01$, $p < .001$) (*see* also Figure 1.2).

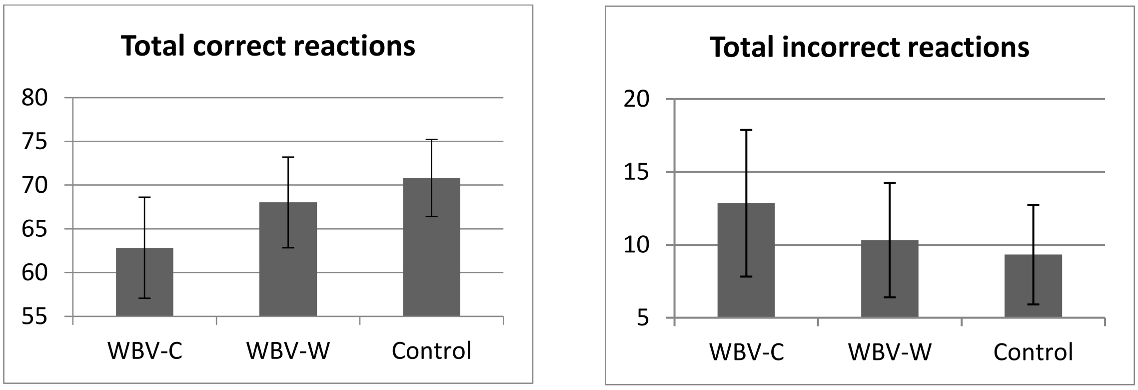

Figure 1.2 *Total correct and incorrect reactions for the different vibration conditions (means and standard deviations).*

Total incorrect non-reactions. The results revealed a statistically significant main effect of the factor *vibration condition* ($F(2, 78) = 56.60$, $\eta^2 = .592$, $p < .001$), showing that the control group made fewer omissions than the WBV-C ($t(39) = 10.39$, $p < .001$) and WBV-W ($t(39) = 4.17$, $p < .001$) groups. Furthermore, the WBV-W group made fewer omissions than the WBV-C group ($t(39) = 6.21$, $p < .001$).

Mean time of correct reactions. The results revealed a statistically significant main effect of the factor *vibration condition* ($F(2, 78) = 33.05$, $\eta^2 = .459$, $p < .001$). The control group performed more quickly than the WBV-C ($t(39) = 7.36$, $p < .001$) and WBV-W ($t(39) = 3.87$, $p < .001$) groups, while the WBV-W group performed more quickly than the WBV-C group ($t(39) = 4.64$, $p < .001$)) (*see* also Figure 1.3).

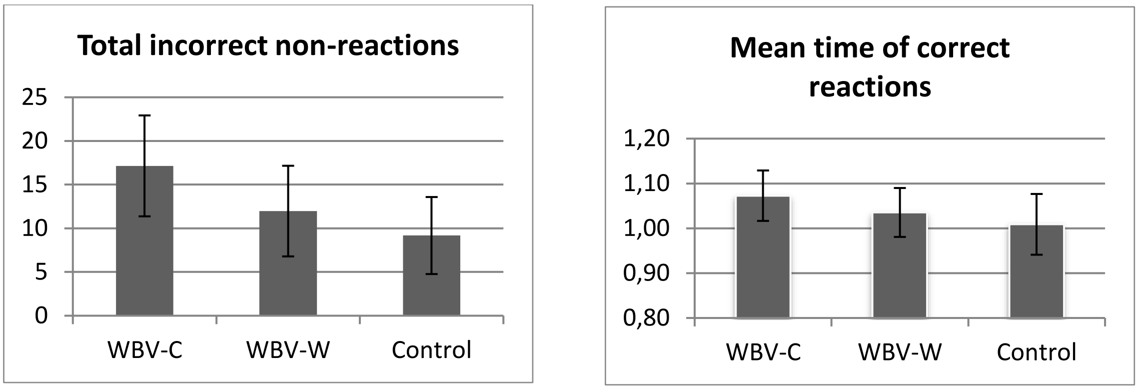

Figure 1.3 *Total incorrect non-reactions and mean time of correct reactions for the different vibration conditions (means and standard deviations).*

Mean time of incorrect reactions. The results did not reveal a statistically significant main effect of the factor *vibration condition* ($F(2, 78) = .84$, $\eta^2 = .021$, $p = .438$).

2.2.3.2 *Course of mean heart rate*

A two-way repeated-measures analysis of variance with the inner-subject-factors *period of heart rate measurement* and *vibration condition* was computed. For the factor *period of heart rate measurement*, Mauchly's test indicated that the assumption of sphericity was violated ($p < .001$). Degrees of freedom were therefore corrected using Greenhouse-Geisser estimates of sphericity. The results revealed that the mean heart rate differed significantly between each period ($F(2.08, 80.95) = 15.47$, $\eta^2 = .284$, $p < .001$). There was no statistically significant difference between the vibration conditions ($F(2, 78) = 1.13$, $\eta^2 = .028$, $p = .327$). A Mauchly's test was conducted in order to verify an interaction effect of vibration conditions and mean heart rate. The test indicated that the assumption of sphericity was violated ($p < .001$). Degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity. The interaction term did not reach statistical significance ($F(2.64, 102.99) = .680$, $\eta^2 = .017$, $p = .548$). For the vibration condition WBV-C, post-hoc tests identified significant differences of mean values between sequences 1 and 2 ($t(39) = -3.27$, $p = .001$), sequences 2 and 3 ($t(39) = 4.22$, $p < .001$) and sequences 3 and 4 ($t(39) = 2.86$, $p = .004$). For the vibration condition WBV-W, post-hoc tests identified significant differences of mean values between sequences 2 and 3 ($t(39) = 3.67$, $p < .001$) and sequences 3 and 4 ($t(39) = 2.42$, $p = .01$). For the control group, post-hoc tests also identified significant differences of mean values between sequences 2 and 3 ($t(39) = 3.94$, $p < .001$) and between sequences 3 and 4 ($t(39) = 1.99$,

p = .027). Table 2.5 presents mean values of heart rate for each vibration condition and sequence.

Table 2.5 *Mean values of heart rate for each vibration condition and sequence of measurement*

Vibration condition	Mean heart rate for each sequence of measurement (bpm)			
	Sequence 1 ***M (SD)***	**Sequence 2** ***M (SD)***	**Sequence 3** ***M (SD)***	**Sequence 4** ***M (SD)***
WBV-C	77.30 (17.82)	82.08 (18.71)*	76.98 (16.98) *	71.75 (19.01)*
WBV-W	77.40 (21.83)	79.23 (21.15)	72.55 (20.69)*	70.43 (19.61)*
Control	79.10 (24.51)	85.35 (11.43)	79.68 (12.94)*	76.00 (16.92)*

**M = mean; SD = standard deviation; "*" = Statistically significant difference compared to previous sequence (p < .05)*

2.2.3.3 Pre-post test of stress using the stress index of the PASA

A two-way repeated-measures analysis of variance with the inner-subject-factors stress index (pre, post) and vibration condition (WBV-C, WBV-W, Control) revealed a significant difference between vibration conditions ($F(2, 76) = 7.34$, $\eta^2 = .162$, $p < .001$). Furthermore, there was no statistically significant difference between the stress index at the beginning and at the end of the test session ($F(1, 38) = .05$, $\eta^2 = .001$, $p = .831$). For the interaction *vibration condition x stress index*, Mauchly’s test indicated that the assumption of sphericity was violated ($p < .001$). Degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity. The results did not show a significant interaction effect (F (1.53, 58.23) = .01, $\eta^2 = .001$, $p = .995$), indicating that the change in stress index did not depend on the vibration condition. Descriptive statistics of the stress index for each vibration condition are presented in Table 2.6, with more negative values indicating higher stress levels.

Table 2.6 *Mean values of stress index (PASA) recorded before and after test sessions for each vibration condition*

Vibration condition	**Stress index before test session *M (SD)***	**Stress index after test session *M (SD)***
WBV-C	-1.38 (.92)	-1.40 (.90)
WBV-W	-1.65 (.84)	-1.67 (.83)
Control	-1.72 (.86)	-1.73 (.81)

**M = mean; SD = standard deviation*

2.2.4 Discussion

The aim of this study was to investigate whether WBV results in differences in task performance in participants performing an attentional test of high task complexity following WBV exposure.

Contrary to our expectations, the results did not show any positive effect of vibration on task performance. Although there were significant differences between the two vibration conditions (WBV-C vs. WBV-W) and the control group for all but one of the test parameters (mean time of incorrect reactions), the participants of the control group performed better than those of both vibration conditions (WBV-C, WBV-W). In addition to the absence of positive effects of WBV on attentional measures, the WBV-W group achieved better test results than the WBV-C group.

The analysis of heart rates revealed no significant differences between the vibration conditions. However, the course of heart rate differed significantly between the four periods of measurement. The heart rate decreased from the beginning of vibration to the end of the test session in all vibration conditions. The PASA was used to determine the awareness of stress at the beginning and end of each test session, allowing a pre-post comparison of the stress level. Stress levels varied according to the vibration condition: In the WBV-C condition, participants showed a significantly higher stress level than participants in the WBV-W condition or the control group, but there was no significant difference between WBV-W and controls.

Since the test performance following WBV was worse than without WBV, vibration may have had a distracting or impairing influence. Heart rate measurement may provide further information regarding the mechanisms underlying WBV effects. In all three experimental conditions, the heart rate of participants increased from the beginning of the test session to the beginning of the attentional test and then decreased. Thus, the changes in heart rate cannot be attributed to WBV. A possible explanation for the decreasing heart rate after the experimental intervention (WBV exposure or passive standing) could be relaxation of the participants (Schröger, 2010). A decline of the reaction to repeated stimulus presentation (Wiedemann, 2014) could be another explanation for the decreasing heart rate. Habituation effects on arousal may explain the short-term increase in heart rate followed by a continuous decrease in all vibration conditions (Kjellberg, 1990).

Arousal describes a person’s activity level in regard to behavioural, emotional, electro-cortical and autonomous reactions (Matthews et al., 2000). Elevated arousal is often associated with agitation and an increase in heart rate or muscle tension. If heart rate is assumed to indicate arousal (Brisswalter et al., 2002), the results of the present study may suggest that the participants’ arousal declined during the test session, irrespective of the vibration condition. An elevated heart rate during cognitive processing should facilitate brain metabolism and also cognitive capability (Scholey et al., 1999). The consistent WBV may have caused relaxation or fatigue, leading to a significant reduction in arousal and a resultant inability to perform well in the test. The relationship between arousal and cognitive performance is consistent with the Yerkes-Dodson law postulating an inverted U-shaped relation between arousal and performance (Cohen, 2011; Yerkes & Dodson, 1968). The consistent vibration of 15 Hz could have led to fatigue followed by a decrease in arousal, with a consequent failure to obtain better test results than subjects of the other vibration condition with fluctuating vibration frequency (WBV-W). The fluctuations in vibration frequency may have maintained arousal level due to repeated short-term muscle stimulation. This may explain the better attentional performance in the WBV-W than in the WBV-C condition. A uniform 15-minute vibration with a frequency 3 Hz has been shown to reduce the alertness of participants more than vibration with varying frequency (Landström & Lundström, 1985).

The present results are at variance with other recent studies pointing to positive effects of WBV on different cognitive abilities when WBV exposure was followed immediately by cognition testing (Fuermaier, Tucha, Koerts, van den Bos et al., 2014; Zamanian et al., 2014). However, another study was also unable to find positive WBV effects on test performance (J. K. Ljungberg & Neely, 2007b). The way in which WBV parameters, such as vibration frequency or duration of WBV exposure, need to be adjusted in order to evoke positive effects of vibration on cognitive functions remains unclear. Therefore, several factors should be addressed when discussing the lack of positive effects of WBV on attention in the present study (Conway et al., 2007; J. K. Ljungberg, 2008; J. K. Ljungberg & Parmentier, 2010).

