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Working memory training: Improving intelligence – Changing brain activity

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ABSTRACT

The main objectives of the study were: to investigate whether training on working memory (WM) could improve fluid intelligence, and to investigate the effects WM training had on neuroelectric (electroencephalography – EEG) and hemodynamic (near-infrared spectroscopy – NIRS) patterns of brain activity. In a parallel group experimental design, respondents of the working memory group after 30 h of training significantly increased performance on all tests of fluid intelligence. By contrast, respondents of the active control group (participating in a 30-h communication training course) showed no improvements in performance. The influence of WM training on patterns of neuroelectric brain activity was most pronounced in the theta and alpha bands. Theta and lower-1 alpha band synchronization was accompanied by increased lower-2 and upper alpha desynchronization. The hemodynamic patterns of brain activity after the training changed from higher right hemispheric activation to a balanced activity of both frontal areas. The neuroelectric as well as hemodynamic patterns of brain activity suggest that the training influenced WM maintenance functions as well as processes directed by the central executive. The changes in upper alpha band desynchronization could further indicate that processes related to long term memory were also influenced.

1. Introduction

Attempts to improve intelligence are by no means new in psychology. The main objective is to improve fundamental processes that form the basis of intelligent behavior and in that way increase general intelligence (*G*), or fluid intelligence (*Gf*). It is of course very easy to increase test performance by simply practising the tests themselves, or by practising similar tasks. However, since Jensen's (1969, 1981) claim that interventions aiming to improve intelligence resulted in only very little if any success at all, only sporadic attempts have been made to investigate interventions that could increase ability. To mention just one, the highly controversial Mozart effect. College students after 10 min of listening to Mozart's Sonata (K. 448) had Stanford–Binet spatial subtest IQ scores 8–9 points higher than students who had listened to a relaxation tape or listened to nothing. The IQ effects did not persist beyond the 10–15 min testing session. (Rauscher, Shaw, & Ky, 1993, for a review see, Pietschnig, Voracek, & Formann, 2010).

1.1. Working memory training

Recently, the debate on whether certain interventions can increase ability has once more gained popularity. The discussion has been triggered by the study of Jaeggi, Buschkuehl, Jonides, and Perrig (2008), showing that working memory (WM) training can increase fluid intelligence. Jaeggi et al. (2008) have shown that an increase in fluid intelligence can be obtained by training on problems that, at least superficially, do not resemble those on the ability tests. They could further show that more training leads to greater IQ gains, which were present across the whole spectrum of abilities, although larger toward the lower end of the spectrum. Despite positive comments like: "Their study therefore seems, in some measure, to resolve the debate over whether fluid intelligence is, in at least some meaningful measure, trainable." (Sternberg, 2008, p. 6791), the study and its design have been also criticized (Moody, 2009; Sternberg, 2008). Sternberg (2008), not calling into question the obtained results, stressed eight limitations of the findings reported by Jaeggi et al. (2008). Among the major ones were the lack of a placebo (active) control group, the use of just one training task, and only one measure of the dependent variable *Gf*. Even more strict was the criticism put forward by Moody (2009). The main objection raised was that different tests were used for the so-called control group (receiving just 8 days of training), and the experimental group, where individuals were tested with an alternative test with a time restriction that may have biased results. Such a time restriction made it impossible for respondents to solve the more demanding tasks. Since the whole weight of Jaeggi's (Jaeggi et al., 2008) conclusions rests upon the validity of the measure of fluid intelligence, in Moody's (2009) opinion, this brings into question the results and inferences reported in the study.

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Buschkuehl and Jaeggi (2010), in a review of 11 studies aimed at improving intelligence, divided the interventions used to influence ability into approaches that were focused on training of WM and executive functions, and interventions which entailed other approaches – video games and other cognitively stimulating activities, like music, or supplementing participants with creatine. Two conclusions have been put forward: First, most of the studies, are heterogeneous on several dimensions and have certain methodological shortcomings, yet most of them reported significant improvements in measures of ability. Second, most numerous were the attempts to improve intelligence by WM training tasks (Klingberg, 2010). This seems reasonable, as there is a strong link between WM and intelligence (Colom, Abad, Quiroga, Chun, & Flores-Mendoza, 2008). Further, there exist well elaborated models of WM, like the multi component model of Baddeley (for a review see Repovš & Baddeley, 2006), or the embedded processes model proposed by Cowan (1999). The models do differ, but they define WM function as the combination of short-term storage and some sort of processing components. It is further worth mentioning that in a recent study by Colom et al. (2008) it could be shown that short-term storage largely accounted for the relationship between working memory and intelligence, and that processing components, like mental speed, updating, and the control of attention had a negligible, or no relation to intelligence.

Morrison and Chein (2011) in a review of WM training studies divided the training approaches into strategy training (intended to promote the use of domain-specific strategies to remember increasing amounts of information), and core training (repetition of demanding WM tasks targeting general WM mechanisms). Their conclusion was that core WM training produced more far-reaching transfer effects. However, they also discussed several limitations that should be addressed. Among the most important were: no control of motivational (expectancy) and repetition effects, and a lack of consistency in experimental methods. A similar conclusion, namely that inadequate control and ineffective measurement of the cognitive abilities of interest cloud the interpretation of the current training literature, was put forward by Shipstead, Redick, and Engle (2010).

A much less favorable view with respect to the trainability of ability was provided by Owen et al. (2010). In their large-scale study, 11,430 individuals participated in a 6-week online training of different cognitive tasks designed to improve reasoning, memory, planning, visuospatial skills and attention. The findings led the authors to the conclusion that, although improvements were observed in every one of the cognitive tasks for which were trained, no evidence was found for transfer effects to untrained tasks, even when those tasks were cognitively closely related, or to any general improvement in the level of cognitive functioning.

1.2. Intelligence, brain activity and neurofeedback

The second strand of research, which is fostering the debate on the possibility of increasing the level of intelligence, comes from the broad area of neuroscience. Until recently neurologists were convinced that neural plasticity is present only in childhood. Plasticity of the nervous system denotes developmental changes in synaptic density and synaptic pruning, and plays the key role in cell loss, and the growth and myelination of white matter (Craik, 2006). There is also evidence that there is some plasticity and fine-tuning that continues across the lifespan. Maguire et al. (2000) found that in London taxi-drivers the posterior region of the hippocampus is much larger than in the rest of the population, whereas the front region is much smaller. One important role of the hippocampus is to facilitate spatial memory in the form of navigation. Similarly, an enlargement of the auditory cortex (25%) in highly skilled musicians, compared with people who never played an instrument was reported by Pantev et al. (2003). That such changes can be rather rapid was shown by Pascual-Leone (2001). Even the amount of five days practising a five-finger piano exercise enlarged areas of the brain responsible for finger movements. On the other hand, when practising stops, the brain tends to return to its normal size. This was shown by a study where people learned to juggle for 3 months. After training, an increase in size in the midtemporal area and the left posterior intraparietal sulcus (areas responsible for visual motion information) was observed. Nonetheless, after 3 months of no practice, these areas returned to their previous size (Draganski et al., 2004; Driemeyer, Boyke, Gaser, Büchel, & May, 2008).

