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The effect of cognitive challenge on brain activity and weight-shifting characteristics during exergaming

- An experimental study on healthy young adults

Master's thesis in Human Movement Science

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ABSTRACT

Background: Exergaming has become a topic of increasing interest during the last decade, not only for entertainment purposes, but also in clinical use. The focus has to date mainly been on the physical benefits of exergaming, and little is known of its effect on brain activity during gameplay. Specifically, there is a lack of knowledge regarding whether exergames can lead to higher activation of the frontal area of the brain during exergaming, and thereby challenge executive functions. This is mainly due to a lack of appropriate empirical methods in the previous years. Additionally, there is a need for further knowledge regarding the effect of cognitive challenge on movement characteristics, such as weight shifting. **Aim:** To investigate whether it is feasible to measure frontal theta activity while playing a balance-based exergame. Furthermore, to investigate whether frontal theta power increases with increased cognitive challenge, and whether cognitive challenge affects the quality of weight-shifting characteristics. **Methods:** Twenty-four healthy young adults (12 men, 12 women, mean age 24.5±0.4 yrs) repeatedly shifted their weight mediolaterally in three conditions: 1) self-paced weight shifting without exergame context, 2) puzzle exergame with one puzzle piece, 3) puzzle game with two puzzle pieces. Brain activity was recorded using a 64-channel EEG system and EOG electrodes (SynAmps RT, Compumedics Neurocscan, US). Ground reaction forces from two Kistler force plates were recorded at 100 Hz, and used to calculate mediolateral amplitude, area, velocity, and smoothness (calculated as jerk) of the Centre of Pressure (CoP). Statistical analysis consisted of paired samples *t*-tests and 1-way and 3-way repeated measures ANOVAs, using pairwise comparisons with Bonferroni corrections as post-hoc follow-up. **Results:** Measuring EEG while playing a balance-based exergame was found to be feasible. Frontal theta power increased significantly in the exergaming conditions compared to shifting weight with no exergaming context. However, no further increase in frontal theta power was found when increasing the difficulty level of the exergame. No significant differences were found in weight-shifting characteristics between the two exergaming conditions. **Conclusion:** The results from this study confirm that it is feasible to measure EEG while moving, even with a passive electrode system. Furthermore, exergaming increases frontal theta activation in healthy young adults. However, neither frontal theta activity nor weight-shifting characteristics were influenced by a further increase in cognitive challenge in the exergame.

Keywords: Exergame, force plate, weight shifts, centre of pressure, EEG, frontal theta.

SAMMENDRAG

Bakgrunn: Interessen for "exergaming", eller aktivitetsspill, har økt det siste tiåret, ikke bare til underholdningsformål, men også for klinisk bruk. Hittil har fokuset hovedsakelig vært på de fysiske fordelene ved exergaming, og det er derfor lite kunnskap om hvordan hjerneaktivitet påvirkes under spill. Mer spesifikt er det mangel på kunnskap om hvorvidt exergaming kan øke aktivering av det frontale området av hjernen under spill, og videre utfordre eksekutive funksjoner. Dette er hovedsakelig grunnet mangel på hensiktsmessig empirisk metode de foregående årene. I tillegg er det behov for ytterligere kunnskap vedrørende effekten av kognitiv utfordring på bevegelseskarakteristikker, som for eksempel vektoverføring. **Hensikt:** Å undersøke hvorvidt det er gjennomførbart å måle frontal theta aktivitet under spilling av et balansebasert exergame. Videre, å undersøke om frontal theta power øker med økt kognitiv utfordring, og om kognitiv utfordring påvirker kvaliteten på vektoverføringen. **Metode:** Tjuefire friske, unge mennesker (12 menn, 12 kvinner, gjennomsnittlig alder 24.5±0.4 år) utførte repetitive vektoverføringer i mediolateral retning i tre kondisjoner 1) vektoverføring i selvvalgt hastighet uten bruk av exergame, 2) puslespill-exergame med én brikke, 3) puslespill-exergame med to brikker. Hjerneaktivitet ble målt ved hjelp av et 64-kanals EEG system og EOG elektroder (SynAmps RT, Compumedics Neurocscan, US). Reaksjonskrefter fra underlaget ble målt ved hjelp av to Kistler kraftplater med en målingsfrekvens på 100Hz, og brukt til å beregne mediolateral amplitude, areal, hastighet og hvor flytende bevegelsene var (beregnet som jerk) av trykksenteret (CoP). Den statistiske analysen bestod av parvise *t*-tester, og enveis og treveis ANOVAer med repeterte målinger, med bruk av parvise sammenligninger med Bonferronis korreksjoner som post-hoc oppfølging. **Resultat:** Å måle EEG under spilling av et balansebasert exergame viste seg å være gjennomførbart. Frontal theta power økte signifikant under exergaming sammenlignet med kun vektoverføring. Det var derimot ingen ytterligere økning i frontal theta power ved økning av spillets vanskelighetsgrad. Ingen signifikant forskjell ble funnet i vektoverføringskarakteristikkene mellom de to vanskelighetsgradene i spillet. **Konklusjon:** Resultatene fra denne studien viser at det er mulig å måle EEG under bevegelse, selv med et passivt elektrodesystem. De viser også at exergaming øker frontal theta aktivering blant unge, friske mennesker. Det er imidlertid ingen ytterligere påvirkning på verken frontal theta aktivitet eller vektoverføringskarakteristikker ved en ytterligere økning av kognitiv utfordring i spillet.

Nøkkelord: Exergame, kraftplate, vektoverføring, trykksenter, EEG, frontal theta.

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INTRODUCTION

In the last decades, the use of welfare technology has become a topic of increasing interest. Welfare technology is a concept described as technological assistance that contributes to increased safety, social participation, physical activity, and the individual's improved ability for independent living despite possible difficulties present in their daily life (1). Exergaming is an example of welfare technology that has gained increased attention, both in the general public as well as for researchers aspiring to further develop such games for clinical use (2). Exergames are videogames that require bodily movement in order to participate in the game. Such games generally promote physical activity, which may include strength, flexibility, and balance training (3). Game consoles such as Nintendo Wii, Microsoft X-box with Kinect, and Playstation with Move have made it possible to play activity-based video games with real-time feedback on the players performance (4). Even though most commercial games are primarily developed for entertainment purposes (5), exergames have in recent years been considered a valuable instrument to encourage participation, and improve adherence, in exercise and rehabilitation tasks (2). Although a wide variety of physical functions can be implemented in an exergame, balance is the one function that has gained the most interest to date (6).

Balance, as defined by Winter (7), is "a generic term describing the dynamics of body posture to prevent falling". Balance training has been shown to be beneficial for both prevention and rehabilitation of decline in physical function and injury, by improving posture and strength through neural adaptations of the central nervous system. These findings have been seen in both older adults as well as active athletes (8). Control of postural sway, or movement of the Center of Mass (CoM), is considered to be important in order to maintain balance (9). The CoM is a passive variable controlled by the balance control system, and its vertical projection onto the ground is referred to as the Center of Gravity (CoG). The point location of the vertical ground reaction force vector is referred to as the Center of Pressure (CoP). This vector represents a weighted average of the pressure applied to a surface. Although the CoP is independent of the CoM and not equal to the CoG (7), the CoP is frequently used as an indirect measure to quantify balance or postural control (7, 9, 10). Gurfinkel (11) states that CoP gives the possibility to evaluate not only the quality of the maintenance of posture, but also the muscle work at hand. As an example, during mediolateral shifting of body weight, the CoP will continuously move mediolaterally with respect to the CoG. When the central nervous system senses that the CoG is moving mediolaterally and is in need of correction, a load/unload mechanism at the hips is activated and the CoP will exceed the CoG. Incorrect weight shifting was identified by Robinovitch and colleagues (12) as the most frequent cause of falling in older adults in long-term care facilities. In addition, it has been shown that weight-shifting capacity provides information regarding balance recovery post stroke (13). Both speed, precision, and symmetry of weight shifting have been shown to be negatively affected by stroke (13). Thus, weight shifting capacity is of importance for several populations, and should therefore be implemented in rehabilitation such as exergames for clinical use that target balance.