The frequency of vibration has been considered to affect an individual's subjective sensitivity to vibration (J. K. Ljungberg & Parmentier, 2010). A model has been proposed assuming three main effects of vibration, namely physiological and psychological functions and a physical reaction to the proliferation of vibration over the whole body (Kubo et al., 2001). From a physiological perspective , vibration in the range of 2 to 5 Hz leads to an increase in heart rate and blood pressure, which may be psychologically linked to a subjective feeling of exhaustion (Jiao et al., 2004). Most studies showing negative effects of vibration have used relatively low frequencies (2-5 Hz: Costa et al., 2012; J. K. Ljungberg & Neely, 2007a), while the studies revealing positive effects have applied higher frequencies (30 Hz: den Heijer et al., 2015; Fuermaier, Tucha, Koerts, van Heuvelen et al., 2014; Regterschot et al., 2014). Future studies should use different vibration frequencies to investigate a dose-response relationship and to identify the optimal vibration intensity for evoking positive effects on cognition. Furthermore, the duration of exposure should be regarded as another factor potentially responsible for the results obtained. Some evidence suggests that increasing exposure time enhances discomfort (Kjellberg, 1990) and may thus have a negative effect on outcome. Future studies should assess the effects of different WBV exposure durations.

Another potentially important factor appears to be the timing of test administration (during vs. post-exercise). Studies on the impact of PA on cognitive task performance have found improvements in cognitive performance on administration of the task immediately following a bout of exercise, irrespective of the kind of PA (Lambourne & Tomporowski, 2010). PA may enhance arousal and thus promote cognitive performance (Audiffren et al., 2008; Tomporowski, 2003). However, significant differences in performance following exercise were not found in tasks with a speed component, in which participants were required to react as quickly as possible (T. McMorris & Hale, 2012). Therefore, future studies should investigate the role of task characteristics on the effects of WBV on subsequent cognitive performance.

In summary, the present study revealed no positive effects of vibration on attention or concentration. WBV may have had a distracting effect leading to worse test performance compared to no WBV exposure. Furthermore, the consistent decrease in heart rate following WBV suggests that a decrease in arousal could have accounted for the negative results in the vibration conditions compared to the control group. The finding that participants exposed to vibration with varying frequency showed better results than those exposed to constant frequency vibration suggests that future studies seeking to establish positive effects of WBV should use and assess fluctuating vibration in more detail. Different frequencies of vibration and a possible dose-response relationship should also be investigated. In considering these aspects, future investigations may be able to establish the conditions under which vibration may improve cognitive abilities.

2.3 Effects of whole body vibration in a mental rotation task

2.3.1 Introduction

The potential value of physical activity (PA) in improving various aspects of health has increasingly been explored (Lachman et al., 2018; Warburton et al., 2006; Warburton & Bredin, 2017). Several types of PA have been linked to a reduction in risk of chronic medical conditions (Sattelmair et al., 2011). Even small changes in PA may result in clinically relevant changes in health outcomes (Rhodes et al., 2017). Regular PA may reduce the health risks associated with obesity or a sedentary lifestyle (Healy et al., 2008) and may also decrease levels of anxiety and depression and enhance well-being (McMahon et al., 2017).

In addition, numerous studies have demonstrated marked benefits of PA on cognitive functioning (Brisswalter et al., 2002; Y. K. Chang et al., 2012; Y. K. Chang et al., 2015; Erickson et al., 2015; Lambourne & Tomporowski, 2010; Terry McMorris & Graydon, 2000; Sibley & Etnier, 2003; Tomporowski, 2003). Theories regarding various physiological responses to acute PA have been preferred as explanations for the modulation of cognition, namely the catecholamine hypothesis (T. McMorris, 2016a), the reticular activation hypofrontality theory (Dietrich & Audiffren, 2011) as well as changes in the levels of brain-derived neurotrophic factor (Ferris et al., 2007; Winter et al., 2007) and heart rate (Hillman et al., 2003). Furthermore, exercise-induced increases in arousal are thought to influence cognitive performance (Y. K. Chang et al., 2015; Lambourne & Tomporowski, 2010).

The optimal level of acute PA for cognitive enhancement is still a matter of debate. Many studies investigating the effects of PA on cognitive functioning during PA found either an inverted U-shaped relationship, with moderate PA intensity associated with better cognitive performance compared to low or high intensities (Arent & Landers, 2003; Chmura et al., 1994) or a linear dose-response relationship, with increasing intensity of PA showing enhanced cognitive performance (Y.-K. Chang et al., 2009b; Davranche & Audiffren, 2004; T. McMorris & Graydon, 1997). A small number of studies examining the connection between PA intensity and cognitive performance after PA also found an inverted U-shaped association (Kamijo et al., 2007; Kamijo, Nishihira, Hatta, Kaneda, Kida et al., 2004; Kamijo, Nishihira, Hatta, Kaneda, Wasaka et al., 2004).

Various studies have shown that the relationship between PA and cognitive performance is influenced by task characteristics such as difficulty and complexity (Y.

K. Chang, Chu et al., 2011; Y. K. Chang & Etnier, 2009; T. McMorris & Hale, 2012). Other important variables potentially modulating the interaction between exercise and cognition include initial fitness level, cognitive task type, timing of test administration relative to PA (during exercise, immediately or with a delay of more than one minute after exercise) and exercise intensity (Y. K. Chang et al., 2012; T. McMorris & Hale, 2012). Both in adolescents (Budde et al., 2008) and older adults (Kamijo et al., 2009), PA has been shown to be associated with improvements in cognitive functioning. However, in elderly people or individuals who experience difficulty exercising, alternatives to PA providing the beneficial effects of PA for cognition and mental health should be sought. In this context, whole-body vibration (WBV) may become a useful alternative (Regterschot et al., 2014).

Whole body vibration is a mechanical stimulation characterised by an oscillating locomotion (Cardinale & Wakeling, 2005; Rehn et al., 2007). The oscillations are conveyed across the entire body (Mansfield, 2004). Vibration can be described using parameters such as frequency, amplitude, duration and acceleration. The frequency of vibration (Hz) indicates the repetition rate of oscillation cycles. The amplitude of vibration is the maximum displacement of the vibration locomotion (Cardinale & Wakeling, 2005; Cochrane, 2011). Whole body vibration can be employed actively, combining WBV with dynamic exercises, or passively, where static positions such as sitting or standing on the vibration platform during WBV are maintained. The latter can be described as a passive form of PA since reflexive muscle contractions take place without active performance (den Heijer et al., 2015). Passive WBV has been suggested as a potentially useful means of fostering physical fitness in elderly individuals or as a strategy in the treatment of chronic disease (Gritschmeier & Lange, 2020).

Associations between regular exercise and different components of executive functions, in particular selective attention, inhibitory control, task switching and working memory, have been revealed (Guiney & Machado, 2013). PA has also been linked to improved attention and memory functions (Smith et al., 2010). Moreover, PA seems to influence the speed rather than the accuracy of reactions (T. McMorris, 2016a) and to affect complex tasks more than simple tasks (T. McMorris & Hale, 2012). Studies investigating effects of WBV on cognition have shown beneficial effects of passive WBV on executive functions when cognitive testing was performed immediately after WBV exposure (den Heijer et al., 2015; Fuermaier, Tucha, Koerts, van Heuvelen et al., 2014; Regterschot et al., 2014), while other studies did not find a positive association of WBV with cognitive performance (J. Ljungberg et al., 2004; J. K. Ljungberg, 2008; J. K. Ljungberg & Neely, 2007a).

In regard to the influence of PA on other cognitive faculties, mental rotation appears to be a visuospatial ability positively affected by exercise (Jansen & Pietsch, 2010). Mental rotation encompasses the mental representation and subsequent rotation of objects. A mental rotation task typically requires the assessment of whether an object constitutes a rotated version of a given object (Shepard & Metzler, 1971). Several studies have shown that various sports may have a positive effect on mental rotation ability (Jansen & Lehmann, 2013; Moreau et al., 2012).

The aim of the present study was to investigate the effects of WBV exposure on subsequent test performance in a mental rotation task. It was hypothesised that the cognitive performance will be improved by WBV when compared to a control condition.

2.3.2 Methods

2.3.2.1 Participants

Eighty undergraduate psychology students (70 females and 10 males; mean age ± standard deviation: 21.6 ± 3.6) voluntarily participated in the study, which was conducted in a laboratory of the University of Regensburg. Exclusion criteria were: age below 18 years and above 35 years, uncorrected sensory or locomotor impairments and pregnancy. The participants received course credits for their participation.

2.3.2.2 Materials

WBV

Passive vibration before testing was applied using the vibrating platform Galileo® Med Advanced (Novotec Medical GmbH, Pforzheim, Germany) (Novotec Medical GmbH, 2015). For all settings of the device used, we refer to section 2.1.2.2 ("WBV"). In the present study, a control condition without vibration and three different vibration conditions (with the Wobble degree normal, i.e., given frequency ± 2.5 Hz) were used (*see* Table 2.7). In the control condition, the vibration platform was turned on but no vibration took place.

Table 2.7 *Parameters of the vibration conditions*

Vibration condition	VC 1	VC 2	VC 3	Control
Frequency	7.5 Hz	12.5 Hz	17.5 Hz	No vibration
Amplitude	0 ± 4.5 mm	0 ± 4.5 mm	0 ± 4.5 mm	-
Duration	4 min	4 min	4 min	4 min

**VC = vibration condition*

Wiener Testsystem: Mental Rotation

The Wiener Testsystem (WTS) is a computerised test battery allowing an objective, reliable and valid assessment of different performance and personality characteristics (Schuhfried, 2011). In the present study, the WTS Rasch homogenous computerised subtest "Mental Rotation" (MR) was used to assess spatial perception skills and in particular the respondents' ability to mentally picture and manipulate spatial content. After a general instruction and three practice examples, the test phase presented the participants with a total of 20 consecutive trials. Each trial presents subjects with a figure composed of a number of blocks. The respondent is required to mentally picture the arrangement of the blocks when viewed from another angle. This angle is indicated by an arrow. Four alternative answers are presented, from which participants select the picture that correctly depicts the arrangement of the bricks from the perspective indicated. The respondents were allowed a maximum of one minute to solve each trial, after which an omission error was counted and the next trial started automatically. This procedure results in a variable duration of the test procedure with a maximum of 20 minutes. Test parameters included the number of correct reactions, the mean time of the test processing and the mean time of the correctly solved test items. The reliability in terms of internal consistency is due to the validity of the Rasch model; Cronbach's α is .81 (Schuhfried, 2011).

2.3.2.3 Study design and procedure

The participants were assigned to one of the four experimental conditions using block randomization. The participants' age and sex for each test condition are presented in Table 2.8. A factorial design with the between-subjects factor vibration condition (0 Hz, 7.5 Hz, 12.5 Hz or 17.5 Hz) as independent variable was used. Prior to exposure to the treatment (vibration or control), participants underwent three trial runs. Each vibration condition lasted four minutes. The test performance with the MR test parameters mentioned above was the dependent variable. The participants stood on the platform without shoes.

At the beginning of the test session, participants filled in a questionnaire of demographic variables. Before and after the test session the respondents completed the rating scale assessing subjective stress levels. After exposure to the vibration or control conditions, they were required to complete the mental rotation task. The entire test session lasted approximately 45 minutes.