In the light of these findings, one could expect that training aimed to increase intelligence, would be also reflected in brain functioning. Further support for this view was provided by several neurofeedback studies. The study by Keizer, Verment, and Hommel (2010) has shown that neurofeedback in the gamma-band (36–44 Hz) could improve episodic retrieving. In another study by (Zoefel, Huster, & Herrmann, 2011), neurofeedback training of the upper alpha frequency band improved cognitive performance on a mental rotation task. Egner and Gruzelier (2003) could further show that learning to progressively raise theta (5–8 Hz) over alpha (8–11 Hz) band amplitudes significantly enhanced music performance. Several additional studies conducted by the author (Gruzelier, 2009) showed the positive influence of theta/alpha neurofeedback on creativity and ballroom dancing. Furthermore, the study by Surmeli and Ertem (2010) showed that quantitative guided neurofeedback could significantly improve intelligence in a group of mentally retarded patients.

Research into the trainability of intelligence and related changes in brain activity could also improve our understanding of the relationship between the psychometric construct of *G* or *Gf* and brain functioning. There exist numerous findings for the intelligence–brain relationship, but few theories. In a recent overview on research pertinent to the relationship between psychometrically determined intelligence and functional characteristics of brain activation observed during cognitive task performance, Neubauer and Fink (2009) concluded that most of the reviewed studies have demonstrated a negative correlation between brain activity under cognitive load and intelligence. The explanation of these findings was an efficiency theory – the non-use of many brain areas irrelevant for task performance, as well as the more focused use of specific task-relevant areas in individuals with high IQ's (Haier, 1993). Some studies have shown a specific topographic pattern of differences related to the level of intelligence. High-ability subjects made relatively greater use of parietal regions, whereas low-ability subjects relied more exclusively on frontal regions (Gevins & Smith, 2000; Jaušovec & Jaušovec, 2004). It was further reported that highly intelligent subjects displayed more brain activity in the early stages of task performance, while average individuals showed a reverse pattern. This temporal distribution of brain activity suggested that cognitive processes in highly intelligent individuals are faster than in average intelligent individuals (Jaušovec & Jaušovec, 2004). A further finding was also that neural efficiency seems to be corroborated mostly when participants work on tasks of low to medium difficulty or complexity (Neubauer & Fink, 2009). In the study by Doppelmayr, Klimesch, Hödlmoser, Sauseng, and Gruber (2005), the expected findings of a negative relation between brain activation and intelligence emerged solely for the easier items of the Raven test, whereas a tendency in the opposite direction was observed for the difficult ones. It was further shown that less intelligent individuals displayed a decrease in activation from easy to difficult tasks, whereas the opposite was true for the brighter participants. It is likely that individuals with low IQ's did not even try on the harder problems, which could explain their lower activation levels compared to those with high IQ's. It could be further assumed that individuals with low IQ's have to work harder on easy problems than do individuals with higher IQ's.

Research has also focused on structural correlates of human intelligence, attempting to answer the question: "Where in the brain is intelligence?" This body of evidence has recently been synthesized by Jung and Haier (2007) in the form of their so-called 'parieto-frontal integration' (P-FIT) model of intelligence. In reviewing 37 neuroimaging studies mostly on structural correlates of intelligence they tried to answer the question of how the anatomical aspects of gray matter and white matter relate topographically to intelligence. The P-FIT model by Jung and Haier (2007) suggested – contrary to the assumption of Duncan (2001) that intelligence is localized in the pre-frontal cortex – that beside frontal areas of the brain also the temporal and occipital lobes are critical in early processing of sensory information which is then fed forward to the parietal cortex, wherein abstraction, and elaboration emerge. These processes are dependent upon the fidelity of underlying white matter necessary to facilitate rapid and error-free transmission of data from posterior to frontal brain regions. The main problem with the P-FIT theory is that only a very small number of discrete brain areas approach 50% of convergence across published studies employing the same neuroimaging technique (Colom et al., 2009; Haier et al., 2009). When different test batteries were used to derive *G*, this changed also the brain areas related to *G*.

The aim of the present study was to investigate whether training of WM functions (short-term storage and processing components like control of attention and executive functioning) can improve performance on tests of fluid intelligence. A second objective was to investigate the influence of WM training on brain activity. In order to gain deeper insight into brain activity under cognitive load a multi-modal brain imaging approach was used, combining electroencephalographic (EEG) methodology (based on electrophysiological principles) with near infrared spectroscopy (NIRS) imaging technique (based on hemodynamic principles). Such a multi-modal approach compensated for the poor spatial resolution of EEG and allowed for a more reliable testing of the hypotheses described below.

Further, the experiment was designed to eliminate some of the criticisms (Moody, 2009; Sternberg, 2008) of Jaeggi's study (Jaeggi et al., 2008), and integrate suggestions for improvements put forward in recent reviews of research (Buschkuehl & Jaeggi, 2010; Klingberg, 2010; Morrison & Chein, 2011) on WM training (e.g., an active control group was included, different types of training tasks as well as different tests of fluid intelligence were used). Given the exploratory nature of the study our expectations were rather general. It was expected that the training would significantly increase test performance of respondents in the experimental group. It was further expected that these differences would be reflected in brain functioning mainly in the frontal and parietal brain areas of respondents and that no such differences would be observed in respondents of the active control group. In considering the relatedness of EEG frequency bands with different cognitive functions it was expected that the main test–retest differences in the experimental group would be observed in the theta and lower-1 alpha bands. Several studies (Klimesch, 1999) have shown that episodic and working memory processes were reflected in theta band synchronization (ERS), and that attentional processes were related to lower alpha band desynchronization (ERD), while on the other hand, semantic or long term memory (LTM) processes were associated with upper alpha band desynchronization (Klimesch et al., 1994).

2. Materials and methods

2.1. Subjects

The sample included 30 right-handed psychology students (mean age 20 years and 3 months; 4 male and 26 female participants – one female student of the working memory group did not complete the training and was therefore not invited for the posttest session), taking a course in educational psychology. The participants were assigned to two groups (WM – working memory group, $n = 14$, $M_{IQ} = 105.38$, $SD = 9.25$; and AC – active control group, $n = 15$, $M_{IQ} = 105.40$, $SD = 8.93$) equalized with respect to gender and intelligence (WAIS-R, Wechsler, 1981). The respondents were informed about the goal of the experiment – to improve intelligence with training. They were further told that the training will aim at improving working memory (WM – group), or components of emotional intelligence (AC – group). The participants were given a partial course credit (40%) for participating in the research. The experiment was undertaken with the understanding and written consent of each subject, following the recommendations of the ethics committee of the Slovene Psychological Association.