In addition to impairments in motor abilities and physical function, deficiencies in attention, memory, and executive functions (EF) can occur following disease or injury such as stroke and brain trauma (14). After the occurrence of such disease or injury, it is crucial to implement effective, targeted, and intensive training early on to effectively improve physical and cognitive function, independence, and quality of life (15). There has also been found a strong relationship between executive functions and the risk of falling in older adults (16). Executive functions (EF) are generally referred to as higher-level cognitive functions that control and regulate lower-level cognitive processes as well as goal-directed and future-oriented behavior (17). Higher-level cognitive functions include problem solving, impulse control, and abstract thinking, while lower-level cognitive functions include visual-spatial perception, visual and auditory attention, and short- and/or long-term memory (cf. 17). Previous research has shown that electroencephalography (EEG) can be used to measure brain activity related to EFs, and that frontal theta activity is related to EFs in both cognitive tasks (18, 19) and tasks requiring motor control (20). Theta activity (4-7.5 Hz) seems to originate in the frontal midline and increases in power when more focused attention is needed (21, 22). Eggenberger and colleagues (23) found evidence suggesting that physical exercise induces prefrontal adaptations, which improves EFs and processing speed. In addition, a systematic review has reported positive effects of exergaming on several cognitive abilities, such as reaction time, processing speed, executive function, and global cognition (24). A meta-analytic study (25) examining cognitive function in healthy older adults after exergaming also found positive effects on reaction time and global cognition, as well as on attention and memory. In addition, Schättin and colleagues (26) found improvements in EFs in both an exergaming group and a group that underwent conventional balance training after an intervention period of 8 weeks. However, the researchers reported that the exergame was more specific and efficient in training EFs compared to conventional balance training. Given that after injury and illness, cognitive functions often are just as crucial to regain as physical functions, one should aspire to implement elements in exergames for clinical use which challenge both these functions simultaneously (27).

However, challenging both cognitive and physical functions simultaneously can have negative effects on physical performance. A previous study with older adults playing different exergames with different levels of difficulty showed negative effect on overall movement characteristics with additional cognitive challenge. When increasing difficulty level in either game it resulted in the participants taking narrower steps and transferring less body weight with each step (28). Also, Albertsen and colleagues (29) reported decreased anteroposterior, mediolateral and total CoP displacement when adding a cognitive challenge to a postural challenge (standing with feet together) in healthy young participants.

Previous research has mainly focused on either cognitive challenge or movement characteristics during exergaming. Furthermore, even when focus was on the effect of cognitive challenge, this was mainly studied indirectly through proxy-measures, not directly through brain activity measure during actual gameplay. So far, no studies have investigated brain activity and movement characteristics while playing exergames with different levels of cognitive challenge simultaneously. This might be due mainly to the lack of appropriate empirical methods that make it possible to measure brain activity during movement. Only recently, equipment has been developed that gives the opportunity to measure brain activity portably, hence, not much is known yet on the subject of brain activity during exergaming. Therefore, we aim to start filling this gap in knowledge by investigating 1) whether it is feasible to measure brain activity and weight-shifting characteristics concurrently, 2) whether frontal theta activity increases with increased cognitive challenge, and 3) whether increased cognitive challenge affects weight-shifting characteristics. Because of the feasibility aim, only healthy young adults were included in this first study.

We expected that measuring brain activity and weight-shifting characteristics concurrently would be feasible if movements would be simple and controlled. Secondly, we expected that frontal theta activity would increase with increasing level of cognitive challenge, and, thirdly, that weight-shifting characteristics would be negatively affected by the increase in difficulty.

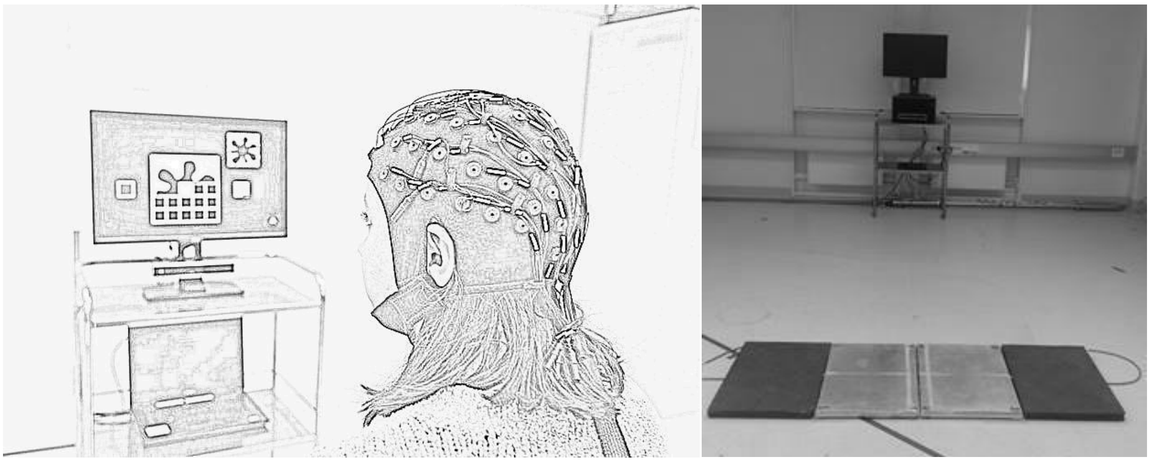
METHODS

Participants

Twenty-four healthy young adults participated in this experimental study (12 women, 12 men; mean age 24.5±0.4 yrs). To be included participants had to be 20-30 years old, have no known injury or surgery in the lower extremity and/or back within the previous 6 months, no known sleeping disorder, and no neurological disorder that could affect balance. Participants were recruited from the Norwegian University of Science and Technology (NTNU) and the Student Welfare Organization in Trondheim in central Norway. All participants were informed about the nature of the study, the equipment used during testing, and that they could withdraw from the experiment at any time without explanation. All participants gave written consent. The study was evaluated by the Regional Ethical Committee for Medical and Health Research Ethics, and conducted in accordance with the Declaration of Helsinki.

Overall design

This study was a quantitative experimental laboratory study aiming to measure body movements and brain activity while performing a balance-based exergame. Participants wore an EEG-cap (see Figure 1a) throughout the experiment and performed seated baseline testing and standing mediolateral weight-shifting movements, the latter while playing a puzzle exergame or at preferred speed with no exergaming context. The lab setting is shown in Figure 1b. Data was collected between 19.09.2016 and 28.10.2016.

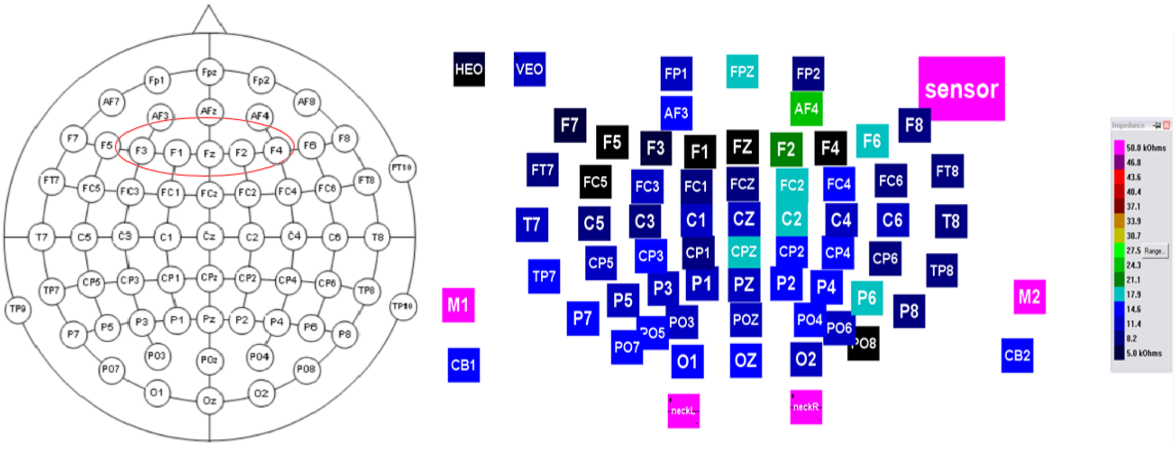


a) b)

Figure 1. a) Illustration of a puzzle game (different motive than in the current study for illustrating purposes) and a person wearing the EEG-cap. b) Lab setting with force plates and the screen where the game was depicted.