Table 2.8 *Age, sex and handedness of study participants for each vibration condition*

Vibration condition	VC 1	VC 2	VC 3	Control
Age (years, mean ± standard deviation)	22.1 ± 4.5	21.5 ± 2.1	20.0 ± 1.8	20.8 ± 1.6
Sex (female/male)	17/3	17/3	16/4	20/0
handedness	18/2	19/1	18/2	19/1

**VC = vibration condition*

2.3.2.4 Statistical analysis

Possible differences in demographic variables between the experimental conditions were assessed using a one-factorial univariate ANOVA with the between-subject factor vibration condition and the dependent variable age. Differences regarding gender and handedness were assessed using χ^2-tests. One-factorial univariate ANOVAs with the between-subjects factor vibration condition were performed for the mental rotation test parameters. A t-test for dependent samples with the within-subjects factor time was used to compare stress levels at the beginning and end of the test session. P-values of less than 0.05 were considered statistically significant. All statistical analyses were performed using the Statistical Package for Social Sciences 22.0 (SPSS, IBM 2015).

2.3.3 Results

2.3.3.1 Demographic variables

There were no statistically significant differences between the four experimental conditions regarding gender ($\chi^2(3) = 4.11$, $p = .25$), handedness ($\chi^2(3) = 0.72$, $p = .87$) or age ($F(3, 76) = 2.08$, $p = .109$, $\eta^2 = .008$). Thirty-one of the 80 participants had used a vibration platform before participating in the study, with no significant difference in distribution between groups ($\chi^2(3) = 3.00$, $p = .39$).

2.3.3.2 WBV effects on mental rotation

Number of correct reactions. The results did not show a statistically significant main effect of the factor *vibration condition* ($F(3, 76) = 0.16$, $\eta^2 = .006$, $p = .92$) (*see* Table 2.9).

Table 2.9 *Mean values of test parameters for each vibration condition*

Vibration condition	Number of correct reactions	Mean time of test processing	Mean time of correctly solved test items
	M (SD)	*M (SD)*	*M (SD)*
VC1	11.35 (3.35)	482.57 (176.22)	22.65 (8.08)
VC 2	11.55 (3.97)	408.84 (164.38)	18.35 (6.80)
VC 3	12.10 (3.71)	569.50 (173.79)	27.45 (8.73)
CG	11.55 (3.28)	569.72 (174.59)	25.55 (7.39)

**VC = vibration condition; M = mean; SD = standard deviation*

Mean time of test processing. The results showed a statistically significant main effect of the factor *vibration condition* ($F(3,76) = 4.05$, $\eta^2 = .171$, $p = .01$). Post-hoc tests showed significant differences of mean values between VC 2 and VC 3 ($t(38) = -3.00$, $p < .01$) and between VC 2 and CG ($t(38) = -3.00$, $p < .01$) (*see* Figure 1.4).

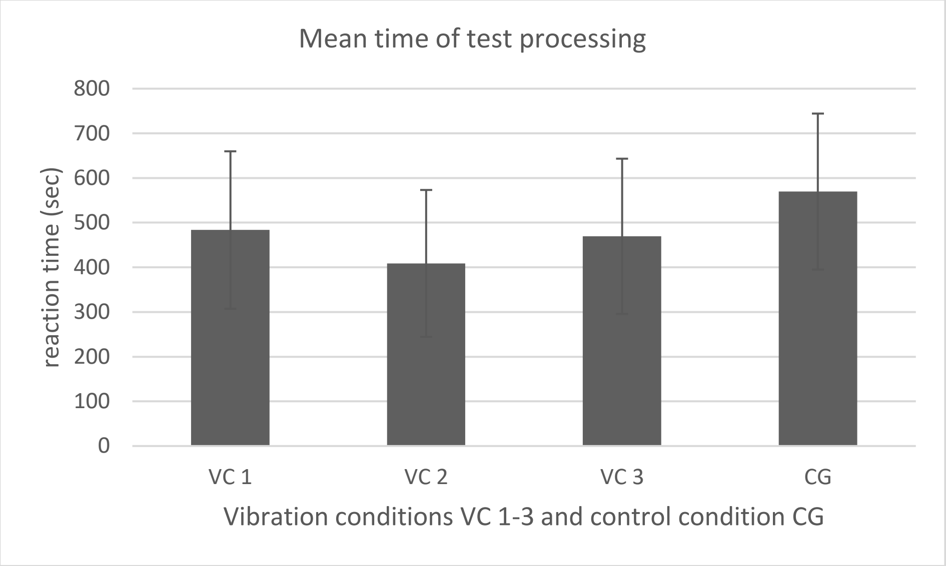

Figure 1.4 *Mean time of test processing following vibration conditions 1-3 and control condition*

Mean time of correctly solved test items. The results showed a statistically significant main effect of the factor *vibration condition* ($F(3, 76) = 5.21$, $\eta^2 = .138$, $p < .01$). Post-hoc analysis showed significant differences of mean values between VC 2 and VC 3 ($t(38) = -3.68$, $p < .01$) and between VC 2 and CG ($t(38) = -3.23$, $p < .01$) (*see* Figure 1.5).

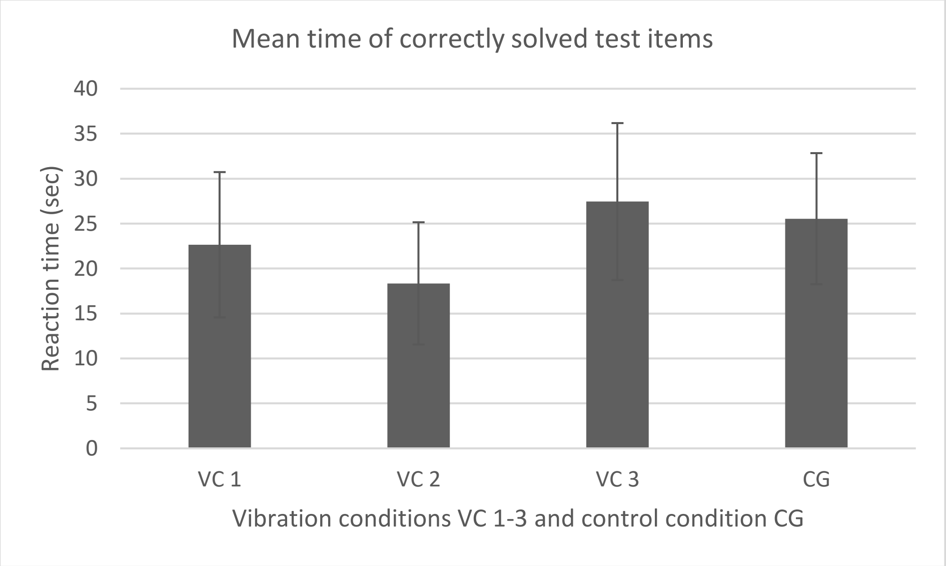

Figure 1.5 *Mean time of correctly solved test items following vibration conditions 1-3 and control condition*

2.3.4 Discussion

While the present results suggest that WBV did not improve mental rotation performance in terms of the number of correct reactions, WBV reduced both the mean time of processing the correctly solved test items and the mean time of processing of all items. These test parameters were significantly shorter in vibration condition 2 (WBV frequency 12.5 Hz) than in vibration condition 3 (WBV frequency 17.5 Hz) and the control group. These findings support an inverted-U shaped relationship between vibration frequency and the time of mental rotation test processing, indicating that a medium WBV intensity leads to faster processing compared to high intensity, low intensity or no vibration. From the perspective of cognitive psychology, PA is regarded as a stressor leading to enhanced arousal with increasing activity (T. McMorris, 2016b). Based on cognitive-energetic models (Sanders, 1983), rest or low PA intensity is associated with low arousal and poor cognitive performance, intermediate intensity induces optimal arousal and performance and intense exercise results in high arousal and poor performance. While beneficial effects of exercise on the speed of test processing have been reported (T. McMorris et al., 2011), effects on accuracy have not been found (Davranche & McMorris, 2009; Joyce et al., 2009). This suggests an inverted U-shaped effect of PA on cognitive processing (T. McMorris et al., 2011). A level of PA that is neither too low nor too high would be expected to provide optimal cognitive functioning in terms of shorter response times.

Exercise-induced increases in the levels of catecholamines, such as dopamine and norepinephrine, in different brain regions may explain why speed and accuracy of test processing are differentially affected by acute and moderate intensity of PA. Thus, increased catecholamine levels may have positive effects on the speed of test processing, while they may not affect those brain regions linked to accuracy of test processing, particularly in working memory tasks (T. McMorris et al., 2011). In regard to physical activity, speed of processing in central executive tasks showed an inverted-U effect, while accuracy was not affected (T. McMorris & Hale, 2012). This is in accord with the present findings in cognitive assessment following WBV

Within the framework of research demonstrating a beneficial effect of acute PA on cognitive performance, the amount of acute PA that can promote an optimal level of cognitive functioning remains unclear (Y. K. Chang et al., 2015). Several randomised controlled trials have investigated the dose-response relationship between PA intensity and cognitive performance following PA. The results of these studies suggest that intermediate PA is likely to lead to the best cognitive performance when compared with low or high PA intensity (Kamijo et al., 2007; Kamijo, Nishihira, Hatta, Kaneda, Wasaka et al., 2004). The present study has shown that the effects of WBV, as a special form of acute PA, on speed in a mental rotation task also appear to be best represented by an inverted U-shaped relationship in respect of different WBV intensities. Future studies should examine whether this also holds true for other tests assessing executive functions or other cognitive domains.

In addition to intensity of PA, other characteristics, such as duration, may play a moderating role. A systematic review of the available literature examining the effects of acute PA on consecutive cognitive functioning concluded that a minimum duration of 11 min is needed for positive effects (Y. K. Chang et al., 2012). In particular, exercising at moderate intensity for 20 min resulted in significantly better cognitive performance, as assessed by shorter response time and higher accuracy, regardless of the type of cognitive function examined. An exposure to PA for 20 min has been observed to elicit faster reaction time and higher accuracy in comparison to no PA and PA for 10 or 45 min, which supports a curvilinear dose-response relationship between exercise duration and cognitive performance (Y. K. Chang et al., 2015). Studies revealing positive WBV effects on executive functions have typically used relatively short durations (2-3 minutes: den Heijer et al., 2015; Fuermaier, Tucha, Koerts, van Heuvelen et al., 2014; Regterschot et al., 2014; Zamanian et al., 2014). Furthermore, the participants in these studies were exposed repeatedly to WBV and subsequent cognitive assessment, and improved cognitive functioning was likely to be affected by learning and practice. Future studies should compare individual test conditions with different durations of WBV exposure in order to identify the optimal exercise duration. Moreover, both the effects of a single bout of WBV and of repeated exposure of WBV on cognition should be elucidated. In the studies revealing positive effects of WBV on executive functions (den Heijer et al., 2015; Fuermaier, Tucha, Koerts, van Heuvelen et al., 2014; Regterschot et al., 2014), both duration and frequency levels of WBV seem to have been set arbitrarily. Thus, the optimal WBV intensity required to achieve beneficial effects on executive functions needs to be investigated in future studies.

In summary, the present study has revealed positive effects of WBV on mental rotation performance in terms of faster reaction times, suggesting that mental rotation is a cognitive ability that can be positively influenced by intermediate intensity of WBV. The present results are in accord with previous findings on the effects of acute exercise on cognition, with processing speed in cognitive tasks representing an inverted U-shaped effect of exercise intensity, while accuracy (number of correct reactions) seems to be unaffected (T. McMorris & Hale, 2012). Further research is needed to explore optimal duration and intensity of WBV and to examine whether other types of cognitive abilities may be positively influenced by WBV. In addition, longer lasting effects on cognition, beyond immediate improvements following WBV, should be investigated.

2.4 Effects of whole body vibration on memory performance

2.4.1 Introduction

Numerous reviews and meta-analyses have provided evidence that regular physical activity (PA) produces positive effects on physical health (Humphreys et al., 2014; Warburton et al., 2010; Warburton & Bredin, 2016). The findings of a systematic review of longitudinal studies showed an inverse relationship between PA and the risk of obesity, type 2 diabetes and coronary heart disease (Reiner et al., 2013). Physical activity is likely to provide benefits for cardiovascular health in middle aged and elderly people. A significantly reduced risk of cardiovascular disease has been shown in moderately physically active people in comparison with less active individuals, demonstrating that even limited PA can lower the risk of cardiovascular disease (Lachman et al., 2018). In addition to the positive association between cardiovascular health and regular PA (Nystoriak & Bhatnagar, 2018), exercise may also confer beneficial effects on mental health (Ruegsegger & Booth, 2018).