2.2. Procedure and test materials

Respondents solved four test-batteries, for which the procedure was the same during pre- and post-testing. The same test-batteries were used on pre- and post-testing. The digit span subtest (WAIS-R) was administered separately, according to the directions in the test manual (Wechsler, 1981). The other three tests (RAPM, verbal analogies and spatial rotation) were administered while the respondents' EEG and NIRS measures were recorded.

The RAPM was based on a modified version of Raven's progressive matrices (Raven, 1990), a widely used and well established test of fluid intelligence (Sternberg, Ferrari, Clinkenbeard, & Grigorenko, 1996). The correlation between this modified version of RAPM and WAIS-R was $r = .56$, ($p < .05$, $n = 97$). Similar correlations of the order of 0.40–0.75, were also reported for the standard version of RAPM (Court & Raven, 1995). Therefore it can be concluded that the modified application of the RAPM did not significantly alter its metric characteristics. Used were 50 test items – 25 easy (Advanced Progressive Matrices Set I – 12 items and the B Set of the Colored Progressive Matrices), and 25 difficult items (Advanced Progressive Matrices Set II, items 12–36). Participants saw a figural matrix with the lower right entry missing. They had to determine which of the four options fitted into the missing space. The tasks were presented on a computer screen (positioned about 80–100 cm in front of the respondent), at fixed 10 or 14 s interstimulus intervals. They were exposed for 6 s (easy) or 10 s (difficult) following a 2-s interval, when a cross was presented. During this time the participants were instructed to press a button on a response pad (1–4) which indicated their answer.

The verbal analogy test was based on a well established Slovene intelligence test-BTI (Mihelič, 1972). The respondents were presented with a verbal analogy with one word missing, and asked to choose among four options presented (e.g., FISH:WATER::BIRD: ?; 1 = AIR; 2 = BRANCH; 3 = SHORE; 4 = WAVE). The presentation was the same as for the RAPM, except that the 25 analogies were exposed for 7 s.

The spatial rotation test was based on the Paper Folding and Cutting – PF&C subtest of the Stanford–Binet IQ test (Rideout & Laubach, 1996). According to the authors it is a measure of visual – spatial reasoning. Respondents had to judge which of the four figures on the right corresponded to the figure in the left frame (see Fig. 1). The figure in the left frame showed how a piece of

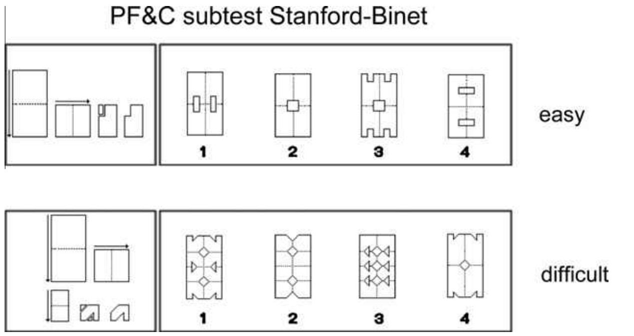

Fig. 1. Two examples (easy and difficult) of the Paper Folding and Cutting subtest PF&C of the Stanford–Binet intelligence test (Rideout & Laubach, 1996). Respondents had to judge which of the four figures on the right corresponded to the figure in the left frame. In the left frame it was shown how a piece of paper was folded and cut out, while in the right frame there are four unfolded pieces of paper. The question was, which of the four unfolded pieces of paper in the right frame corresponded to the one folded in the left frame? The correct answers for the two tasks were: 2 and 1.

paper was folded and cut, whereas in the right frame four unfolded papers were shown, one of which corresponded to the folded paper in the left frame. The presentation of the 25 items was the same as for the verbal analogy test.

The respondents, upon arrival at the lab, were asked to relax with their eyes closed. During this time (5 min) the baseline EEG and NIRS recordings were made. Then the tasks were administered in a fixed order: RAPM, verbal analogies and PF&C. Prior to each test the respondent solved 4–5 probe items to get acquainted with the response pad and the way of presentation. The procedure was the same during the initial testing and for the retest. The retest was administered 6 months after initial testing, within 10 days after the training stopped. This 10-day time span was necessary to allow for the female respondents to be tested at about the same time (±2 days) of their menstrual cycle as on the pretest. It was shown that the relative release of sexual hormones in different phases of the menstrual cycle affected cognitive responses of females (e.g., Amin, Epperson, Constable, & Canli, 2006; Berman et al., 1997). High levels of estrogen and progesterone were associated with positive affect and higher activity in the prefrontal cortex.

2.3. Training tasks

The tasks used in the working memory training were theoretically based on the multi component model of WM proposed by Baddeley (for a review see Repovš & Baddeley, 2006). The tasks aimed at short-term WM storage plus processing components – control of attention and executive function. Five different task types, three of which were presented on a projection screen, were used in the training.

Matrices consisted of 4×4 matrices with eight pairs of elements; 4×5 matrices with 10 pairs and 5×6 matrices with 15 pairs of elements (see upper part of Fig. 2, showing an example of an eight pairs matrix). The matrices were, dependent on the number of pairs, displayed between 45 and 90 s on a 2×2 m projection screen. After this time period the matrix showing all elements was replaced with a matrix in which just one element of the previously shown was displayed. The respondents were asked to mark the position of the corresponding pair on the answer sheet provided. The task continued until all pairs were identified. We gradually increased the difficulty level of the tasks by increasing the number of pairs, their similarity, and by reducing the number of times the initial matrix with all elements was presented from 4 to just one presentation. The elements in the matrices were presented as visual (e.g., pictures, words), or aural (e.g., piano tones, beep tones, short music clips). The content of the elements was figural, symbolic or semantic. The difficulty level was further increased by changing the content of the target and initially presented elements (e.g., figural-semantic in the example provided in Fig. 2).

Working memory maintenance tasks were similar to the task used by Crone, Wendelken, Donohue, van Leijenhorst, and Bunge (2006). They contained different visual and auditory elements. At each session all of the elements used in the session (10–50) were first presented on the projection screen, then a blank screen was presented for 500 ms followed by a set of 3–5 items (800–1500 ms presentation per item and 500 ms between items). Next, the instruction forward, or backward appeared on the screen, followed by a time delay of 6000–8000 ms. Finally, one of the target elements, was displayed for 2000 ms. At that time, participants wrote down the number, to indicate the correct order of the presented target element with respect to the instruction provided (see middle part of Fig. 2). The number of elements presented (3–5), as well as rules (forward versus backward) were randomly alternated between trials. As in the matrices tasks, the content of the elements was figural, symbolic or semantic. In some tasks the content, or the form of presentation (visual versus auditory) of the 3–5 set of elements differed from the target element (symbolic–semantic in the example in Fig. 2). These properties of the elements were used to gradually increase the level of difficulty.