Equipment

Two Kistler force plates (40x60 cm) (type 9286A, Kistler Group, Switzerland) were placed alongside each other, without being in contact, and measured ground reaction force for each foot separately. Sampling rate was 100Hz. A 64-channel EEG cap (QuikCap, Compumedics Neuroscan, US), as well as four individual electrodes places around the eyes (above and below the left eye and on the lateral side of each eye; electrooculography), sampled data with a sampling frequency of 1000Hz. A SynAmps amplifier (SynAmps RT, Compumedics Neurocscan, US) amplified the signal, and was carried in a backpack during the experiment. A Microsoft Kinect v2 camera was used to record point cloud data during the experiment. In addition, a Garmin video camera was placed behind the participants and recorded during the entire data collection. The game used in the experiment was the balance-based "Puzzle"-game by SilverFit (SilverFit BV, the Netherlands). This game uses a motion-sensing technology time-of-flight (ToF) camera to control the game. All used equipment was non-invasive.



a) **b)**

Figure 2. a) Map of electrode-location on the EEG-cap with an ellipse surrounding the five electrodes analysed in the current study. b) Example of electrode sites with impedance level indicated by colour. Darker colour indicates lower kΩ, indicating better contact between electrode and scalp.

Procedures

Data collection took place in the movement laboratory at the Department of Neuromedicine and Human Movement Science at NTNU, Trondheim. All participants were invited to the testing facility 2-5 days prior to testing in order to receive more detailed information about the project and testing protocol. After introduction of the testing equipment, participants were asked to sign a consent form (Appendix 1) in which they agreed to the terms of participation. At the end of the information meeting, participants were asked to fill out the Waterloo Footedness Questionnaire-Revised (WFQ-R), a short custom-made questionnaire regarding physical activity and exclusion criteria (see Appendix 2), and measurements of height, weight, and head circumference were collected.

On the day of testing, participants were first fitted with the EEG equipment in a seated position. The EEG-cap was prepared for measuring data by inserting electrolyte-solution in each of the 64 electrodes, and adjusting the electrodes' position to obtain optimal contact between electrode and skin surface. To achieve optimal contact, we aimed for impedance to be below (or close to) 10kΩ (dark blue or black, see Figure 2b). Electrodes were placed according to the international 10:20 system (see Figure 2a) (30). Thereafter, the EEG-amplifier was placed on the participant's back in a back-pack.

There were four different conditions measured during data collection (see Figure 3 for complete overview of the testing protocol). For the baseline measurement, the participants were asked to sit in a relaxed position on a stool for three minutes while receiving no additional external stimuli. For the “Left/Right” condition they were asked to stand with one foot on each force plate and repeatedly shift their body weight from one side to another at preferred speed for three minutes. The two remaining conditions involved gameplay where participants played a puzzle game (consisting of 5x5 pieces) which they controlled by leaning towards the left or the right side to collect the correct puzzle piece. In the “No Choice” condition only one puzzle piece was presented, while in the “Choice” condition the game presented two pieces from which the players had to choose the one they thought was correct. In order to choose the puzzle piece to fit into the frame, they had to move towards the side (left or right) of the respective puzzle piece (see Figure 4). Two different puzzle motives were used (flower-bed and peacock), and motive and puzzle conditions were counter-balanced pairwise across participants over four blocks of five trials each. Participants were asked to avoid sudden movements, such as stiffening the neck or excessive head motion, in all conditions measuring EEG in order to prevent movement artefacts. In addition, the participants were asked to move at a controlled pace and not aim to compete against their own gameplay time.

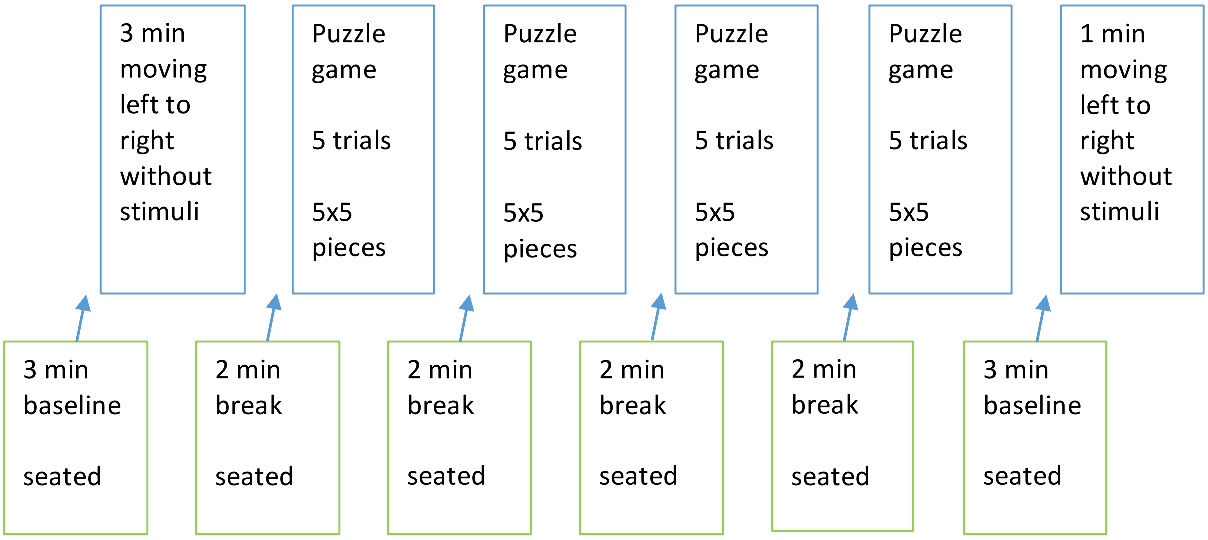


Figure 3. Overview of testing protocol.

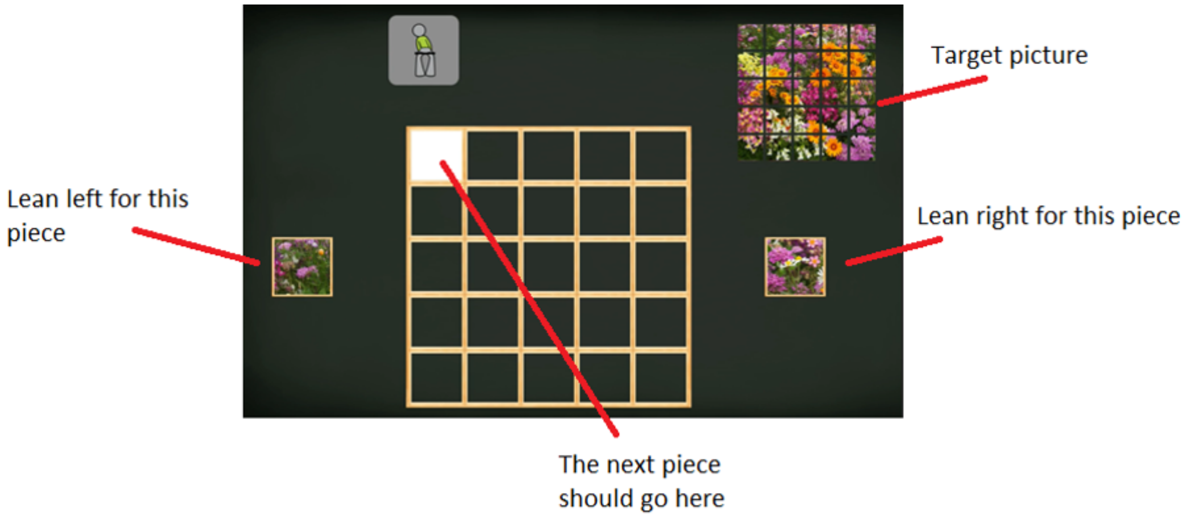


Figure 4. Illustration of the Choice condition with the “Flower-bed” motive.

Data analysis

The focus of this study was on gameplay time, EEG data, and force plate data from the first Left/Right condition, and the No Choice and Choice conditions. The variables derived from these measurements are further described below.