Recent research has expanded its focus from physical and mental health outcomes of PA to include potential benefits of exercise for cognitive functioning, including attention, executive functioning, memory, information processing and processing speed (Y. K. Chang et al., 2012). In particular, cognitive tasks assessing executive functions have shown better results following PA (Hillman et al., 2008). Executive functions are involved in the regulation, management and control of other cognitive processes, such as mental flexibility, inhibition, working memory and attention (Chan et al., 2008). Several randomised controlled trials have shown facilitating effects of an acute bout of PA on various executive functions (Y. K. Chang et al., 2019; Y. K. Chang, Tsai et al., 2011).

Potential biological underpinnings of the relationship between PA and cognition remain ambiguous. Several concepts are premised on the assumption that PA triggers physiological responses and directly influences various aspects of cognition. Thus, optimal arousal (Byun et al., 2014) and increased cerebral blood flow (Guiney et al., 2015) are assumed to mediate the interaction between acute PA and cognitive enhancement in an inverted U-shaped fashion. Moreover, an upregulation of brain-derived neurotrophic factors (Dinoff et al., 2017) and catecholamines (T. McMorris et al., 2008) have been proposed to underlie the interaction between acute PA and cognitive performance. Furthermore, systematic literature reviews have suggested potential moderating variables, such as baseline performance and age (Pontifex et al., 2019) as well as intensity, duration, cognitive task type, timing of cognitive test administration and fitness level (Y. K. Chang et al., 2012).

Evidence has shown an association between PA and cognition in different age groups, including children and adolescents (Sibley & Etnier, 2003) as well as younger (Hopkins et al., 2012; Ratey & Loehr, 2011) and older adults (Colcombe & Kramer, 2003; Zhu et al., 2017). In elderly people or individuals who experience difficulty exercising, alternatives to PA providing the beneficial effects of exercise should be sought. Among others, whole body vibration (WBV) has been suggested as a useful alternative (Regterschot et al., 2014).

WBV is a training method which exposes an individual's whole body to a mechanical oscillation produced by a vibrating platform. The utilization of WBV may take an active form, which combines WBV with dynamic exercises, or a passive form with static positions, such as sitting or standing on the platform during WBV (den Heijer et al., 2015). The locomotor processes generated by WBV comprise a variety of neuromuscular reactions (Rittweger et al., 2001). WBV increases various physiological measures, including heart rate, diastolic blood pressure and oxygen uptake (VO2) (Cochrane et al., 2008; Fuermaier, Tucha, Koerts, van den Bos et al., 2014; Rittweger et al., 2001). With respect to possible effects of WBV on cognition, several studies have found beneficial effects of passive WBV on executive functions in participants performing the cognitive test immediately after WBV exposure (den Heijer et al., 2015; Fuermaier, Tucha, Koerts, van Heuvelen et al., 2014; Regterschot et al., 2014).

While many studies have found a correlation between PA and cognition, the underlying mechanisms are unclear. Studies examining the influence on cognitive performance have explored different forms of PA (Barella et al., 2010). Even a single bout of PA can induce acute effects on different cognitive functions (Ratey & Loehr, 2011). Improvements in executive functions have been shown following a single spell of aerobic (Hogervorst et al., 1996) or resistance exercise (Y. K. Chang & Etnier, 2009). Furthermore, a 30-minute bout of resistance exercise increased the speed of information processing, but did not show a significant effect on inhibition (Y. K. Chang & Etnier, 2009). Thirty minutes of cycling or running also enhanced some aspects of cognitive functioning, such as speed of information processing or reaction time (Joyce et al., 2009). Cognitive psychology has hypothesised that the allocation of available resources or increases in arousal plays a role in the mediation of the beneficial effects of exercise on cognition, while other studies have proposed exercise-induced changes in brain neurotrophic factors or catecholamines as important factors (Pesce, 2012). Studies on the effects of chronic exercise on cognition have emphasised the importance of fitness level, neurotrophic stimulation and alterations in specific brain regions including cingulate cortex, temporal and parietal cortices, prefrontal cortex and hippocampus as potential mediators of the exercise-cognition relationship (J. Etnier, 2009; Hillman et al., 2008).

In addition to the characteristics of exercise undertaken, the type of cognitive functions assessed needs to be considered. Many studies examining the effects of PA on executive functions using different behavioural tasks have revealed enhanced executive functioning through PA (Y. K. Chang, Tsai et al., 2011). Learning has also been shown to be improved after intense PA compared to sedentary behaviour or less intense PA, indicating an intensity-dependent effect of PA on learning (Winter et al., 2007). Furthermore, the importance of the temporal relationship between exercising and cognitive testing has been shown. For example, the effect of PA on long-term memory appears to be most effective when it is undertaken before the encoding and consolidation of new information (Labban & Etnier, 2011).

The evidence regarding the effects of PA on cognition has also revealed positive effects on memory functions. Based on the findings of randomised controlled trials, WBV has been demonstrated to produce positive effects on memory in both animals and humans. A daily 10-minute exposure to WBV over five weeks showed an improvement in spatial memory in mice (Lahr et al., 2009). Other findings demonstrated that a one-hour treadmill training of rats for ten days led to improved spatial memory in the Morris water-maze (Ahmadiasl et al., 2003). In human studies, participants who underwent a resistance training or an aerobic training twice weekly for six months showed improved spatial memory compared to a control group (Nagamatsu et al., 2013). Furthermore, PA was found to provide beneficial effects on verbal memory (Potter & Keeling, 2005). Conversely, WBV has been demonstrated to adversely affect short-term and long-term memory (Sherwood & Griffin, 1990, 1992). The testing of people on a modified version of the Sternberg task during WBV (with a frequency of 16 Hz and different amplitudes of 0, 1.0, 1.6 und 2.5 m/s^2), found no positive relationship between WBV intensity and cognitive performance. The results showed a detrimental effect of WBV on performance as assessed using mean reaction time and number of attentional lapses. In addition, error scores were significantly elevated in the 1.0 m/s^2 condition (Sherwood & Griffin, 1990). However, these findings could not be replicated when the same memory task and vibration exposure were used (J. Ljungberg et al., 2004). In another WBV study, participants performed a memory task with an unlimited time response during a vibration of 16 Hz and an amplitude of 2.0 m/s². This study revealed a worse performance of the experimental group than of controls (Sherwood & Griffin, 1992).

The examination of immediate and delayed recall after a single bout of WBV would be expected to further elucidate the effects of WBV on memory function. In the present study, participants were required to remember items both immediately following a learning phase and after an interval of 20 minutes. Our hypothesis was that recall in both conditions would be enhanced by WBV.

2.4.2 Methods

2.4.2.1 Participants

This study was conducted in a laboratory of the University of Regensburg, Germany. A sample of 80 undergraduate psychology students (61 females and 19 males; mean age ± standard deviation: 21.5 ± 3.2 years) participated voluntarily in the study. The students received course credits for their participation. Exclusion criteria were: age below 18 years and above 35 years, uncorrected sensory or locomotor impairments, pregnancy and first language other than German.

2.4.2.2 Materials

Demographic Variables

At the beginning of the test session, each participant was required to fill in a questionnaire on the demographic variables *age* and *gender*.

WBV

Passive vibration was administered using the vibrating platform Galileo Med Advanced (Novotec Medical GmbH, 2015) (650 x 510 x 120 mm; 36 kg), which generates mainly vertical sinusoidal vibrations. The vibration frequency can be adjusted with 0.5 Hz increments from 5 Hz to 30 Hz, and the vertical vibration amplitude can be set from 0 to ± 4.5 mm. In addition to frequency and amplitude, duration is among the adjustable parameters of the platform. The platform provides an additional setting (Wobble), with the frequency of vibration fluctuating continuously within the range of a given frequency. Four different degrees are available: soft, normal, hard and custom. For the current study, a control condition without vibration and three different vibration conditions were implemented. Table 2.10 shows the different vibration conditions and the control condition. In the control condition, the vibration platform was activated but no vibration took place. The participants stood on the platform without shoes.

Table 2.10 *Parameters of the vibration conditions*

Vibration condition	**1**	**2**	**3**	**4**
Order of vibration	WBV / No WBV	No WBV / WBV	WBV / WBV	Control group
Frequency	15 Hz			
Amplitude	0 ± 4.5 mm			
Duration	4 min			

**"WBV" means the administration of vibration with the above-mentioned parameters. "No WBV" indicates that no vibration took place when the participants stood on the platform.*

Registration of memory performance: word list

The test assessing memory performance encompassed the learning and free recall of a word list of 20 nouns. The categories and items were randomly selected based on the category norms from Van Overschelde, Rawson and Dunlosky (2004) (see table 2.11). The items were presented on a computer screen in black (type size 66 of font Calibri) on a white background. The words were presented consecutively, each for four seconds. Following the presentation of the word list, participants wrote on a sheet of paper all words remembered both immediately after the presentation (immediate recall) and after a delay of 20 minutes (delayed recall). Simple arithmetic problems and a research article (Meier & Volkhardt, 2017) were used as distractors after immediate recall and before delayed recall.

Table 2.11 *Overview of the categories and items used in the study (20 German nouns from 10 categories)*

Category	**Fruits**	**Tools**	**Four-legged animals**	**Furniture**	**Flower**
Item 1	*Kirsche (cherry)*	*Zange (pliers)*	*Igel (hedgehog)*	*Couch (couch)*	*Distel (thistle)*
Item 2	*Orange (orange)*	*Nagel (nail)*	*Esel (donkey)*	*Lampe (lamp)*	*Veilchen (violet)*
Category	**Job**	**Foods**	**Clothes**	**Insects**	**Vehicle**
Item 1	*Polizist (policeman)*	*Waffel (waffle)*	*Jacke (jacket)*	*Mosquito (mosquito)*	*Fahrrad (bike)*
Item 2	*Reporter (reporter)*	*Quark (curd)*	*Bluse (blouse)*	*Ameise (ant)*	*Auto (car)*

2.4.2.3 Study design and procedure

The participants were randomly assigned to one of four vibration conditions (independent variable). Each vibration condition lasted four minutes on two occasions (before immediate and delayed recall). Memory performance (number of correctly recalled items) as assessed using the study and recall of a word list was the dependent variable. In the vibration conditions, participants were either exposed or not exposed to WBV before the learning phase and the delayed recall. Thus, the participants underwent either two vibration periods (vibration condition 3: WBV / WBV), one period of vibration and one period of no vibration (vibration condition 1: WBV / No WBV; vibration condition 2: No WBV / WBV) or two periods of no vibration (vibration condition 4: control group). Following the learning phase, during which a list of words was presented for study, participants were required to recall as many items as possible from the list both immediately after its presentation (immediate recall) and after a delay of 20 minutes (delayed recall). A 4x2 repeated measures factorial design with the between-subjects factor vibration condition (see Table 1) and the within-subjects factor time of recall (immediate or delayed) as independent variables was used.

After the first exposure to vibration (or no vibration), the participants were shown the word list and required to retrieve all items that they could remember. Immediate recall was followed by an interval of 20 minutes. Subsequently, the second exposure to vibration (or no vibration) and the second free recall of the learned items took place. The duration of the entire test session was approximately 45 minutes. Figure 1.6 shows a schematic representation of the study procedure.