N-back tasks were similar to the tasks used in the Jaeggi et al. (2008) study. The task consisted of blocks of 20 items presented visually, aurally or in a combination of both (1000–2000 ms presentation per item and 500 ms between items – see lower part of Fig. 2). The respondents were asked to indicate if the currently presented item on the screen was identical with the previously presented item (1-back), the item presented before the previously presented item (2-back), or the item presented before the penultimate item (3-back). Beside the n-back condition, the complexity of the presented items was used to gradually increase the difficulty level.

The memory and sentence construction tasks were game like and played in groups of 4–5 participants. The memory game consisted of 72 cards (36 pairs). At the beginning all cards were facing backside-up and were spread out on the table. One of the participant in the group uncovered two of the cards, if identical he/she kept the pair and may have uncovered the next pair, if not, the cards were returned backside-up to the set on the table, and the next player proceeded. The game was played until no card was left. The sentence construction task required the first respondent in the group to say a word, the next one had to repeat this word and add another word and so on, till one of the respondents could not correctly repeat the word chain.

The training session started with one of the tasks presented on the screen and was then alternated by one of the tasks played in groups. Each of the tasks was administered for about 15–20 min. The training took place during the 2nd semester from February to May for 12 weeks with one training session weekly (75–100 min). The matrices, n-back and short term memory maintenance tasks were uploaded on the university server and respondents were instructed to practise the uploaded WM tasks at least twice a week for at least 30 min. If they failed to do so (the E-learning program provided information about student's individual training sessions) they were reminded by E-mail to do so. On average each of the participants completed 30 h of training. The respondents were weekly provided with information about their training results.

The active control group was trained in communication and social skills mainly based on Gordon' communication training (Gordon, 1974). It was assumed that this training was not directly

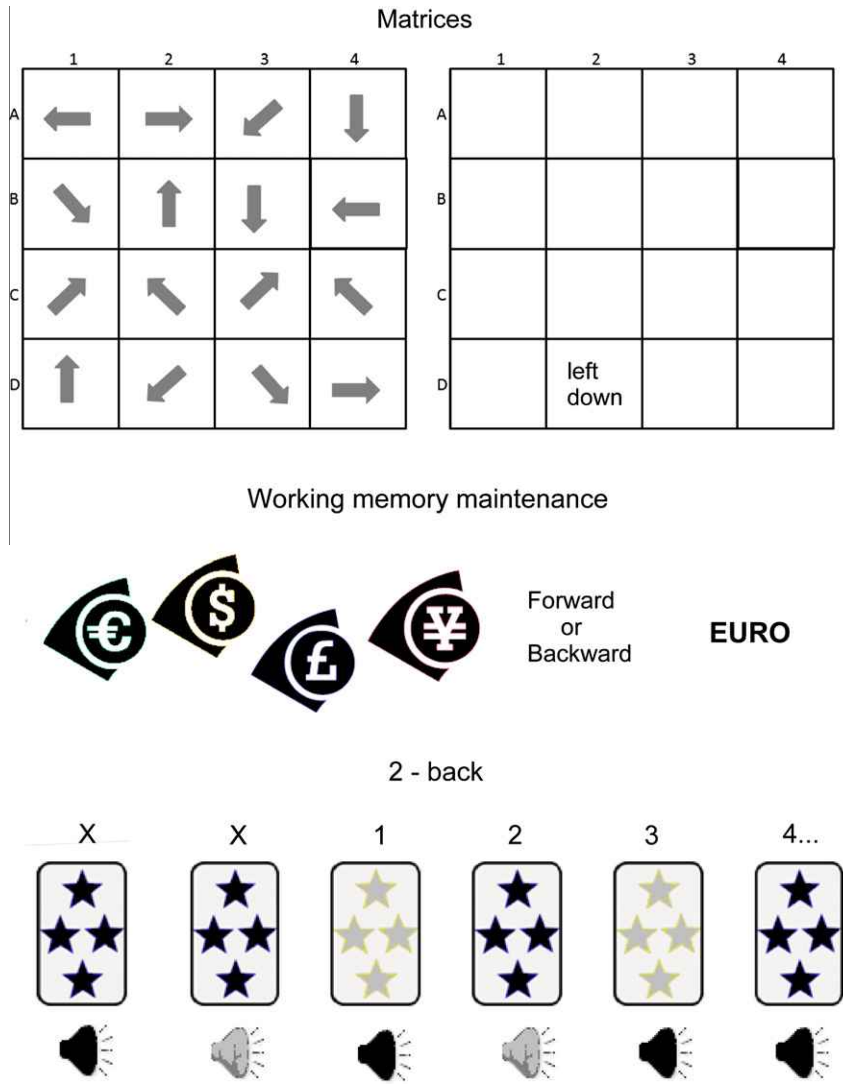

Fig. 2. Examples of the three computer generated tasks used for working memory training. The matrices tasks required subjects to remember the position of the eight pairs presented in the left matrix (exposed for 75 s). For example, the arrow in A1 corresponds to the arrow in B4; A2 corresponds to D4, and so forth. After this exposition period the left matrix was replaced by the right matrix showing one element of the previously displayed pairs (the arrow in D2). Usually the pairs were physically identical. However, in more demanding versions of the task (example above) instead of the arrow pointing to the left bottom corner (figural content) a description was provided (left down – semantic content). The respondents were asked to mark the position of the corresponding pair, which was for the present example – A3 (see left matrix, the arrow in A3 is pointing left down as is the arrow in D2). After respondents marked their answer, the left matrix was presented again, followed by a matrix showing just one of the arrows. This procedure continued until all 8 pairs were identified. The memory maintenance tasks consisted of sets of 3–5 items (800–1500 ms presentation per item and 500 ms between items). Next, the instruction forward, or backward appeared on the screen, followed by a time delay of 6000–8000 ms. after which, one of the target elements, was displayed for 2000 ms. At that time, participants wrote down the number, to indicate the correct order of the presented target element with respect to the instruction provided. In the above example the correct answer would be 1, for the forward instruction and 4 for the backward instruction. The n-back tasks consisted of blocks of 20 items presented visually, aurally or in a combination of both (1000–2000 ms presentation per item and 500 ms between items). The respondents were asked to indicate if the currently presented item on the screen was identical with the item presented before the previously presented item (2-back). The dark and light loud-speakers below the cards indicate beep tones (1000 Hz and 2000 Hz) presented simultaneously with the card for 1000 ms. The correct responses for elements 1–4 would be: not-identical, identical, identical, not-identical.

related to intelligence. However, to resemble the training conditions of the WM group, similar forms of presentation, interaction between participants and duration of the training sessions were applied. The training took place during the same time interval as the WM training. The same number of lessons as for the WM group was provided. The tasks and videos used were presented on a screen, whereas role-playing and interactive exercises were practiced in groups of 2–3 participants. Participants were further asked to practise weekly the acquired techniques with their friends and colleagues and to report on that on the training sessions by presenting a written or video report (all together 9 h). The training consisted of 12 h (1 h weekly) of a theoretical introduction accompanied by examples (video clips). An experimenter pointed out different communication skills, obstacles in communication, active and passive listening, examples of effective communication, mirroring, identifying emotions in others and one self. After each theoretical introduction, about 45 min (all together 9 h) were devoted to applying the learned skills in provided scenarios. One of the scenarios would read:

"A friend asks you for advice. His/her company has just announced that about 30% of the people will lose their jobs sometime in the next 6 months. The final decisions are still being made, and it will be at least 4 weeks before there is any announcement about which people are being cut. What should he/she do?".