Gameplay time was derived from video by manually setting markers at the start and end of each game using the video analysis software ANVIL version 5.1.16 (Augsburg, Germany). The mean of Gameplay time is presented both across ten trials and without the first two trials (trials 3-10) for both exergaming conditions (No Choice and Choice). This was done in order to evaluate any difference in result with and without the acute learning effects from when participants first tried the game. In addition, the mean of each trial is presented graphically to show the learning effects in time. Due to loss of data, one participant is missing from the gameplay time analysis.

EEG data was processed in Matlab (Mathworks, MA, US) using the EEGlab-toolbox (31). Sampling frequency was reduced to 250 Hz and a band-pass filter (1-100 Hz) was applied. Non-stereotypical artefacts due to for example movement and electrode “pops” were removed manually in EEGlab. Subsequently, independent component analysis (ICA) was used to remove stereotypical artefacts (e.g., eye blinks) from the raw signal. Channels with severe disturbances were removed from the data. The EEG analysis of this study was channel-based, and independent component analysis was used solely for the removal of stereotypical artefacts such as eye movements. Using markers set manually during the data collection the raw signal was divided into the different conditions in the protocol (Baseline 1, Left/Right 1, No Choice, Choice, Baseline 2, and Left/Right 2). Frontal theta power was calculated by averaging five frontal midline electrodes (F3, F1, Fz, F2, F3, see Figure 2a). Two male participants were excluded from the EEG-analysis, one due to sleeping problems and the other due to poor EEG data quality.

Force plate data was processed in Matlab (Mathworks, MA, US). First, the CoP was derived from the ground reaction forces. The first two trials were excluded in order to avoid the results being skewed by the acute learning of the task required by the game. Therefore, all CoP-variables are a mean of trials 3-10. Mediolateral amplitude (cm) was calculated as the average of absolute local maxima and minima per weight shift in the mediolateral displacement of the CoP. Area (cm^2) was calculated by fitting an ellipse covering 95% of the CoP-points (see example in Figure 5). Velocity (m/s) was calculated by taking the average of the velocity between each CoP-point and the following point. Jerk (m/s3) was the rate of change of acceleration, the derivative of acceleration with respect to time, and indicates how smooth the CoP was, with lower jerk indicating a smoother movement. Due to technical issues and loss of data, two participants are missing from the analysis of force plate data.

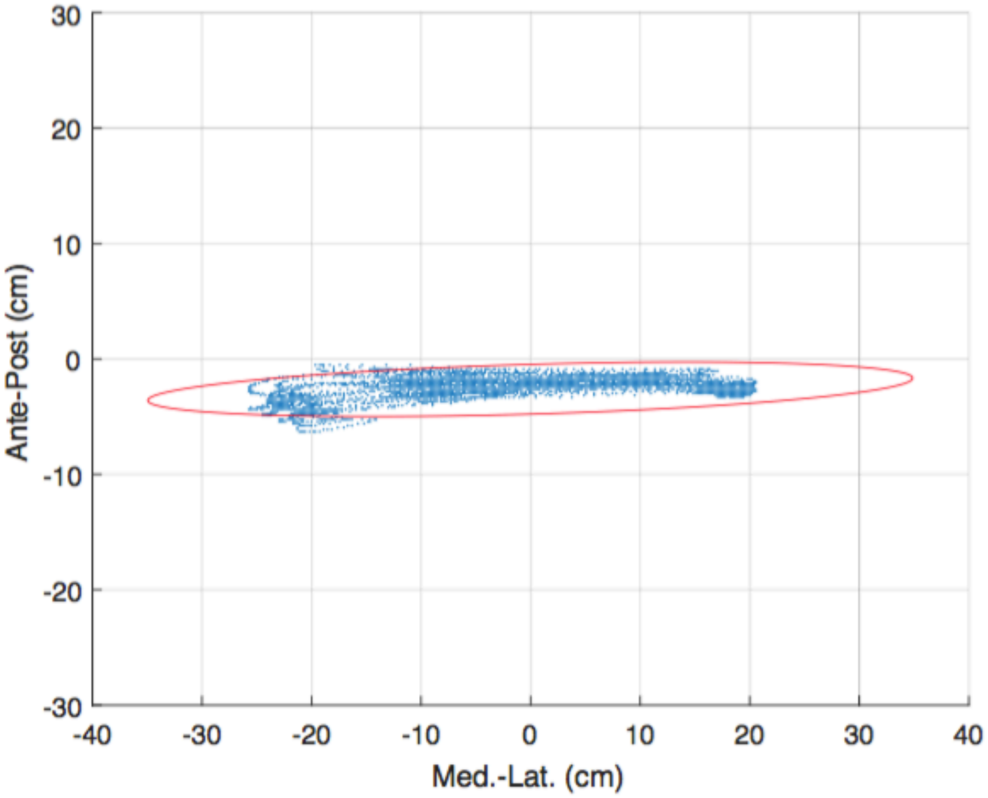


Figure 5. Example-stabilogram showing CoP-points with an ellipse surrounding 95% of the respective points.

Statistical analysis

All variables were tested for distribution of normality using Shapiro-Wilk tests. All variables were within or close to normal distribution as indicated by histograms, Q-Q plots, and descriptive statistics, which allowed the use of parametric tests. Descriptive analyses were performed on the participants' background data and information regarding physical activity. Paired samples *t*-tests were performed to check for possible differences caused by game motive. As no significant difference was found between the different motives, data from both motives were pooled, resulting in 10 trials per gameplay condition (No Choice and Choice).

Paired samples *t*-tests were performed on gameplay time, mediolateral amplitude, area, velocity, and jerk, to compare the No Choice and Choice condition.

A one-way analysis of variance (ANOVA) for repeated measures was used to analyse frontal theta activity in three conditions (Left/Right, No Choice, Choice). For gameplay time a three-way analysis of variance (ANOVA) for repeated measures was used on condition (No Choice, Choice) by trial (1-10) by gender (male, female). In *Post-hoc* follow-up, Bonferroni corrections for multiple comparisons were applied to minimize the likelihood of type I error. Mauchley's test of sphericity was used to verify compound symmetry. When the assumption of sphericity was violated, the Greenhouse-Geisser adjustment was used to determine the significance of F-ratios. All statistical analyses were performed using IBM SPSS version 24. Results are presented with mean ± standard error (SE). Significance level was set at $p<.05$.

RESULTS

Although all 24 participants (age: 24.5±0.4 yrs) successfully completed all trials, two participants had to be excluded from the EEG analysis due to either sleeping disorder or poor quality data. In addition, one participant was excluded from the gameplay time analysis, and an additional participant was excluded from force plate analysis due to loss of data. All participants' background and physical activity characteristics are presented in Table 1.

Table 1: Mean, range and standard error (SE) for age, height, weight, body mass index (BMI), and frequency, strenuousness and duration of physical activity calculated for women, men, and all participants.

	Women (n=12)			**Men** (n=12)			**All** (n=24)		
	Mean	**Range**	**SE***	**Mean**	**Range**	**SE***	**Mean**	**Range**	**SE***
Age (yrs)	23.4	20-26	(0.4)	25.5	22-29	(0.7)	24.5	20-29	(0.4)
Height (cm)	166.8	155.5-175.0	(1.7)	182.2	173.5-198.0	(1.9)	174.5	155.5-198	(2.0)
Weight (kg)	69.0	51.2-90.6	(3.5)	80.6	62.2-92.6	(2.4)	74.8	51.2-92.6	(2.4)
BMI (kg/m^2)°	24.8	19.1-34.5	(1.2)	24.3	20.3-28.8	(0.7)	24.5	19.1-34.5	(0.7)
Frequency[1]	4.8	3-7	(0.3)	4.9	3-7	(0.4)	4.9	3-7	(0.3)
Strenuous[2]	3.1	2-4	(0.1)	2.9	2-4	(0.1)	3.0	2-4	(0.1)
Duration[3]	2.8	2-3	(0.1)	2.7	1-4	(0.3)	2.7	1-4	(0.2)

*SE=Standard error.

°BMI=body mass index (weight (kg)/ (height (m) x height (m)).

[1] Frequency="How often are you physically active per week?" (1=less than once a week, 2=1-2 times a week, 3=2-3 times a week, 4=3-4 times a week, 5=4-5 times a week, 6=5-6 times a week, 7=6 times or more).