Figure 1.6 *Schematic representation of the study procedure.*

2.4.2.4 Statistical analysis

A one-factorial univariate ANOVA with the between-subject factor vibration condition and the dependent variable age was used to examine potential differences between vibration conditions. χ^2-tests were used for the analysis of the variable gender. A two-factorial univariate ANOVA with repeated measures was performed for the analysis of the effect of the vibration condition on memory performance. Vibration condition was defined as one between-subjects factor with four steps (see Table 1) and time of testing (immediate vs delayed) was the within-subjects factor (immediate recall, delayed recall). All statistical analyses were performed using the Statistical Package for Social Sciences 22 (IBM Corp. Released, 2013). P-values of less than 0.05 were considered statistically significant.

2.4.3 Results

2.4.3.1 Demographic variables

The analysis did not reveal any significant differences in the demographic variables *age* ($F(3, 76) = 0.82$, $\eta^2 = .031$, $p = .489$) or *gender* ($\chi^2(3, N = 80) = 1.31$, $p = .726$) between the vibration conditions (*see* also Table 2.12).

Table 2.12 *Descriptive statistics of the sociodemographic variables of the study sample*

Vibration condition	n	Age	Gender
WBV / No WBV	20	*M* = 22.35 *SD* = 4.39	5 men 15 women
No WBV / WBV	20	*M* = 20.75, *SD* = 2.45	3 men 17 women
WBV / WBV	20	*M* = 21.55, *SD* = 2.89	6 men 14 women
Control Group	20	*M* = 21.45, *SD* = 2.91	5 men 15 women
Overall	80	*M* = 21.53 *SD* = 3.23	19 men 61 women

**n = number; M = mean; SD = standard deviation*

2.4.3.2 Effect of WBV on memory performance

Number of correctly remembered items. The results revealed a statistically significant main effect of the factor *memory performance* ($F(1, 76) = 5.760$, $\eta^2 = .070$, $p = .019$). In addition to the finding of a significant main effect in "*time of recall*", neither a significant main effect in regard to "*vibration condition*" ($F(3,76) = .449$, $\eta^2 = .017$, $p = .719$) nor a significant interaction effect ("*recall x group*": $F(3,76) = .466$, $\eta^2 = .018$, $p = .707$) were seen. Thus, there were no statistically significant beneficial effects of WBV.

Table 2.13 *Mean values of immediate or delayed recall of previously learned items for each vibration condition*

	Vibration condition	*M*	*SD*
Immediate recall – correct words	**WBV / No WBV**	14.60	3.789
	No WBV / WBV	14.40	3.761
	WBV / WBV	13.80	4.479
	Control group	15.10	3.640
Delayed recall – correct words	**WBV / No WBV**	14.50	4.020
	No WBV / WBV	13.95	3.913
	WBV / WBV	13.30	4.669
	Control group	14.85	4.234

**M = mean; SD = standard deviation*

2.4.4 Discussion

The study investigated the potential effect of WBV on subsequent learning and recall from long-term memory. Contrary to our hypothesis, no beneficial effect of different WBV conditions on memory performance was found. The comparison of immediate and delayed recall showed time-dependent forgetting, with the participants recalling significantly more words directly after the learning phase than after a delay of 20 minutes. A statistically significant interaction between groups and time of testing was not shown. Thus, no vibration condition was shown to have beneficial effects on immediate or delayed recall. The descriptive results revealed that participants of the control group recalled the highest number of correct words at both times of assessment, followed by vibration condition 1 (WBV/No WBV), 2 (No WBV/WBV) and 3 (WBV/WBV).

The results of the present study indicating that WBV treatment did not affect recall either immediately or later are in accord with other randomised controlled trials examining the effects of WBV on memory performance (Sherwood & Griffin, 1990, 1992). The findings of these studies demonstrated a detrimental effect of vibration on the concurrent processing of the learning task. In addition, the results of the present study did not reveal the longer-lasting effects that have been shown following PA (Miles & Hardman, 1998). In contrast, another randomised controlled trial explored the effects of PA on long-term memory and showed that participants performed better in delayed recall than controls (Labban & Etnier, 2011). The largest positive effect of PA was found when it took place before learning. This may suggest disruptive effects of WBV on long-term memory compared to other forms of PA. Memory may represent a cognitive domain not positively affected by WBV, unlike executive functions or attention (den Heijer et al., 2015; Fuermaier, Tucha, Koerts, van Heuvelen et al., 2014; Regterschot et al., 2014).

The findings of several randomised controlled trials suggest several factors that may explain the absence of positive effects of WBV on memory performance. It might be assumed that, in contrast to other forms of PA, positive effects of WBV do not occur after its first administration, and that several repetitions are required before positive or negative effects result. A recent randomised controlled trial, for example, found that the positive effect of WBV on inhibitory control was most pronounced in the last of three performance sessions (den Heijer et al., 2015). A repeated administration of WBV may also be necessary to produce effects on memory performance. Therefore, future well-designed randomised controlled trials assessing the effect of repeated application of WBV on memory performance over a longer period should be conducted.

A systematic literature review assessing psychological effects of combined noise and WBV suggested that the frequency of WBV could be another potential moderating variable (J. K. Ljungberg & Parmentier, 2010). While two studies examining the effect of WBV on memory performance have shown that the use of a vibration frequency of 16 Hz did not reveal any positive effects of WBV on memory recall (Sherwood & Griffin, 1990, 1992), other studies using similar or higher frequencies of WBV found positive effects of WBV on cognition (Fuermaier, Tucha, Koerts, van Heuvelen et al., 2014; Regterschot et al., 2014). Importantly, since these studies differed in the administration of vibration (during vs. after exercise), their findings cannot readily be compared. Future studies should therefore investigate different frequencies and a dose-response relationship in order to reveal the most effective vibration intensity for eliciting positive effects on memory or other cognitive functions. Moreover, the duration of WBV exposure has been suggested as a potential moderator of the effects of WBV on cognition. Since some studies have concluded that vibration may produce discomfort (Kjellberg, 1990), the duration of WBV needed to evoke positive effects of WBV on cognitive abilities is unclear. More research is required to explore the duration of WBV in the context of WBV as an exercise modality.

Taken together, the results of the present study did not show any positive effects of WBV on memory recall when WBV was administered directly before the immediate or delayed test phase. Taking into account several potential factors moderating the effects of WBV on memory performance, future studies should attempt to identify the best combination of relevant factors required to obtain beneficial effects of WBV on cognition, especially memory performance.

2.5 Effect of whole body vibration on inhibitory control

2.5.1 Introduction

Numerous studies have provided evidence of the effects of physical activity (PA) on different aspects of health (Febbraio, 2017; Gritschmeier & Lange, 2020; Miller et al., 2016; Warburton & Bredin, 2017). A systematic literature review showed that regular physical exercise offers benefits in the prevention and treatment of cardiovascular diseases, hypertension and type-2 diabetes (Adamu et al., 2006). Another more recent systematic review and meta-analysis evaluating the results of published controlled trials assessing health effects of PA found a statistically significant risk reduction in regard to chronic medical conditions, such as cardiovascular diseases, hypertension, type-2 diabetes, stroke, osteoporosis and breast and colon cancer (Warburton & Bredin, 2016). Furthermore, regular PA has been demonstrated to reduce the risk of obesity and the negative impacts of sedentary behaviour (Healy et al., 2008). A recent meta-analysis of observational and intervention studies showed beneficial effects of both running and recreational football on aerobic fitness and cardiovascular function at rest and shed light on the role of different sports and exercise programs (Oja et al., 2015). However, the specific volume of PA (which is a measure of the total amount of physical exercise performed during either single exercise sessions or during a more prolonged program of exercise) needed to engender positive health outcomes is unclear. The findings of a systematic literature review suggested that a relatively small amount of PA was linked to distinct risk reduction for chronic medical conditions (Sattelmair et al., 2011). The findings of a randomised controlled trial comparing five 13-week exercise programs of different volumes and intensities suggested that three sessions per week, with one session lasting at least 30 minutes, showed a positive effect on health status (Foulds et al., 2014). While similar benefits of PA for mental health outcomes have been demonstrated (Rebar et al., 2015; Schuch et al., 2016), the intensity and duration of PA needed to improve health outcomes are still unclear.

Systematic reviews and meta-analyses of the scientific literature have also found benefits of PA and exercise on various cognitive abilities (Brisswalter et al., 2002; Colcombe & Kramer, 2003; T. McMorris & Graydon, 2000; Tomporowski, 2003). Theories concerning the PA-related physiological mechanisms contributing to improved cognitive performance include the catecholamines hypothesis ((T. McMorris, 2016a), the reticular activation hypofrontality theory (Dietrich & Audiffren, 2011) and theories/hypotheses involving changes in levels of brain-derived neurotrophic factor (Ferris et al., 2007) or heart rate (Hillman et al., 2003). Moreover, exercise-induced increases in arousal have been found to influence cognitive performance (Lambourne & Tomporowski, 2010).

While the positive effects of PA on cognitive functioning have been established, the optimal level of acute PA needed to enhance cognition remains unclear. The evidence in regard to the effects of PA on cognition suggests that moderate intensity may lead to greater improvements in cognition compared to low or vigorous intensities (Pontifex et al., 2019). Moreover, acute PA of moderate intensity has been shown to have a positive effect on the speed component of cognitive processes, but a deleterious effect on accuracy in working memory tests (T. McMorris et al., 2011). In comparison to controls reading a text, a bout of PA of moderate intensity for 20 minutes showed improved Stroop test performance in terms of shorter response time and higher accuracy while moderate exercise of either shorter or longer duration produced only tenuous benefits in regard to Stroop test performance. These findings suggest a curvilinear relation between PA and cognition (Y. K. Chang et al., 2015). Improvements of executive functions have also been found following a higher intensity of PA compared to a lower intensity (Tsukamoto et al., 2017). Several studies have explored the effects of PA on cognitive functioning during PA rather than immediately after the cessation of PA. While several randomised controlled trials assessing the effects of PA on cognition during PA have shown an inverted-U relationship (Arent & Landers, 2003; Chmura et al., 1994), other studies have demonstrated a linear dose-response trend, indicating that an elevated intensity of PA is directly associated with enhanced cognitive performance (Y. K. Chang & Etnier, 2009; Davranche & Audiffren, 2004; T. McMorris & Graydon, 1997). However, only a small number of studies have investigated the dose-response relationship between PA intensity and cognitive performance when participants engaged in PA prior to cognitive testing. The findings of these randomised controlled trials also suggested an inverted-U association (Kamijo et al., 2007; Kamijo, Nishihira, Hatta, Kaneda, Kida et al., 2004; Kamijo, Nishihira, Hatta, Kaneda, Wasaka et al., 2004). More research is required to explore the dose-response relation between acute PA and cognitive performance with testing immediately following PA.

Several variables have been found to be involved in the mediation of the relationship between PA and cognitive performance. The main moderators found in a systematic review and meta-analysis evaluating the results of published randomised controlled trials included the initial fitness level, the type of cognitive task, the timing of test administration relative to PA (during exercise, directly after exercise or after a delay of more than 1 min) and exercise intensity (Y. K. Chang et al., 2012). Furthermore, other characteristics, such as task specificity (Y. K. Chang et al., 2009a; Y. K. Chang, Tsai et al., 2011), the use of counterbalancing/randomization of testing (T. McMorris & Hale, 2012) and age (Budde et al., 2008; Kamijo et al., 2009), have been shown to affect the relationship between PA and cognitive performance.