The Participants were constantly provided with feedback about their improvements. On average each of the participants completed 30 h of training.

2.4. EEG and NIRS recording and quantification

EEG was recorded using a Quick-Cap with sintered (Silver/Silver Chloride; 8 mm diameter) electrodes (see Fig. 3). Using the Ten-twenty Electrode Placement System of the International Federation, the EEG activity was monitored over nineteen scalp locations (Fp1, Fp2, F3, F4, F7, F8, T3,T4, T5, T6, C3, C4, P3, P4, O1, O2, Fz, Cz and Pz). All leads were referenced to linked mastoids (M1 and M2), and a ground electrode was applied to the forehead. Additionally, vertical eye movements were recorded with electrodes placed above and below the left eye. The 19 EEG traces were digitized online at 1000 Hz and stored on a hard disk. Epochs were comprised from the 2000 ms preceding and 10000 ms following the stimulus presentation and automatically screened for artifacts. Excluded were all epochs showing amplitudes above ±50 μV. All together 2.1% of epochs were excluded from further analysis.

The frequency bands were individually determined for 2.0 Hz steps, based on the individual alpha peak frequency (IAF) determined separately for the test and retest conditions: upper alpha = [IAF to IAF + 2.0 Hz]; lower-2 alpha = [IAF to IAF – 2.0 Hz];, lower-1 alpha = [IAF – 2.0 Hz to IAF – 4.0 Hz]; and theta = [IAF – 4.0 Hz to IAF – 6.0 Hz]; (Burgess & Gruzelier, 1999; Klimesch, 1999). The induced event-related desynchronization/synchronization (ERD/ERS) was determined using the method of complex demodulation with a simultaneous signal envelope computation (Andrev, 1999; Otnes & Enochson, 1978; Thatcher, Toro, Pflieger, & Hallet, 1994). In this method the raw data for each channel were multiplied, point by point, by a pure cosine based on the selected center frequency, as well as by a pure sine having the same center frequency. Both time series (multiplied by a pure sine and cosine) were then lowpass filtered by the half-bandwidth (1 Hz).

The quantification of induced ERD was done using the intertrial variance method (induced, non-phase-locked activity). The formulas used were as follows (Pfurtscheller, 1999):

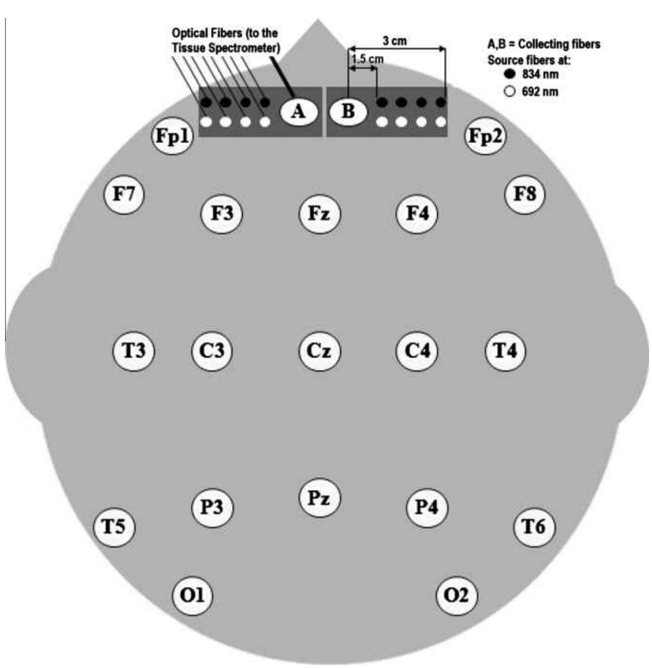

Fig. 3. Position of the optical probes (NIRS) and electrodes (EEG) on the respondents' head.

$$\mathrm{IV}_{(j)} = \frac{1}{N-1}\sum_{i=1}^{N}\left\{y_{f(i,j)} - \bar{y}_{f(j)}\right\}^2 \tag{1}$$

In Eq. (1) N is the total number of trials, $y_{f(i,j)}$ is the jth sample of ith trial data, and $\bar{y}_{f(j)}$ is the mean of the jth sample over all trials. The ERD (IV) data were used to calculate the ERD/ERS values which were defined as the percentage change of the power at each sample point (A_j), relative to the average power in the resting 1000 ms reference interval (R) preceding the stimulus onset (−1500 ms to −500 ms):

$$\mathrm{ERD}_{(j)}\% = \frac{R - A_j}{R} \tag{2}$$

A positive ERD indicates a power decrease, and a negative ERS a power increase (Pfurtscheller, 1999). The ERD/ERS values were determined for six 1000 ms time windows (from stimulus onset till 6000 ms). The ERD/ERS values were collapsed for different electrode locations, distinguishing the hemispheres as well as frontal, central and parietal brain areas. The electrode positions were aggregated as follows: frontal left (Fp1, F3, F7), frontal right (Fp2, F4, F8), central left (T3, C3), central right (T4, C4), parietal left (T5, P3, O1), and parietal right (T6, P4, O2).

The NIRS measurements were carried out with an OxiPlex (Non-invasive tissue oximeter; ISS Inc., Champaign, Ill., USA). The instrument is described in detail elsewhere (Fabbri et al., 2003). This instrument features sixteen intensity-modulated laser diodes, eight emitting at a wavelength of 692 nm, and eight at 834 nm, and two gain-modulated photomultiplier tube detectors. The two optical probes were placed on the right and left side of the respondent's forehead (see Fig. 3). The data from all four illumination–collection distances were analyzed using a frequency-domain multidistance method to calculate the absolute values of the oxy-hemoglobin concentration (HbO_2) in the tissue. This multi-distance approach to NIRS is relatively insensitive to superficial tissue layers (Fantini, Franceschini, & Gratton, 1994). The NIRS data were recorded concurrently with the EEG data by connecting the analog outputs of the STIM to the auxiliary inputs of the NIRS spectrometer. The absorption of near-infrared light was measured with a time resolution of 0.1 s. The first stage of the NIRS analysis was to filter the data in the temporal domain to remove artifacts due to respiration and cardiac variations (using a lowpass filter 0.3 Hz). In the next step the absolute values of the oxy-hemoglobin concentration (HbO_2) in the tissue for the 6000 ms post-stimulus interval for all items of the three tasks, separately for the left and right optical probes, were determined. The HbO_2 marker for hemodynamic analysis was used because no differences in resting conditions between respondents of the WM and AC groups were observed, and because it is regarded as an adequate indicator of mental activity Horovitz and Gore (2004).