[2] Strenuous="How strenuous is the activity?" (1=not strenuous, 2=somewhat strenuous, 3=quite strenuous, 4=very strenuous).

[3] Duration="What is the average duration of the activity?" (1=0-30 min, 2=31-60 min, 3=61-90 min, 4=91-180 min, 5=>180 min).

Gameplay Time

Gameplay time reflects the time the participants used to play each puzzle game, from start to completion. Participants generally needed more time to complete games with two puzzle pieces compared to the games with only one piece. Time decreased considerably from the first to the second trial, while a slight increase in time was seen in trial 6, where the puzzle motive changed (see Figure 6). The overall average gameplay was 84.74 seconds (±5.42) and 110.40 seconds (±5.53) for No Choice and Choice, respectively. For trials 3-10 the average time was 79.05 seconds (±4.23) and 100.86 seconds (±3.80) for No Choice and Choice, respectively. Average time for each trial is shown in Figure 6. Paired-samples *t*-tests confirmed that participants used significantly more time on average when playing with two puzzle pieces (Choice) compared to only one (No Choice) (*t*(22)=-4.333, p<.001). This difference remained significant when excluding the first two trials from analysis (*t*(22)=-6.674, p<.001), indicating that the slower first two trials were not responsible for the difference in gameplay time between No Choice and Choice. A three-way ANOVA on condition (2) by trial (10) by gender (2) showed a significant main effect of condition (F(1,1)=19.273, p<.001), as well as of trial (F(9, 1.476)=30.714, p<.001). *Post hoc* follow-up of all trials (1-10) showed that participants used significantly more time on the first trial compared to trials 2-9 (all p’s<.005), as well as the second trial compared to trials 5, 7, 8, 9, and 10 (all p<.05). The third and sixth trial also took significantly longer to finish compared to the last trial (trial 10) (p=.007 and p=.018, respectively). Although mean time increased from trial 5 to trial 6 (90.4sec±4.09 to 98.39±5.37), the increase was not statistically significant (p=.103). None of the interactions were significant (all p’s>.05).

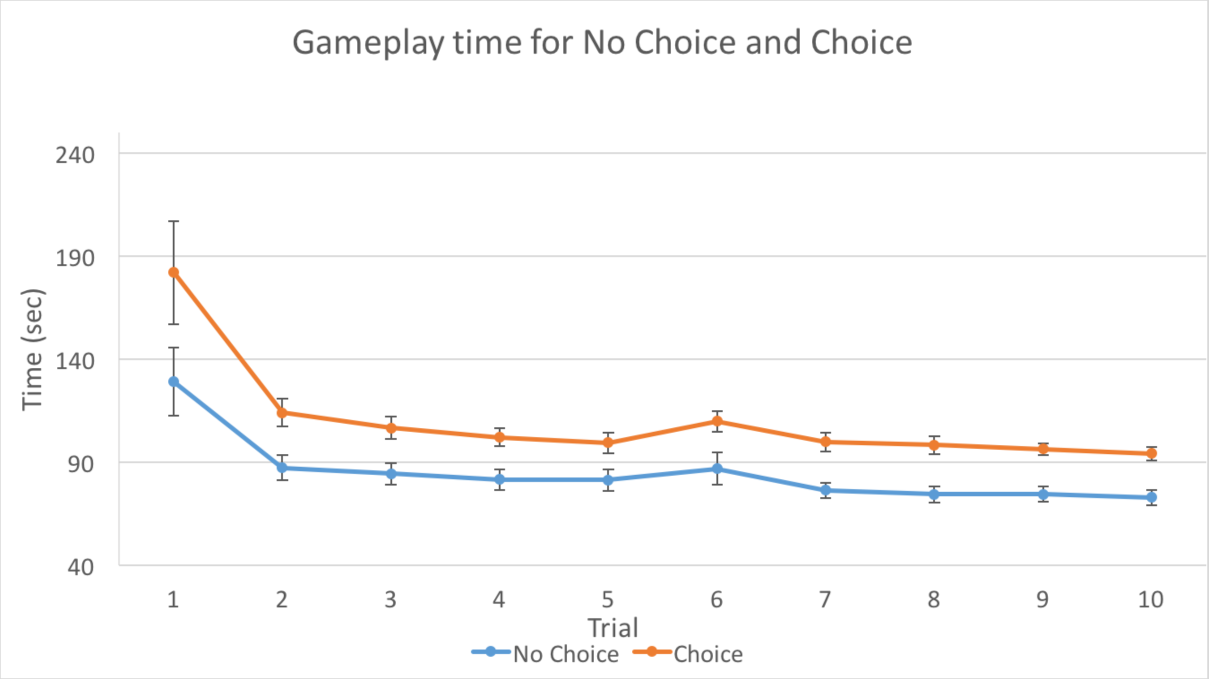


Figure 6. Mean gameplay time (sec) with standard error bars of trials 1-10 for conditions "No Choice" and "Choice".

Frontal Theta

The mean frontal theta represents the mean theta power of the five frontal electrodes (F3, F1, Fz, F2, F4; see Figure 2a in methods). As can be seen in Figure 7, mean frontal theta was higher in the two exergaming conditions (No Choice and Choice) compared to the condition with only mediolateral movement without the exergaming context (Left/Right). Participants had an average power of 39.87 (± .50), 41.37 (± .46), and 41.53 (± .51) in the theta frequency range for the Left/Right, No Choice, and Choice conditions, respectively. A one-way ANOVA on condition showed a significant difference between the three conditions (F(2, 1.457)=8.550, p=.003). *Post-hoc* follow-up showed that theta power significantly increased in the two exergame-conditions (No Choice and Choice) (p=.027 and p=.008, respectively) compared to the Left/Right condition, while there was no significant difference between the two exergaming conditions (No Choice and Choice) (p=1.000).

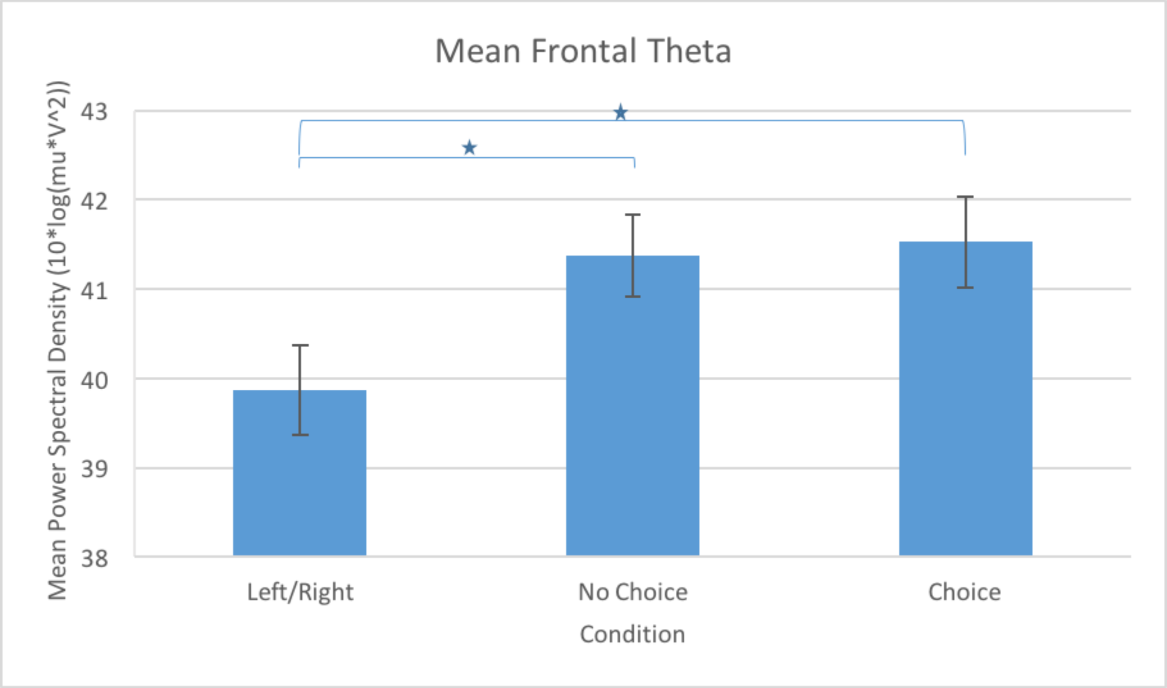


Figure 7. Mean frontal theta activity with standard error bars for conditions “Left/Right”, “No Choice”, and “Choice”. The stars indicate significant differences between conditions.