Alternative exercise modalities able to induce beneficial effects on health and cognition are needed for elderly people or those who are unable to exercise actively. Whole body vibration (WBV) appears to be a method able to produce similar effects to PA (Regterschot et al., 2014). WBV is characterised by mechanical, oscillating stimuli (Cardinale & Wakeling, 2005; Rehn et al., 2007) conveyed over distinct surfaces and capable of affecting the entire body (Mansfield, 2004). Vibration is determined by parameters such as frequency, amplitude, duration and acceleration. The frequency of vibration (Hz) describes the repetition rate of oscillation cycles. The amplitude of vibration is defined as the maximal displacement of the vibration locomotion in millimetre (mm). The duration of vibration is given in seconds (sec) or minutes (min) and the acceleration in g ($g = 9.81$ m/s^2) or m/s^2 (Cardinale & Wakeling, 2005; Cochrane, 2011). WBV may be conducted in an active form, combining vibration with dynamic exercises, or a passive form involving continuous static positions, such as sitting or standing on the vibration platform. The latter form is referred to as passive WBV, since the body is put in motion through reflexive muscle contractions but does not perform active exercise.

The findings of several randomised controlled trials have suggested positive effects of repeated exposure to WBV on executive functions (den Heijer et al., 2015; Fuermaier, Tucha, Koerts, van Heuvelen et al., 2014; Regterschot et al., 2014). However, whether a single exposure to WBV suffices to evoke positive effects on executive functions is unclear. Therefore, the aim of the present study was to investigate the possible effects of a single bout of WBV on subsequent test performance in the Stroop Interference Test. It was hypothesised that cognitive performance can be improved by WBV compared to a control condition without exposure to WBV.

2.5.2 Methods

2.5.2.1 Participants

Eighty undergraduate psychology students (39 females and 41 males; mean age ± standard deviation: 20.9 ± 3.9 years) voluntarily participated in the study, which was conducted in a laboratory of the University of Regensburg. Exclusion criteria were: age below 18 years and above 35 years, uncorrected sensory or locomotor impairments and pregnancy. The participants received course credits for their participation.

2.5.2.2 Materials

WBV

Passive vibration was applied via the vibrating platform Galileo Med Advanced (Novotec Medical GmbH, 2015). For all settings of the device used, we refer to section 2.1.2.2 ("WBV"). In the present study, a control condition without vibration and three different vibration conditions (with the Wobble degree normal, i.e. given frequency ± 2.5 Hz) were used (*see* Table 2.14). In the control condition, the vibration platform was switched on, but no vibration took place. The participants stood on the platform without shoes.

Table 2.14 *Parameters of the different vibration conditions*

Vibration condition	VC 1	VC 2	VC 3	Control
Frequency	7.5 Hz	12.5 Hz	17.5 Hz	No vibration
Amplitude	0 ± 4.5 mm			
Duration	4 min			

**VC = vibration condition*

Stroop Interference Test (Wiener Testsystem)

The Stroop Interference Test was chosen to assess inhibitory control, an aspect of selective attention. The German version of the computerised Stroop task from the Wiener Testsystem was used (Schuhfried GmbH, Mödling, Austria) (Schuhfried, 2011) to measure the color-word interference tendency, i.e. the disturbance of color recognition or reading speed caused by interfering information. The Stroop interference test is a sensorimotor speed test that records speed both in reading words and naming colors (with and without color interference/word interference). The test is based on the assumption that the speed in reading a color word will decrease when the word is presented in a different font color. Furthermore, it is assumed that the naming of the color of the word will be delayed when the color word is depicted in a different font color.

At the start of testing, the participants' reaction speed and accuracy were established as a baseline. This involved the presentation of color words without coloring or colored rectangles. The Stroop task used four different colors (green, red, yellow and blue) and included the following assignments: reading color words displayed in black font color (reading baseline), naming the ink color of differently colored rectangles (naming baseline), naming the ink color of color words in an incongruent format (Stroop effect) and denominating semantically expressed words displayed in incongruent colors (Reverse Stroop effect). These conditions were tested in separate consecutive testing blocks (reading baseline / naming baseline / reading interference / naming interference), with each testing block including 128 successively presented items. The participants were required to read the color words and to name the color of the colored rectangles correctly and as quickly as possible. The participants reacted using a special keyboard with four correspondingly colored buttons.

The median of reaction time and the number of false reactions were registered for each of the four test assignments. The variables reading interference tendency and naming interference tendency were also recorded. The reading interference tendency is the difference of the reaction time medians at Stroop condition and at baseline. Similarly, the naming interference tendency depicts the difference of the reaction times between Reverse Stroop condition and baseline. The interference tendency describes the failure proneness in regard to irrelevant items (inhibitory control), indicating how well a subject can inhibit the automatic inclination to read the color word. The smaller the difference of the results between baseline and interference, the less prone to failure the participants appear in respect of irrelevant cues. Test processing lasted 15 minutes.

2.5.2.3 Study design and procedure

The participants were assigned to one of the four experimental conditions using block randomization. A factorial design with the between-subjects factor vibration condition (0 Hz, 7.5 Hz, 12.5 Hz or 17.5 Hz) as independent variable was used. Each vibration condition lasted four minutes. The test performance with the Stroop test parameters mentioned above was the dependent variable.

At the beginning of the test session, participants filled in a questionnaire of demographic variables. After exposure to the vibration or control conditions, they were required to complete the inhibitory control task. The entire test session lasted approximately 45 minutes.

Table 2.15 *Age and sex of study participants for the vibration conditions used*

Vibration condition	VC 1	VC 2	VC 3	Control
Age (years, mean ± standard deviation)	21.2 ± 2.4	20.6 ± 2.7	20.3 ± 3.1	21.2 ± 6.4
Sex (female/male)	9/11	11/9	9/11	10/10

**VC = vibration condition*

2.5.2.4 Statistical analyses

Possible differences in demographic variables between the experimental conditions were assessed using a one-factorial univariate ANOVA with the between-subject factor vibration condition and the dependent variable age. Differences regarding gender were assessed using χ^2-tests. Two-factorial univariate ANOVAs with the between-subjects factor vibration condition and the within-subjects factor test condition (baseline, interference) were performed for the Stroop test parameters of both reading and naming condition of the Stroop test. Post hoc analyses were performed using paired t-tests. P-values of less than 0.05 were considered statistically significant. All statistical analyses were performed using the Statistical Package for Social Sciences 22.0 (SPSS, IBM 2015).

2.5.3 Results

2.5.3.1 Demographic variables

No statistically significant differences between the four vibration conditions were found regarding the variables gender ($\chi^2(3) = .55$, $p = .91$) and age ($F(3, 76) = 0.41$, $\eta^2 = .01$, $p = .75$).

2.5.3.2 Effect of WBV on inhibitory control (Stroop test)

Compared to the baseline condition, the participants needed a longer completion time both in the reading and naming interference conditions, which demonstrated a main interference effect for both test conditions (reading: $F(1, 76) = 325.08$, $\eta^2 = .81$, $p < .01$;

naming: $F(1, 76) = 218.30$, $\eta^2 = .74$, $p < .01$). The results did not show a statistically significant main effect of the factor *vibration condition* in both test conditions of the Stroop Interference Test (reading: $F(3, 76) = .09$, $\eta^2 = .004$, $p = .97$; naming: $F(3, 76) = .91$, $\eta^2 = .04$, $p = .44$). Furthermore, no significant interaction effect of vibration condition and test condition was found in the reading ($F(3, 76) = 2.46$, $\eta^2 = .09$, $p = .07$) or naming condition ($F(3, 76) = 1.94$, $\eta^2 = .07$, $p = .13$) (*see* Table 2.16).

Table 2.16 *Median (interquartile range) of the reaction times for the different test and vibration conditions*

	Reading		**Naming**	
	Baseline condition	**Interference condition**	**Baseline condition**	**Interference condition**
VC 1	.62 (.08)	.81 (.13)	.60 (.08)	.65 (.09)
VC 2	.63 (.06)	.72 (.11)	.59 (.12)	.68 (.16)
VC 3	.65 (.05)	.78 (.11)	.62 (.06)	.66 (.15)
Control	.64 (.07)	.73 (.13)	.61 (.08)	.67 (.10)
Total	.64 (.11)	.77 (.15)	.60 (.10)	.66 (.08)

**VC = vibration condition*

The analysis of the number of false reactions showed a main effect of the factor *test condition* indicating that participants made more mistakes in the interference condition compared to baseline in both the reading ($F(3, 76) = 17.07$, $\eta^2 = .18$, $p < .01$) and naming condition ($F(3, 76) = 15.99$, $\eta^2 = .17$, $p < .01$). Furthermore, a significant interaction effect of vibration condition and test condition was found in the reading condition ($F(3, 76) = 3.56$, $\eta^2 = .12$, $p = .02$) indicating that the interference effect in the reading condition varied between the different vibration conditions. A post hoc analysis showed a significant increase of false reactions in the interference condition compared to baseline for WBV condition 1 ($t(19) = -2.01$, $p = .05$) and 2 ($t(19) = -3.45$, $p < .01$). However, no significant interaction effect of vibration condition and test condition was found in the naming condition ($F(3, 76) = .54$, $\eta^2 = .02$, $p = .65$). Furthermore, no significant main effect of the factor *vibration condition* was found in either Stroop condition (reading: $F(3, 76) = .69$, $\eta^2 = .03$, $p = .56$; naming: $F(3, 76) = .88$, $\eta^2 = .03$, $p = .46$) (*see* Table 2.17).

Table 2.17 *Number of false reactions (mean and standard deviation) for the different vibration and test conditions*

	Reading		Naming	
	Baseline condition	**Interference condition**	**Baseline condition**	**Interference condition**
VC 1	3.90 (3.88)	5.05 (4.32)	4.00 (3.26)	4.95 (3.50)
VC 2	3.20 (2.87)	6.35 (5.42)	4.65 (3.76)	5.95 (6.35)
VC 3	3.60 (4.19)	4.15 (3.76)	3.40 (2.62)	4.40 (3.33)
Control	2.95 (3.73)	3.50 (2.91)	2.60 (3.28)	4.60 (3.62)
Total	3.41 (3.65)	4.76 (4.26)	3.66 (3.28)	4.97 (4.34)

**VC = vibration condition*

2.5.4 Discussion

The present study examined the effects of WBV on the control of cognitive interference using a Stroop task, which involves two competing information-processing pathways and requires the respondent to use the less dominant pathway in the face of interference from the dominant pathway. The Stroop Interference Test measures speed in reading words and naming colours under conditions of colour/word interference.

The results of the present study demonstrated an interference effect in both test conditions (reading, naming) indicating that the speed of reading a colour word or naming the ink of a colour word is significantly increased in the interference condition compared to the baseline condition. However, these differences in reaction times in the reading condition (reading interference tendency) and the naming condition (naming interference tendency) did not differ significantly between the four conditions (three WBV conditions and control condition). These findings suggest that a single bout of WBV for four minutes does not have a beneficial effect on inhibitory control as assessed using the Stroop Interference Test.

The present results are not in accord with those of other randomised controlled trials which demonstrated improved cognitive performance in attention and inhibition following WBV treatment (den Heijer et al., 2015; Fuermaier, Tucha, Koerts, van Heuvelen et al., 2014; Regterschot et al., 2014). Two studies reported benefits of WBV on inhibitory control compared to a resting condition in healthy adults (Fuermaier, Tucha, Koerts, van Heuvelen et al., 2014; Regterschot et al., 2014). WBV was also found to improve inhibitory control in healthy children aged 8-13 years (den Heijer et al., 2015). The differences between the present and previous results may be due to the use of different protocols regarding WBV settings (frequency: 5-30 Hz, duration 2-4 minutes) and assessment of cognitive performance. In contrast to studies using repeated WBV administration and several assessments of cognitive performance, participants in the present study underwent only one WBV treatment (vibration/no vibration) and one assessment of cognitive performance. Thus, beneficial effects of WBV on inhibitory control may require repeated WBV for cognitive facilitation. Therefore, future studies should investigate the number of WBV treatments needed to produce improvements in inhibition and attention. However, practice effects cannot be ruled out in the context of repeated administration of a cognitive test.