3. Results

3.1. Behavioral data

The averages of test scores obtained during initial testing and on retests are summarized in Table 1. The training influence on performance scores was analyzed with a General linear model (GLM) for repeated measures test/retest × type of task (digit-span, RAPM, spatial rotation, verbal analogy) × group (working memory, active control). The analysis showed only a significant interaction effect between the test/retest condition and the type of training the two groups were exposed to ($F(1,27) = 6.66$; $p < .05$; *partial* $eta^2 = .20$). Subsequent paired sample t-tests revealed no significant increase in test performance (test–retest comparison) for the respondents of the active control group. After the training they showed an about equal level of performance as prior to training

Table 1
Means, SD, and paired sample *t*-tests for the active control and working memory group obtained on initial and retesting sessions for the digit-span subtest (DS), Raven's progressive matrices test-battery (RAPM), Paper Folding and Cutting test-battery (PF&C), and verbal analogies test (VA).

Task	Active control					Working memory				
	Test		Retest			Test		Retest		
	M	*SD*	*M*	*SD*	*df*(14)	*M*	*SD*	*M*	*SD*	*df*(13)
DS	11.20	2.73	11.73	2.60	$t = .98$; $p < .34$; $d = .25$	11.21	3.33	12.92	3.63	$t = 3.02$; $p < .01$; $d = .81$
RAPM	29.00	6.08	29.20	6.34	$t = .11$; $p < .91$; $d = .03$	28.71	6.33	32.43	5.65	$t = 3.30$; $p < .006$; $d = .88$
PF&C	13.60	4.00	14.13	5.67	$t = .48$; $p < .64$; $d = .12$	12.00	4.62	13.64	5.30	$t = 2.25$; $p < .04$; $d = .60$
VA	17.20	3.26	17.67	2.87	$t = .50$; $p < .34$; $d = .13$	17.14	2.69	18.50	2.03	$t = 2.08$; $p < .06$; $d = .56$

(see Table 1). By contrast, after the training respondents of the working memory group showed significant increases in performance. The differences were especially pronounced for the RAPM as well as for the digit-span subtest, while less pronounced differences were observed for the PF&C test, and no significant differences were observed for the verbal analogies test battery.

To further investigate possible influences of task difficulty on the observed performance gains on the RAPM a GLM for repeated measures test/retest × easy/difficult-items × group (WM, AC) was conducted. The analysis showed only a significant interaction effect for the test/retest condition and type of training used in the two groups ($F(1,27) = 4.47$; $p < .05$; *partial* $eta^2 = .15$). A GLM conducted for the WM group showed only a significant test/retest effect ($F(1,13) = 30.11$; $p < .05$; *partial* $eta^2 = .70$), but no interaction between the test/retest conditions and the difficulty level ($F(1,13) = 1.79$; $p = .17$ *not-significant*; *partial* $eta^2 = .12$). As can be seen in Fig. 4 after WM training an about equal increase in respondents' performance for the easy and difficult test items was observed. On the other hand, no increases in performance, neither for the easy nor for the difficult test items, in respondents of the active control group were observed ($F(1,14) = .47$; $p = .50$ *not-significant*; *partial* $eta^2 = .03$).

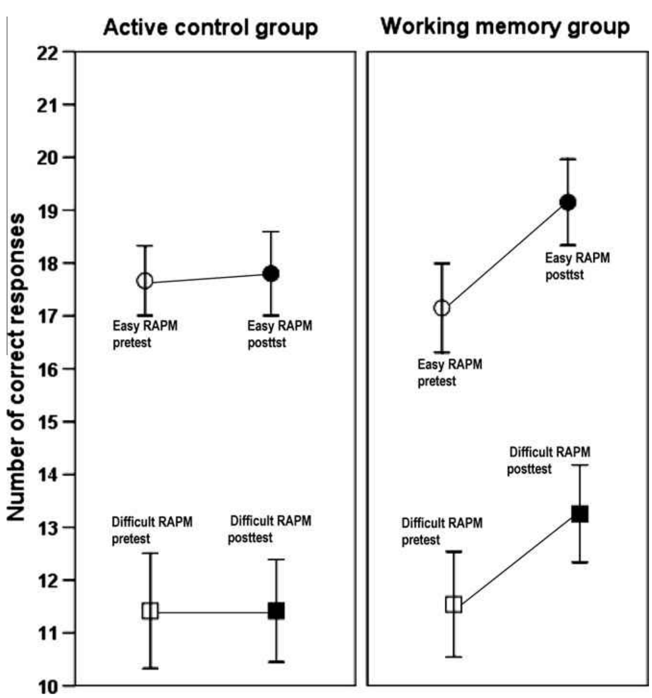

Fig. 4. Respondents' (active control and working memory group) pretest–posttest scores of the 25 easy and 25 difficult items of the RAPM.

3.2. EEG data

The influence of the two training approaches on neuroelectric patterns of brain activity was analyzed with a GLM for repeated measures – test/retest × task type (RAPM, PF&C, analogies) × time (six 1000 ms segments) × left/right hemisphere × location (frontal, central, parieto-occipital) × group (WM, AC). Significant interaction effects between test occasion and type of training (group) were observed for the lower-2 alpha ($F(1,27) = 6.47$; $p < .05$; *partial* $eta^2 = .19$), and upper alpha band ($F(1,27) = 4.45$; $p < .05$; *partial* $eta^2 = .14$). In the upper alpha band also a significant interaction effect between test occasion, type of training and location was observed ($F(2,54) = 4.02$; $p < .05$; *partial* $eta^2 = .13$). On the other hand, in the theta band only a significant interaction effect between test occasion, group and time was observed ($F(5140) = 2.47$; $p < .05$; *partial* $eta^2 = .08$). In the lower-1 alpha band the same interaction effect only slightly missed the $p < .05$ significance level ($F(5140) = 1.93$; $p = .09$ *not significant*; *partial* $eta^2 = .06$). To get a detailed insight into the influence of the WM training on changes in brain activity we analyzed the data separately for each group (WM and AC) with a GLM for repeated measures – test/retest × task type (RAPM, PF&C, analogies) × time (six 1000 ms segments) × left/right hemisphere × location (frontal, central, parieto-occipital). For the active control group the only significant test/retest effect was observed in the theta band ($F(1,14) = 5.05$; $p < .05$; *partial* $eta^2 = .27$). Respondents of the active control group showed during the retest session higher theta synchronization (ERS) than during initial testing. On the other hand, in the three alpha bands no differences in ERD/ERS measures between the test and retest sessions could be observed.