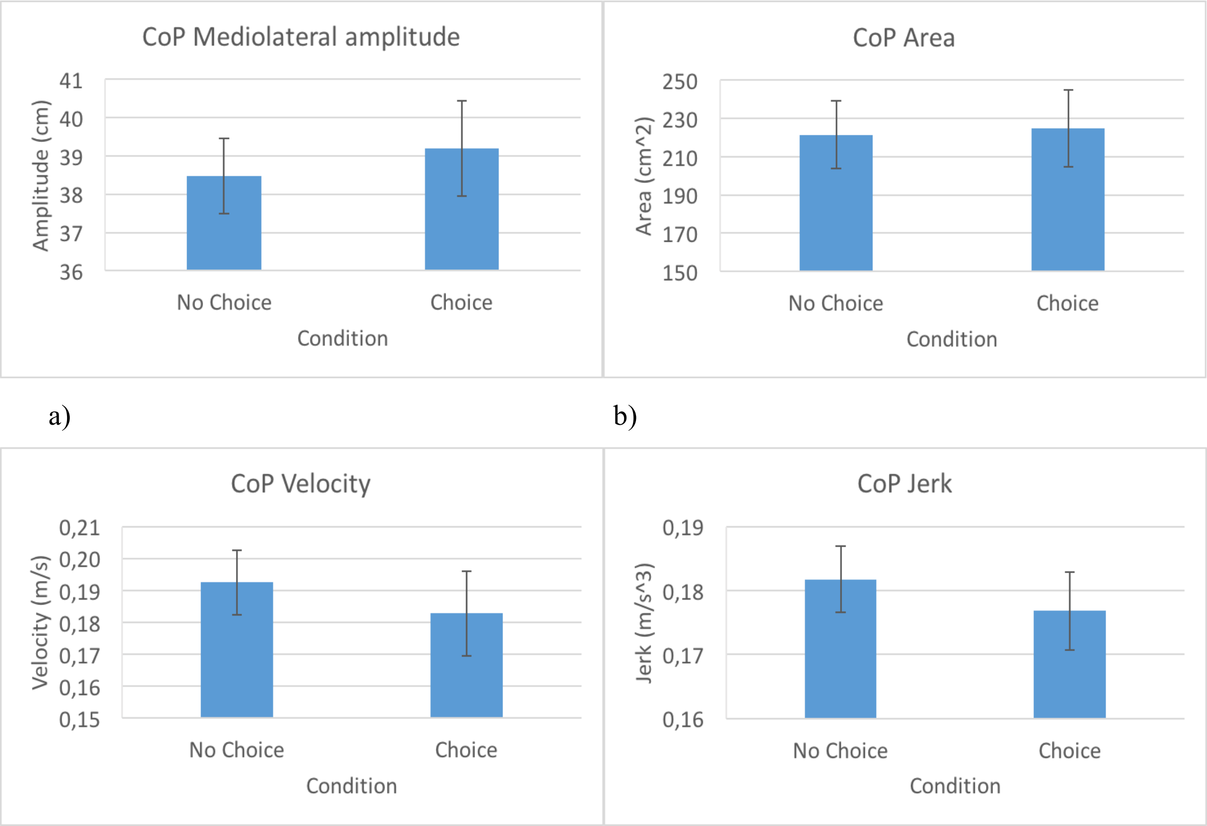
Weight-shifting characteristics

The average mediolateral deviation of the CoP from its centre is reflected in mediolateral amplitude, which is a measure of how much the CoP moves with each weight shift. Mediolateral amplitude was slightly higher while playing the Choice condition compared to the No Choice condition (39.20cm±1.17 versus 38.48±.98, respectively; see Figure 8a).

The amount of overall CoP displacement is reflected in the area. The area was slightly larger in the Choice condition compared to the No Choice condition (224.66 cm^2±20.11 and 221.47±18.62, respectively; see Figure 8b).

The speed of moving is reflected in the average velocity of the CoP. As shown in Figure 8c, mean velocity across all trials was, on average, higher in the No Choice condition compared to the Choice condition (.1925m/s±.0105 and .1828±.0132, respectively).

The smoothness of the movement during gameplay is reflected in the CoP jerk, where lower values indicate smoother movements. The Choice condition had on average a slightly lower jerk compared to the No Choice condition, indicating a smoother movement pattern during the Choice condition (.1768m/s^3±.0061SE and .1817±.0054, respectively; see Figure 8d). Paired-samples *t*-tests on all four weight-shifting characteristics indicated that there were no significant differences between No Choice and Choice in any of the CoP parameters (mediolateral amplitude *t*(21)=-.859, p=.405; area *t*(22)=-.252, p=.803; velocity *t*(22)=1.138, p=.268; jerk *t*(22)=1.823, p=.082, respectively).



a) b)

c) d)

Figure 8. Mean CoP a) mediolateral amplitude, b) area, c) velocity, and d) jerk, with standard error bars, in the No Choice and Choice conditions.

DISCUSSION

The aim of this study was to investigate whether brain activity can be measured using EEG while participants are playing a game that requires body movements, as well as to compare the effect of cognitive challenge on frontal theta activation and weight-shifting characteristics.

The results of this study show that it is feasible to measure brain activity using EEG while playing an exergame. Furthermore, the current findings indicated significantly higher frontal theta activity in exergaming conditions (No Choice and Choice) compared to the condition with weight-shifting movement without exergaming context (Left/Right). However, no significant difference was found in frontal theta activity between the two exergaming conditions. Participants used more time when playing the Choice condition compared to the

No Choice condition, but there were no significant effects of condition on any of the weight-shifting characteristics investigated in this study.

Measuring brain activity and movement concurrently

This study showed that it is, in fact, feasible to measure brain activity using EEG while performing a controlled weight-shifting movement, even with passive electrodes. Only one of the participants had to be excluded from EEG analysis due to low signal-to-noise ratio of the EEG data, that is, too much noise and too many artefacts. A second participant had to be excluded because of sleeping problems that can affect brain activity patterns. After cleaning the EEG data for artefacts, all other participants had enough remaining data of good quality to be analysed further. This finding of feasibility is consistent with earlier research where EEG was successfully measured during activities similar to the weight-shifting movement in the present study, such as golf putting (20, 32) and voluntary postural sway (33, 34). Although the present study used passive electrodes, new EEG products with so-called active electrodes have recently appeared on the marked. These electrodes perform an impedance conversion (equal to using an amplifier with a gain of 1) of the signals directly at the scalp, thereby decreasing noise from movement artefacts and improving the signal-to-noise ratio (35). These systems might be even better suited to measure brain activity while participants are moving, opening up to further pursue the effect of exergames on both cognitive and movement functioning.

Playing the game

The overall decrease in gameplay time throughout the testing suggests that the participants learned how to play the game, and perhaps even the pattern of the puzzle motive. This enabled them to improve their gameplay time across trials, with the exception when the puzzle motive changed in trial 6. The decrease in gameplay time could also suggest that participants develop more effective movement strategies through motor learning over time in order to collect the puzzle pieces faster (36). Although the participants were instructed not to compete against time, it should be noted that during data collection the researchers observed some competition, either with oneself or other participants, by stating for example “Yes! I beat my record” or “What is the high score?” This was most prominent in the male portion of the group, which is consistent with Staiano’s findings of male youth being more competitive compared to female peers during exergaming (37).

Cognitive challenge and frontal theta activity

As expected, the mean of frontal theta activity from the five frontal electrodes (F3, F1, Fz, F2, F3) increased in the gaming conditions compared to the condition with only voluntary mediolateral sway. Although this was not previously studied in healthy young adults, our findings are consistent with previous research finding exergaming to effectively target EFs in healthy older adults (26).