Several mechanisms underlying the beneficial effects of repeated administration of WBV on cognition have been considered. WBV is thought to enhance neuromuscular performance by improving the gravitational load on muscle activity and therefore causing adaptations in skeletal muscles (Cardinale & Bosco, 2003). Furthermore, WBV is assumed to induce an activation of muscle spindles resulting in a reflex contraction that may increase muscle activity and lead to enhanced heart rate and oxygen uptake (den Heijer et al., 2015; Regterschot et al., 2014). Another hypothesis suggests that mechanoreceptors in the skin are activated by WBV and lead to an activation of various brain regions, such as sensory areas of the neocortex, the brainstem, the basal forebrain and the cerebellum (Taiar et al., 2019). In particular, the Meissner corpuscles are likely to be excited by WBV of 30 Hz, and other vibration parameters should also be considered in the context of potential brain activation (Taiar et al., 2019). Information from mechanoreceptors is transferred to the primary somatic sensory cortex, including sensory association areas, and the prefrontal cortex, which plays an important role in cognitive processing. Thus, sensory stimulation may underlie acute beneficial effects of WBV on cognitive performance (Regterschot et al., 2014). WBV appears to produce improvements in cognitive functioning through increased neurotransmitter activity. In particular, the cholinergic system has been shown in mice to be stimulated by WBV (Van der Zee et al., 2010). The findings of the present and previous studies suggest that only repeated WBV exposure elicits beneficial effects on cognition, and potential neurophysiological mechanisms underlying WBV effects may require vibratory stimulation for more than four minutes to develop their effects.

A number of parameters, including intensity and duration of PA, type of activity, cognitive task type, fitness level and timing of cognitive test administration, should be considered as potential moderators of the positive effects of PA on cognition (Y. K. Chang et al., 2012; Pontifex et al., 2019). However, it is unclear how far such parameters are relevant for the association between WBV and cognitive performance. In a previous trial, a pilot study compared 10 different vibration conditions in order to identify the optimal frequency of WBV (Regterschot et al., 2014), but the influence of the duration of WBV has not as yet been explored systematically. A further specification of all relevant WBV parameters is needed in order to optimise the experimental setup (Wuestefeld et al., 2020).

The present study should be viewed in the context of several limitations. First, the WBV parameters were chosen according to previous trials and were not based on a systematic analysis generating the optimal settings for the experimental setup. Future studies should therefore methodically vary frequency and duration of WBV. Second, cognitive performance was assessed only after WBV, which does not allow a comparison with inhibitory control at baseline. A single assessment of cognitive performance was chosen to avoid practice effects. Third, while previous studies concluded that repeated WBV was needed to produce beneficial effects on cognition, the present study aimed to explore the effect of one WBV treatment on subsequent cognitive performance. Since the present results did not show beneficial effects of WBV on cognition, future studies should systematically examine the effects of single compared to repeated WBV administrations.

Taken together, the results of the present study found no beneficial effects of a single WBV treatment lasting four minutes on subsequent assessment of inhibitory control. The differences in results between the present and previous studies may be due to the choice of different settings and study procedures. More research is needed to establish the optimal WBV treatment needed to produce positive effects on cognition.

3 General Discussion

3.1 Summary of findings

In sum, **Study 1** does not show that WBV immediately before assessment of attentional functions has been associated with better performance in tests examining tonic and phasic alertness, working memory, divided attention and response inhibition. Participants in the vibration conditions produced neither quicker responses nor fewer mistakes than controls. Moreover, they did not work more carefully, as shown by the numbers of omissions or false reactions.

The findings of **study 2** do not reveal any positive effect of vibration on task performance in participants performing an attentional test of high task complexity following WBV exposure of a longer duration as compared to study 1. Despite significant differences between the two vibration conditions (WBV-C vs. WBV-W) and the control group with regard to all but one of the test parameters (mean time of incorrect reactions), the participants of the control group performed better than those of both vibration conditions (WBV-C, WBV-W). However, results showed that the WBV-W group achieved better test results than the WBV-C group, indicating that a fluctuating vibration frequency appears to produce improved attentional performance due to sufficient maintenance of arousal level.

Thus, in comparison to a control group, **study 3** examines the effect of three different vibration conditions with fluctuating vibration frequency on subsequent test performance in a mental rotation task. Whereas results suggest that WBV did not improve mental rotation performance in terms of the number of correct reactions, it was found that WBV reduced both the mean time of processing the correctly solved test items and the mean time of processing of all items. These test parameters were significantly shorter in vibration condition 2 with a frequency of 12.5 Hz than in vibration condition 3 with a frequency of 17.5 Hz and the control group. These findings support an inverted-U shaped relationship between vibration frequency and the time of mental rotation test processing, indicating that a medium WBV intensity leads to faster processing compared to high intensity, low intensity or no vibration. However, it remains unclear whether other types of cognitive abilities may be positively influenced by a similar WBV treatment.

Therefore, **study 4** examined the immediate and delayed recall after a single bout of WBV to further elucidate the effects of WBV on memory function. The comparison of immediate and delayed recall showed time-dependent forgetting, with the participants recalling significantly more words directly after the learning phase than after a delay of 20 minutes. A statistically significant interaction between groups and time of testing was not shown. Thus, no vibration condition was shown to have beneficial effects on immediate or delayed recall.

Finally, **study 5** examined the effects of WBV on the control of cognitive interference using a Stroop task. The results demonstrated an interference effect in both test conditions (reading, naming) indicating that the speed of reading a colour word or naming the ink of a colour word is significantly increased in the interference condition compared to the baseline condition. However, these differences in reaction times in the reading condition (reading interference tendency) and the naming condition (naming interference tendency) did not differ significantly between the four conditions (three WBV conditions and control condition). These findings suggest that a single bout of WBV for four minutes does not have a beneficial effect on inhibitory control as assessed using the Stroop Interference Test.

3.2 Theoretical Considerations

3.2.1 Dose-response association between WBV and cognitive performance: Implications for a suitable research design

Based on several reviews of the scientific literature indicating beneficial effects of acute exercise on cognitive functioning (Y. K. Chang et al., 2012; J. L. Etnier et al., 1997; Kelly et al., 2014; Tomporowski, 2003), the studies 1-5 summarised above have found mixed results. The differences in results may have been due to different research designs, including various characteristics of both the vibration treatment and the cognitive test used. Whereas WBV treatment has been defined by frequency, duration, mode and number of trials, task type and task complexity are important factors with respect to the assessment of cognitive performance. Moreover, the timing of test administration (during WBV versus post WBV) should be regarded as another potentially important factor.

In line with numerous systematic reviews and meta-analyses showing beneficial effects of moderate intensity exercise on cognitive performance (Y. K. Chang et al., 2012; Ludyga et al., 2016; Verburgh et al., 2014), the results of study 3 showed beneficial effects of moderate WBV on mental rotation across the available range of vibration frequency (5–30 Hz). This implied an inverted-U shaped relationship with vibration intensity, which has been found in studies showing beneficial effects of WBV on cognition (den Heijer et al., 2015; Fuermaier, Tucha, Koerts, van Heuvelen et al., 2014; Regterschot et al., 2014). In contrast, studies 4 and 5 did not reveal a facilitation of cognitive performance, although similar intensities of WBV were used. As optimal application conditions remain unknown, it seems necessary to examine different frequencies to identify the optimal frequency of WBV treatment that may cause beneficial effects.

Furthermore, the duration of WBV exposure should also be considered. Whereas some research has recommended that increasing the duration of exercise elevates subjective discomfort (Kjellberg, 1990), a longer duration may promote more beneficial effects of WBV on cognitive performance. However, due to the absence of ample evidence, the optimal duration of WBV has not been sufficiently explored. In comparison to randomised controlled trials that have shown improvements in cognitive performance following WBV with relatively short durations (den Heijer et al., 2015; Fuermaier, Tucha, Koerts, van Heuvelen et al., 2014; Regterschot et al., 2014), only the results of study 3 showed beneficial effects of WBV on subsequent testing using a similar duration of WBV treatment (4 minutes). Therefore, future studies should assess the effects of various durations of WBV exposure.

As a new feature, the specific mode of WBV frequency (consistent vs. fluctuating) was found to differentially affect cognitive performance measured after cessation of WBV treatment. Whereas study 1 did not show any statistically significant effects between the two vibration conditions used, study 2 revealed that participants exposed to vibration with varying frequency showed better results than those exposed to constant frequency of vibration. Therefore, WBV with varying frequencies was used in studies 3 to 5, although only study 3 found statistically significant effects across different conditions of WBV with varying frequency compared to a control condition without WBV. This pattern of results indicated that additional studies should explore the differential effects of the mode of WBV frequency.

Regarding the number of trials of WBV treatment, several studies have revealed differences based on the number of trials, with one trial consisting of WBV exposure and subsequent testing of cognitive functioning usually followed by a resting period before the next trial. While the studies summarised above used only one trial of vibration, with the exception of study 1, and did not identify positive results, with the exception of study 3, other studies showing beneficial effects of WBV on cognition provided either six sessions with exposure to WBV in alteration to six control sessions without WBV

(Regterschot et al., 2014), four sessions with exposure to WBV in alteration to four control sessions (Fuermaier, Tucha, Koerts, van Heuvelen et al., 2014) or three sessions with exposure to WBV in alteration to three control sessions (den Heijer et al., 2015). However, as the optimal number of repetitions of WBV treatment and subsequent testing is still unknown, this factor should be further investigated in future studies.

When discussing factors accounting for the different effects of WBV on cognition, task type and task complexity should also be considered. A meta-analytical investigation regarding various moderating variables in the exercise-cognition interaction showed that the effect sizes with central executive tasks were larger overall than those with alertness and attention tasks, which suggests a pronounced effect of acute exercise on the mediating of executive functioning by the prefrontal cortex (T. McMorris & Hale, 2012). Moreover, the feasibility that simpler tasks have a ceiling effect should also be discussed (Pontifex et al., 2019). In general, several authors have argued that more complex tasks may be more likely to be affected by PA than simple tasks (T. McMorris & Hale, 2012). Therefore, it is reasonable that the studies summarised above have examined various cognitive tasks with differing levels of complexity to identify those cognitive tasks that may benefit from acute WBV treatment. However, as the findings of the studies presented above could not clarify the moderating role of cognitive task type, future studies should further explore different task types to fulfil this task.

Finally, the timing of test administration (during WBV versus post WBV) may also play an important role in the context of defining a suitable research design for identifying beneficial effects of WBV on cognition. It was found that PA improved cognitive performance when cognitive testing was administered immediately after PA, regardless of the kind of exercise (Lambourne & Tomporowski, 2010). While studies have shown negative effects on performance during WBV treatment (Conway et al., 2007; Costa et al., 2012; Sherwood & Griffin, 1992), studies have revealed positive effects on performance when WBV treatment precedes cognitive testing (den Heijer et al., 2015; Fuermaier, Tucha, Koerts, van Heuvelen et al., 2014; Regterschot et al., 2014). These differences in results may be due to the vibration stimulus, which could be treated as a distracting or an impairing influence when performance has been assessed during WBV exposure.

Taken together, as only study 3 of the studies presented above showed beneficial effects of a single session of WBV on subsequent assessment of cognitive performance, it remains necessary for future studies to examine WBV and the task characteristics summarised above to detect those conditions under which an acute bout of WBV may improve subsequent cognitive performance.

3.2.2 Dose-response association between WBV and cognitive performance: Possible underlying mechanisms

The findings of various systematic reviews have addressed the potential mechanisms responsible for the effects of acute PA on cognitive functioning, including changes in arousal (Byun et al., 2014; T. McMorris, 2016b), brain-derived neurotrophic factor (BDNF) (Dinoff et al., 2017; Szuhany et al., 2015), cerebral blood flow (CBF) (Brown et al., 2010; Guiney et al., 2015) and catecholamines (Da Silva de Vargas et al., 2017; T. McMorris et al., 2008). In addition, numerous studies have been performed to explore how beneficial effects of WBV on cognition can be achieved, whereas the biological or psychological underpinnings are still unclear. Thus, different hypotheses are discussed below regarding the mechanisms that may mediate the effects of WBV on cognitive performance.