Much more numerous and pronounced were the test/retest differences in neuroelectric activity observed in respondents of the working memory group. In the theta band, significant interactions between the test/retest condition and time ($F(5,65) = 4.22$; $p < .05$; *partial* $eta^2 = .25$), as well as hemisphere and location ($F(2,26) = 4.51$; $p < .05$; *partial* $eta^2 = .26$) were observed. As can be seen in the upper half of Fig. 5, respondents after WM training showed more intense parieto-occipital theta synchronization, accompanied by theta synchronization in the right temporal area that was from 3000 ms on associated with bipolar frontal theta synchronization (ERS). It is worth mentioning that in the retest condition the respondents' activation patterns at 4000 ms to some extent resembled neuroelectric patterns that were on initial testing displayed by respondents at 6000 ms, which could point to similar but intensified and faster working-memory processing.

In the lower-1 alpha band significant interactions between the test/retest conditions and time ($F(5,65) = 3.66$; $p < .05$; *partial* $eta^2 = .22$), location ($F(2,26) = 4.38$; $p < .05$; *partial* $eta^2 = .25$), as well as time and location ($F(10,130) = 2.63$; $p < .05$; *partial* $eta^2 = .17$) were observed. As can be seen in the lower half of Fig. 5, after WM training respondents showed more intense occipital lower-1 alpha ERS. Further they displayed a change in bipolar

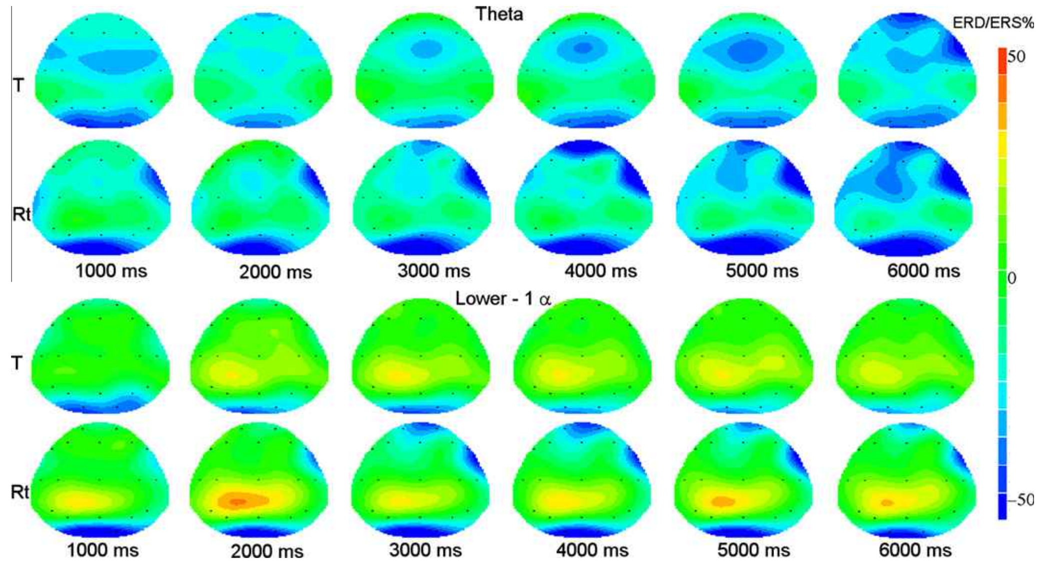

Fig. 5. Topographic ERD/ERS maps of respondents' (working memory group) neuroelectric activity in the theta and lower-1 alpha bands averaged for all three test batteries for 1000 ms time segments from item onset till 6000 ms, during initial testing (T) and during retest (Rt). In the theta band (upper part) respondents after WM training showed more intense parieto-occipital theta synchronization, accompanied by theta synchronization in the right temporal area that was from 3000 ms on associated with bipolar frontal theta synchronization (ERS). In the retest (Rt) condition the respondents' activation patterns at 4000 ms to some extent resembled neuroelectric patterns that were on initial testing (T) displayed by respondents at 6000 ms. As can be seen in the lower half of Fig. 5, after WM training respondents showed earlier and more intense parieto-occipital lower-1 alpha ERS. Further they displayed a change in bipolar frontal and right temporal areas from a predominantly ERD pattern during initial testing to an ERS pattern during retest.

frontal and right temporal areas from a predominantly ERD pattern during initial testing to an ERS pattern during retest.

In the lower-2 alpha band significant interactions between the test/retest condition and location ($F(2,26) = 6.17$; $p < .05$; *partial* $eta^2 = .32$), as well as time and location ($F(10,130) = 2.34$; $p < .05$; *partial* $eta^2 = .15$) were observed. The ERD/ERS topographic maps in Fig. 6 (upper part) showed that after the WM training a bipolar increase in lower-2 alpha ERD was observed in the parieto to central brain areas. In the upper alpha band significant interactions between the test/retest condition and location ($F(2,26) = 6.77$; $p < .05$; *partial* $eta^2 = .34$), as well as hemisphere and location ($F(2,26) = 3.90$; $p < .05$; *partial* $eta^2 = .23$) were observed. The ERD/ERS topographic maps (lower part of Fig. 6) show a significant increase in right hemispheric parietal upper alpha ERD which at 5000–6000 ms expanded to the whole left hemisphere.

3.3. NIRS data

Test/retest differences in the absolute values of the oxy-hemoglobin concentration (HbO_2) in brain tissue were analyzed with a GLM for repeated measures test/retest × task type (RAPM, PF&C, analogies) × left/right hemisphere × group (control, working

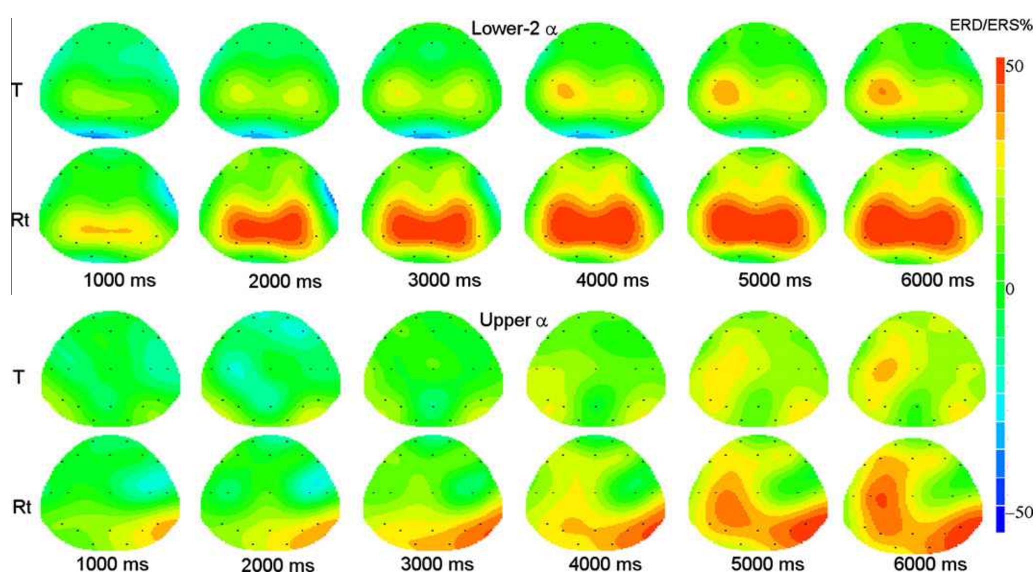

Fig. 6. Topographic ERD/ERS maps of respondents' (working memory group) neuroelectric activity in the lower-2 and upper alpha bands averaged for all three test batteries for 1000 ms time segments from item onset till 6000 ms, during initial testing (T) and during retest (Rt). In the upper part the ERD/ERS topographic maps showed that after the WM training an earlier and more intense bipolar increase in lower-2 alpha ERD was observed in the postcentral brain areas. The ERD/ERS topographic maps for the upper alpha band (lower part) showed a significant increase in right hemispheric parieto-occipital upper alpha ERD which at 5000–6000 ms expanded to the whole left hemisphere.