The finding that participants consistently needed more time to complete the puzzle games when they had two puzzle pieces to choose from suggests that the Choice condition did indeed increase cognitive challenge. However, no significant difference was found in frontal theta power with the increase in cognitive difficulty level. One possible explanation for this could be that channels with a low signal-to-noise ratio had to be removed. These were predominantly located in the frontal region and were especially prone to movement artefacts from the facial muscles. This left us with a lower number of potentially significant channels.

An earlier study found higher frontal theta power in tasks with increased cognitive challenge (e.g., a manipulation task) compared to simple retention tasks (remembering a sequence of letters without manipulating the order) (38). Furthermore, theta power was found to be higher also when increasing game speed to increase difficulty (39), and when performing a memory task that required a higher level of focused attention compared to a simpler memory task (22). This could indicate that the increase in difficulty level in our study was not sufficient to further challenge cognitive functions in healthy young adults as we expected. Perhaps the exergaming task did not specifically target EFs, or perhaps the Choice condition did not require focused attention to such a degree that it triggered additional frontal activation compared to the No Choice condition. A previous meta-analytic review (17) questioned whether EFs can be generalized to only the frontal lobe of the brain. This meta-analytic review evaluated results from different cognitive tests (Wisconsin Card Sorting Test, Phonemic Verbal Fluency, and Stroop Color Word Interference Test) and neuroimaging to examine executive functioning and localization of brain activity. Their results indicate that there may not be a one-to-one relationship between EFs and frontal lobe activity, and that involvement of other parts of the brain and additional cognitive functions are required in order to optimize executive functioning (17). The current study focused on frontal channel EEG analysis. Further analysis of the EEG data should focus on source localization of the brain activity using all channels, thereby shedding more light on where in the brain activity is located in the different conditions.

Previous research on exergaming and cognitive function has mostly tested cognitive functioning in pre-post designs using various cognitive tasks. The few studies that have measured brain activity in relation to exergaming have either done the measurements during a cognitive pre-post-test (26), or with functional Near-Infrared Spectroscopy (fNIRS) during a treadmill-walking task before and after intervention (23). In the randomized-controlled study performed by Schättin and colleagues (26), healthy older adults underwent a training intervention of 24 sessions over 8 to 10 weeks. The participants were divided into an exergaming group and a conventional balance training group (control group), and EEG was measured during a divided attention task pre- and post-intervention. This study reported a significant decrease of relative theta power in the auditory-stimuli (as opposed to visual stimuli) part only of the attention task, along with a decrease in relative time in the exergaming group post intervention (26). The results from this study indicated that an exergaming intervention positively influenced EFs, and additionally caused a decrease in theta activity in one of the attention tasks. The latter contradicts the findings from our study showing theta power to be increased by exergaming. However, since Shättin and colleagues (26) measured EEG in a pre-post design rather than during exergaming, their results may not be directly comparable to ours. Eggenberger and colleagues (23) tested functional brain plasticity during treadmill walking before and after an eight-week period of exergaming versus conventional balance training using fNIRS. The results from this study showed reduced hemispheric prefrontal cortex oxygenation during the acceleration of walking in both groups, while the exergaming group showed a somewhat lager reduction compared to conventional balance training. This reduction in prefrontal cortex oxygenation is believed to correlate with improvements in EFs. Similar to our study, exergaming was found to affect prefrontal cortex activity. However, decreased oxygenation may not be directly comparable to our theta power measurements.

To the best of our knowledge, only one study has previously measured EEG while playing an exergame. O'Leary and colleagues (40) performed EEG measurements on healthy young adults during seated video gaming, treadmill-based aerobic exercise, and exergame-based aerobic exercise. Their study reported enhanced neuroelectric indices during treadmill-based aerobic exercise, but no changes in seated video gaming or exergame-based aerobic exercise. This indicated higher brain activity during actual gameplay, which fits well with the findings of our study. However, only epoch measures of all frequencies together are reported in this study, in contrast to the current study reporting only theta frequencies averaged across trials within a condition. Nevertheless, this does suggest that there is increased overall brain activity during exergaming, even though O'Leary and colleagues (40) measured only short periods of the actual gameplay.

Cognitive challenge and weight-shifting characteristics

The current study found no significant differences between conditions in any of the weight-shifting characteristics that were studied, namely mediolateral amplitude, area, velocity, and jerk of the CoP. This might be in part because the participants in this study were healthy young adults, and our tasks may not have challenged their balance and cognitive functioning more than what they encounter on a daily basis through work and/or studies.

An alternative factor that may have affected our results is perhaps found in the different movement strategies that were observed while the participants played the exergame. Two main strategies were observed, with a number of varieties within each strategy. The first strategy consisted of flexing the ankle joint (plantar flexion) to shift the weight towards the side while keeping the rest of the body relatively stiff. The other main strategy involved a movement similar to a side lunge towards the side one was transferring weight to, hence, involving glutes and thigh muscle to a higher extent. These different strategies challenge different muscle groups and move the CoM through different trajectories. This could, in turn, challenge the postural control system differently and could have led to different results in the point measure (CoP) on the force plates.

Additionally, judging from the physical activity information participants gave in our questionnaire (Table 1; see Appendix 2 for the questionnaire), many of them are quite physically active compared to the general population. SilverFit specializes in providing tools for older adults to become or keep physically active in order to prevent, or rehabilitate, loss of physical function (41). Therefore, one possible explanation for the lack of significant differences in the weight-shifting characteristics could be that our participants had better physical and cognitive function than the players the puzzle game was originally designed for. This could explain why the more difficult version of the game (puzzle with choice) did not significantly alter frontal theta activity, and also why none of the weight-shifting characteristics were influenced significantly by the increased challenge. Therefore, in order to thoroughly investigate how healthy young adults' weight-shifting characteristics are affected by increased cognitive challenge, future research should imply a game more suited for this age group that presents a larger cognitive challenge. However, it may be speculated that had our study been conducted on the original target group of the game, older adults, our results may have shown deteriorating weight-shifting characteristics, as in the previous study by Skjæret-Maroni and colleagues (28). However, this should be further investigated by including older adults in a future study similar to the current one.

Although not significant, the results from the CoP data indicate that the Choice condition tends to bring forth slower, smoother, and larger weight-shifting movements compared to the No Choice condition. This suggests that the participants in general transferred their weight further towards the sides in a more controlled manner when having to choose between two pieces compared to when they merely had to move toward a single piece on the screen. These findings stand in contrast to the findings of Skjæret-Maroni and colleagues (28), where movement characteristics in older adults worsened overall when difficulty level was increased. Further research is needed to investigate whether these differences in results are caused by the different games used or the different populations.

Methodological considerations

There are several methodological considerations that could be improved in follow up studies on brain activity during exergaming. First of all, the passive EEG system that we used is sensitive to movement artefacts. Therefore, the participants were asked to avoid sudden movement such as stiffening the neck or excessive head motions. These instructions could have made the movements less natural and may have influenced the way the participants executed their weight shifts. As mentioned above, future studies should attempt to measure brain activity using an active electrode system in order to obtain EEG data with a higher signal-to-noise ratio. With this system, researchers may not need to instruct the participants' movement, thereby allowing them to move more naturally when playing the game.

As previously mentioned, the CoP is only an indirect measure of balance and postural control. A more direct measure would have been the CoM, but we did not have the data to estimate the CoM position and movement accurately enough, which was therefore outside the scope of this thesis. In addition, during gameplay participants tended to drift in various directions on the force plates, which is likely to have affected the area of CoP displacement reported in the current study. To prevent this drift one could attempt to instruct the participants to stay in the middle of the force plates throughout the gameplay. However, the researchers observed that even when participants became aware that they had drifted towards the edge of the force plates, they still did not keep in one place when continuing the gameplay. To get a more ecologically-valid picture of the players' movement during gameplay, they should be constricted as little as possible. Therefore, we did not restrict the participants' movements even when we noticed that they drifted across the force plates.

Due to technical problems, a small portion of the data was lost during data collection. The loss of data was either due technical issues with the force plates (e.g., loss of connection), or due to loss of video.