Initially, WBV was supposed to enhance neuromuscular performance by improving the gravitational load on muscle activity thereby causing adaptations in skeletal muscles (Cardinale & Bosco, 2003). It has been assumed that WBV induced the activation of muscle spindles, resulting in a reflex contraction that may increase muscle activity and lead to enhanced heart rate and oxygen uptake (Cochrane et al., 2008; Rittweger et al., 2001). Another approach supported the assertion that mechanoreceptors in different strata of the skin are activated by WBV and accelerate information transfer through the spinal cord and the thalamus to various brain regions, such as sensory areas of the neocortex, the brainstem, the basal forebrain or the cerebellum (Taiar et al., 2019). In particular, Meissner corpuscles are likely to be excited by WBV of 30 Hz, but other settings should also be investigated when discussing the appropriate parameters that lead to activation of the brain (Taiar et al., 2019). The afferences of the mechanoreceptors are transferred to the primary somatic sensory cortex, including sensory association areas. These areas have different pathways to the prefrontal cortex which is an important brain region involved in cognitive processing. Thus, sensory stimulation may underlie the acute beneficial effects of WBV on cognitive performance (Regterschot et al., 2014). In relation to the mechanisms assumed to mediate the effects of PA on cognitive functioning, WBV seems to cause similar improvements in cognitive functioning by means of increased neurotransmitter systems, for example, the cholinergic system in particular has been shown to be evoked by WBV compared to other forms of PA (Van der Zee et al., 2010).

Here, two models are discussed as theoretical frameworks in the context of the examination of detrimental effects of WBV on human performance (Conway et al., 2007). The maximal adaptability model described by P. A. Hancock und Warm (2003) defines stress as a concept involving three components (“trinity of stress”), including the environmental source of stress (input), its depiction as a direct assimilation to the stressor (adaptation) and the expression of the adoption as a disruption of the subsequent performance (output). To maintain performance capacity, subjects often successively match environmental stressors while the process of adaptation takes place at various levels (physiological/behavioural/affective). As the intensity or duration of a stressor is enhanced, adaptation is likely to incrementally fail. Accordingly, WBV may be seen as an input factor that can operate differently depending on intensity or duration, whereas task characteristics may also be considered important determinants of the adaptation process (Conway et al., 2007). Thus, the maximal adaptability model describes the combination of WBV and task characteristics as a multiplicative rather than additive effect and suggests that empirical examinations should be designed in a way that systematically vary the characteristics of WBV (e.g., frequency and duration) and should explore the effects of WBV on different cognitive tasks with various task characteristics (Conway et al., 2007).

Alternatively, the compensatory control model (CCM) of Hockey (1997) proposed the importance of suitable measures to assess stressor effects. Under both environmental strains and task requirements, subjects’ performance can be sustained by investment in enhanced effort or alternative strategies. However, the preservation of performance as a function of enhanced effort mobilization occurs at the cost of other psychological factors, such as increased fatigue or subjective workload (R. Hancock, Mansfield, Goel & Vellani, 2008). Moreover, the biological and motivational context underpinning observable performance should be noted, as high performance is only one of various motivational goals, and goals may vary when performance is prolonged. However, a high amount of performance needs increased motivation, but motivation tends to decrease as the costs appear to be too high (R. Hancock, Mansfield, Goel & Vellani, 2008). Hockey’s model seems to provide a reasonable framework for the studies mentioned above, and studies mentioned earlier demonstrated no differences in cognitive performance between subjects in WBV and control groups (R. Hancock, Mansfield, Goel & Narayanamoorthy, 2008; J.

Ljungberg et al., 2004; J. K. Ljungberg & Neely, 2007b; Newell & Mansfield, 2008). Thus, it may be important that the effects of WBV on cognition should be assessed not only by psychophysiological parameters but also by means of subjective variables such as exertion or exhaustion, which might illustrate the costs emerging from the maintenance of performance (Conway et al., 2007).

Taken together, since little is known about the potential processes generating positive effects of WBV on cognition, psychophysiological or neuroimaging studies may shed light on the biological processes, whereas the use of suitable measures for participants' perception of stress, exertion or exhaustion may illuminate the psychological processes underlying potential effects of WBV on cognition.

3.3 Possible Applications of WBV

Whereas WBV exposure has been shown to be a promising exercise modality in the management of various chronic conditions (Gritschmeier & Lange, 2020), the results of the studies summarised above shed more light on the conditions that should be regarded to achieve beneficial effects of WBV exposure on cognitive functioning. Furthermore, it seems necessary to address the question of which areas may benefit from the reported improvements in cognition. Thus, the following three sections illustrate evidence in different domains where WBV was found to provide beneficial effects on mental health outcomes and cognitive functioning.

3.3.1 WBV and sleep quality

The evidence in regard to the effects of insomnia on different cognitive abilities, including attention, memory and executive function, have produced mixed results across these various cognitive domains (Brownlow et al., 2020; Y. Li et al., 2016). Specific sleep disturbances were found to be linked to differences in cognitive performance in both younger (Miyata et al., 2010) and older adults (Blackwell et al., 2006; Nebes et al., 2009). A systematic review of meta-analyses recommended that physical activity was related to improvements in specific sleep outcomes, including overall sleep quality, subjective sleep and sleep latency (Kelley & Kelley, 2017). However, the specific associations among PA, sleep and cognitive performance remains inconclusive. Whereas sleep efficiency has been reported to mediate the relationship between PA and cognitive performance (L. Li et al., 2021; Wilckens et al., 2018), it was also found that PA may play a mediating role in the association between sleep quality and physical and mental health (Zhao et al., 2021). As

PA has been shown to produce beneficial effects on sleep quality (Banno et al., 2018), few studies have investigated whether WBV may be a reasonable exercise modality to improve sleep quality and thereby cognitive performance.

A clinical trial study that compared a WBV protocol with a fixed frequency of 5 Hz and a WBV protocol with a fluctuating vibration frequency between 5 and 16 Hz investigated the effect of WBV on the sleep quality of individuals with metabolic syndrome (MetS). Both WBV interventions were performed two times a week for six weeks. The findings of this study indicated that WBV revealed improved sleep quality assessed by different measures (Figueiredo Azeredo et al., 2019). With regard to elderly women older than 65 years, a three-month WBV training did not show better post test results on sleep quality measured by the Pittsburgh sleep quality index (PSQI) (Lin et al., 2020), whereas a combination of an exercise program and vibration training two times a week for three months provided improvements in sleep quality also assessed by the PSQI (Palop-Montoro et al., 2020).

However, future studies are needed to explore whether WBV represents a suitable exercise type for improving sleep quality, especially for older people. Possible advantages may be that exercises can be performed at home, the dosage of WBV can be individually adopted and the duration is reduced compared to other forms of PA (Palop-Montoro et al., 2020). Furthermore, WBV as a treatment method for sleep disturbances might contribute to the facilitation of cognitive functioning.

3.3.2 WBV and ADHD

Numerous systematic reviews have stated that physical activity may be an alternative and effective method in the management of ADHD symptoms, particularly for children, indicating beneficial effects on cognitive functions and behavioural measures (den Heijer et al., 2017; Neudecker et al., 2019; Vysniauske et al., 2020). The results suggested that cardiovascular exercise showed both acute and chronic beneficial effects on academic and cognitive performance, whereas valid conclusions in regard to acute and chronic positive effects of non-cardiovascular exercise on ADHD symptomatology did not exist due to methodological weaknesses. Thus, cardiovascular exercise seems to be a more auspicious treatment option for symptoms of ADHD than non-cardiovascular exercise to provide both acute and chronic facilitative effects on cognitive and behavioural functions (den Heijer et al., 2017). However, with regard to exercise characteristics, mixed exercise programs have been proposed to result in improvements in ADHD symptoms and motor skills in children and adolescents with ADHD (Neudecker et al., 2019). Among others, WBV has been suggested as a reasonable supplement in the context of ADHD symptom management. A recent randomised controlled trial comparing two exercise groups (chronic treadmill training with and without WBV training) for 8 weeks showed that treadmill training ameliorated ADHD symptoms, while additional WBV training improved classroom behaviours (Durgut et al., 2020). Moreover, two studies explored the potential effects of WBV on executive functions in children and adults with ADHD and concluded that WBV may be a potent and harmless treatment method in the management of ADHD (Fuermaier, Tucha, Koerts, van Heuvelen et al., 2014; Regterschot et al., 2014). However, further research is needed to determine the possible value of WBV training on different ADHD symptoms.

3.3.3 WBV and depression

Different types of physical activity have been shown to produce beneficial effects on the mental health status of young adults (Pascoe & Parker, 2019). Numerous reviews have suggested that physical activity may be an effective treatment for reducing depressive symptoms (Bailey et al., 2018; Radovic et al., 2017; Schuch et al., 2018). Thus, physical activity should be added to established treatment protocols, including pharmacotherapy and/or psychotherapy. However, specific symptoms such as poor mood, fatigue or lack of motivation were identified as common obstacles to engaging in physical activity among depressive individuals (Busch et al., 2016), while adolescents appeared to accept physical activity more readily than other treatment options (Oberste et al., 2020). In addition to existing treatments for depressed adolescents with low motivation for engagement in exercise, WBV has been suggested to be an appropriate exercise treatment compared to other forms of exercise (Wunram et al., 2018).

A recent semi-randomised controlled trial examined the effects of two exercise types (WBV or ergometer training) as add-ons to treatment-as-usual (TAU) on the reduction of depressive symptoms in adolescents (Wunram et al., 2018). All study attendees were not on antidepressant medication and were randomly assigned to one of three study conditions. In both intervention groups, participants had to exercise 30 minutes a day for 3-5 days for 6 weeks in addition to TAU, while participants of the control group just had TAU. Depression scores for all groups were assessed by the Depressions-Inventar für Kinder und Jugendliche (DIKJ) at baseline (t0), 6 weeks after completing the exercise intervention (t1) and 14 (t2) and 26 weeks (post t2). The findings in this study indicated that both exercise interventions showed significant reductions in depressive symptoms after 26 weeks compared to TAU, whereas only a statistical trend was found in the WBV group after week 6 suggesting a faster decline in symptom severity.

In another randomised controlled trial, participants were randomly allocated to either a WBV training condition three times weekly for 12 weeks or a control condition where no training took place. The severity of depression was measured by the Beck Depression Inventory (BDI) in both groups before and after treatment. BDI scores did not differ between the test conditions at baseline. The results showed that the difference between the BDI scores before and after WBV training was statistically significant, while the difference between the BDI scores of the control group was not (Aksoy, 2019).

Based on the findings from these randomised controlled trials, passive WBV can be viewed as an alternative stand-alone or additional treatment for the reduction of depressive symptoms (Aksoy, 2019; Oberste et al., 2020). Most likely, WBV training could be used in highly depressed individuals with low motivation to engage in physical activity or before more active exercise interventions can be applied (Wunram et al., 2018).

3.4 Conclusion

The results of the five studies summarised above revealed different implications concerning the requirements that should be regarded to obtain beneficial effects of WBV on cognition. Both parameters of WBV treatment (frequency, duration, mode, and number of trials) and cognitive task characteristics (task type, task complexity, and timing of test administration) should be considered. Since only study 3 showed significant improvements following WBV compared to a control condition, various factors should be taken into account when searching for the mechanisms that are responsible for the positive effects of WBV on cognitive performance. Since little is known about the potential processes generating positive effects of WBV on cognition, psychophysiological or neuroimaging studies may elucidate the biological processes underlying the potential effects of WBV on cognition. Furthermore, future studies should modify both the parameters of WBV described above and the task characteristics to provide a better understanding of the way in which improvements in cognitive functioning through WBV could be effected.

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