Lastly, the first two trials were partly or fully excluded from analysis for gameplay time and CoP measures, respectively. This was due to the acute learning effects of the initial gameplay. Therefore, some effects of the exergaming session could be lost with the first two trials that may carry important information about learning the exergame itself. However, for the study at hand the learning effect was not relevant in order to answer the research questions. Rather, the general effect of conditions after acute learning had passed was of interest in this thesis, and therefore the first two trial were excluded from the analysis of weight-shifting characteristics.

Future research

The current study shows that it is feasible to collect EEG data in young healthy adults during exergaming. This opens the path towards studying other populations, such as older adults and clinical populations with movement problems or cognitive disorders. However, it should be noted that the protocol used in the current study might be perceived as somewhat wearing by e.g., older adults due to its long duration. The length of this protocol was required in order to obtain a sufficient amount of usable EEG data after the removal of artefacts. However, with the new active electrode systems that are less prone to artefacts it should be possible to shorten the duration of the data collection and still obtain sufficient usable EEG data. Furthermore, the feasibility of measuring brain activity during exergames which require more exertive movements should be assessed. With further studies, it should be possible to provide further evidence on how brain activity and movement characteristics are affected by exergaming, thereby opening up new avenues for clinical intervention in different patient groups.

Conclusion

This is, to the best of our knowledge, the first study to objectively measure brain activity using EEG and ground reaction forces simultaneously during exergaming. The findings may prove useful for further research on exergames for training balance and postural control, as well as EFs, as they provide insight into how healthy young individuals respond to such a game. Our findings indicate that it is feasible to measure brain activity while playing an exergame. It also shows that there is an effect of exergaming on frontal theta activation compared to moving without an exergaming context. As an increase in theta power in the prefrontal cortex is presumed to be associated with attentional control, these results indicate that attention-related involvement is required in exergaming, which in turn suggests that exergaming could be used to train executive functioning. However, the added difficulty level of the game applied in the current study did not lead to a further increase in frontal theta power, and none of the weight-shifting characteristics investigated were affected by the increase in cognitive challenge. It remains to be seen whether similar effects will be found in older adults or different patient groups, and how exergaming could be used in these populations to train physical and cognitive functioning.

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Appendix 1

Forespørsel om deltagelse i forskningsprosjektet

"Brain activity and body movements during balance-based exergaming"

Bakgrunn og hensikt
Dette er en forespørsel til deg om å delta i en forskningsstudie ved Institutt for Nevromedisin ved NTNU. Hensikten med studien er å kartlegge bevegelsene og hjerneaktiviteten i ulike deler av hjernen under spilling av et balansebasert treningsspill hos unge, friske mennesker.

Hva innebærer studien?
Studien innebærer at du skal stå på en kraftplate og styre et spill ved å bevege deg fra side til side. Mens du spiller spillet vil du ha på deg en EEG-hette som måler hjerneaktiviteten din under forsøket. Denne hetten vil være koblet til en boks via en ledning og skal sitte på hodet under hele forsøket. Boksen vil være i en sekk som festes på ryggen. Klargjøring av hetten gjøres ved å tilføre vann-basert væske til små svamper slik at elektrodene får best mulig kontakt med huden din, her må det påberegnes litt tid. Det vil også bli festet overflateelektroder ved øynene, som skal måle øye-bevegelse. Før spillet starter vil det gjøres en "baseline"-måling hvor din oppgave er å sitte avslappet i en stol i 3 minutter, deretter skal du bevege deg fra side til side i 3 minutter. Etter disse målingene starter spillet og du skal spille et puslespill med fire forskjellige variasjoner. Hver variasjon utføres fem ganger, og du får 2 minutter pause mellom hver variasjon. Testingen vil også bli filmet for å dobbeltsjekke dataene, men kameraet vil bli plassert bak deltageren slik at det ikke er mulig å gjenkjenne personen. Til slutt vil det bli målt totalvekt (med utstyret på).

Mulige fordeler og ulemper
EEG systemet er et passivt system som ikke påfører smerte eller skade. Bevegelsen som styrer spillet kan oppleves som noe slitsom over tid, men er ikke ment å slite ut deg eller oppleves som vanskelig. Risikoen for uønskede hendelser (fall og/eller skader) er veldig lav. Heller ikke elektrodene rundt øynene vil ha noen påvirkning på kroppen, sett bort fra mulig irritasjon i huden som følge av klisteret som brukes for å feste disse på huden.

Hva skjer med informasjonen om deg?
Informasjonen som registreres om deg skal kun brukes slik som beskrevet i hensikten med studien. Alle opplysningene og prøvene vil bli behandlet uten navn og fødselsnummer eller andre direkte gjenkjennende opplysninger. Det vil ikke være mulig å identifisere deg i resultatene av studien når disse publiseres.

Frivillig deltagelse
Det er frivillig å delta i studien. Du kan velge å avslutte testingen når som helst, uten å oppgi grunn. Du kan også velge å fjernes fra studien dersom du gir beskjed før du forlater testlokalet, dette fordi data ikke blir lagret med navn. Dersom du ønsker å delta undertegner du samtykkeerklæringen på siste side.

Utdypende forklaring av hva studien innebærer

Deltagerne vil være 20 friske personer, 10 kvinner og 10 menn, mellom 20-30 år. Hvis du har hatt skader/operasjon i underekstremitet og/eller rygg de siste 6 måneder, eller nevrologiske lidelser/balanseproblem, kan du dessverre ikke delta. Testingen foregår på St. Olavs Hospital ved Nevro-Øst i Bevegelseslab 2 (2.etg). Testen gjennomføres kun en gang og tar omtrent 2,5 timer fra start til slutt. Vi ønsker også å møte deg som vil delta for å informere og vise deg rundt i labben et par dager før testing. Her vil du bli bedt om å fylle ut to korte spørreskjemaer. Dette tar ikke mer enn 30 min. Det vil også bli målt høyde og hodeomkrets på dette møtet.

Dersom du velger å bli med på studien vil du bli bedt om å ha på/med klær uten refleks som ikke er for løse. For at EEG-målingen skal bli optimal er det viktig at du vasker håret kort tid før målingen, men håret må være tørt og uten produkter. Du bør også møte uthvilt og kan ikke ha inntatt alkohol de foregående 24 timene. Om du har nedsatt syn er det viktig at du har på linser eller briller under forsøket. Forsøket vil bli gjennomført uten sko.

Du vil bli orientert så raskt som mulig dersom ny informasjon blir tilgjengelig som kan påvirke din villighet til å delta i studien.

Økonomi

Studien er finansiert gjennom forskningsmidler fra NTNU.
Du vil ikke få betalt for å delta i studien.

Informasjon om utfallet av studien

Resultater fra studiet vil bli forsøkt publisert. Du kan kontakte prosjektmedarbeidere om du er interessert i å få informasjon om resultat av studien.

Samtykke til deltagelse i studien

Jeg er villig til å delta i studien

____
(Signert av deltager, dato)

Jeg bekrefter å ha gitt informasjon om studien

____
(Signert, rolle i studien, dato)

Appendix 2

Spørreskjema

Deltakernummeret:____________ Dato:_______________

Kjønn: Mann ☐ Kvinne ☐ Alder:_______________

Hodeomkrets:________________ Høyde: _____________

Fysisk aktivitet

Driver du eller har du drevet med en idrett eller hobby som krever eller trener balanse?

Om ja, hvilken? ____

Hvor ofte er du fysisk aktivt per uke? (kryss av)

☐Mindre enn 1 gang i uka

☐1-2 ganger i uka

☐2-3 ganger i uka

☐3-4 ganger i uka

☐4-5 ganger i uka

☐5-6 ganger i uka

☐6 eller flere ganger i uka

Hvor anstrengende er aktiviteten? (Kryss av)

☐Veldig lett

☐Litt anstrengende

☐Ganske anstrengende

☐Veldig anstrengende

Hvor lenge varer aktiviteten gjennomsnittlig?

☐0-30 min

☐31-60 min

☐61-90 min

☐91-180 min

☐181 min +

Hva trener du?____

Har du eller har du hatt…	**Ja**	**Nei**
Nervesykdommer?	☐	☐
Epilepsi eller lignende?	☐	☐
Søvnforstyrrelse?	☐	☐
Sykdommer som påvirker balansen?	☐	☐
Skader/operasjon i underekstremitet og/eller rygg de siste 6 måneder?	☐	☐