memory). The analysis showed a significant test/retest by group and hemisphere interaction effect ($F(1,27) = 22.84$; $p < .05$; *partial* $eta^2 = .46$). As can be seen in Fig. 7 the main change in respondents' (active control group) frontal brain oxy-hemoglobin concentration after training was an increase in the already existing discrepancy in the initial condition between the left and right hemispheric oxy-hemoglobin concentrations (lower left and higher right hemispheric oxy-hemoglobin concentration). By contrast, respondents of the working memory group showed after training an increase in left hemispheric and a decrease in right hemispheric oxy-hemoglobin concentration resulting in an almost equal oxy-hemoglobin concentration of respondents' frontal brain areas.

4. Discussion

The main objectives of the present study were, first, to investigate whether training on working memory (storage and processing components) led to increases in performance on tests of fluid intelligence; and second, to investigate the influence WM training had on neuroelectric and hemodynamic patterns of brain activity.

The analysis of behavioral data revealed a significant increase of performance in respondents of the working memory group. This increase was most pronounced for the RAPM, but also present on the other three test-batteries used. It is worth mentioning that the improvement on the RAPM, was observed not just for the more easy test items, but was also pronounced for the difficult test items. On the other hand, respondents of the active control group displayed no significant increase in performance. The findings support recent research (Jaeggi et al., 2008; Klingberg, 2010), indicating that WM training can increase fluid intelligence – the abilities involved in coping with novel environments and in abstract reasoning (Sternberg, 2008). In the present study transfer effects of WM training could be also observed on two other tests of *G*, a spatial reasoning test and on a test of memory span for numbers, even though no explicit training of mnemonic strategies was provided. For the verbal-analogy test the posttest increases in performance only slightly missed the .05 *p*-value cutoff. The main reason for the diverse influence WM training had on performance was probably the difficulty level of the tasks used in the test sessions. The most difficult test to solve was the PF&C, with just 54% correctly solved items, followed by the RAPM, 58% correctly solved items, whereas the verbal analogy test was the easiest to solve, with 69% correctly solved items. It cannot be excluded that such a distribution of difficulty levels was partly due to the sample structure being predominantly female.

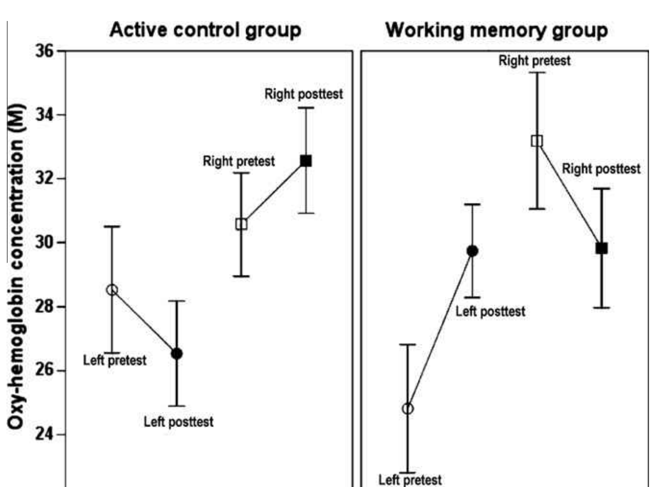

Fig. 7. Oxy-hemoglobin concentrations in the right and left frontal brain areas of respondents (active control and working memory group) averaged for all three test-batteries during pre- and post-testing.

The differences between test and training items with respect to content and form of presentation, minimizes the possibility that performance improvements could be the result of similarities between tasks used in the WM training and items used for testing. However, some limitations of the obtained behavioral results that restrict the generalization of conclusions must be mentioned. First, the investigated sample was rather small and not representative of the full population of 20-year old individuals. Second, a more essential constraint was the predominantly female structure of the sample. Given the immense body of evidence with regard to gender related differences in general as well as specific abilities (e.g., Johnson & Bouchard, 2007; Nyborg, 2005), this might have had some influence on the results obtained. It should be further mentioned that the use of an identical tests battery on both, pre- and post-tests, in combination with the small and predominantly female sample might have to some extent influenced the obtained gains on different tests of fluid intelligence. This shortcomings should be addressed in future research.

Our second hypothesis was that WM training would be reflected in neuroelectric and hemodynamic patterns of brain activity. Working memory training effects on neuroelectric brain activity were mainly expected in the theta to upper alpha bands. Research (Klimesch, 1999; Klimesch, Freunberger, Sauseng, & Gruber, 2008; Sauseng, Griesmayr, Freunberger, & Klimesch, 2010) has indicated that theta oscillations are related to working memory processes. It was further suggested that theta synchronizes (ERS) during WM processes and serves as a gating mechanism, providing optimal neural conditions for specific processing (Sauseng et al., 2010). Klimesch et al. (2008) has further suggested that upper alpha (above IAF) is related to long-term memory processes. Alpha band activity desynchronizes (ERD) in relation to task performance (Pfurtscheller & Aranibar, 1977). Until recently alpha synchronization (ERS) was considered as a cortical idling phenomenon (Pfurtscheller, 1999). However, recent evidence suggests that synchronization of alpha activity does not merely reflect cortical deactivation (Fink et al., 2009; Jensen & Mazaheri, 2010; Klimesch, Sauseng, & Hanslmayr, 2007) but is a sign of internal top-down processes, a selective inhibition of brain regions similar to Baddeley's (1992) concept of working memory and the central executive processes. An attentional control function that maintains the focus on highly selective elements of task performance by inhibiting distracting interferences from task-irrelevant brain areas. Thus, it is suggested that the working and long-term memory systems have their own types of top-down processes that control access and manipulation of stored information which are based on the theta and upper alpha frequency bands (Klimesch et al., 2008).

The characteristic of the impact of WM training on neuroelectric brain activity was a time related synchronization (ERS) in the theta and lower-1 alpha bands and a more topographically significant (location, hemisphere) increase in lower-2 and upper alpha desynchronization (ERD). The increase in theta synchronization was most pronounced in the frontal and parieto-occipital brain areas. The fronto-parietal topography of theta synchronization (for a review see Klimesch et al., 2008; Sauseng et al., 2010), is an often reported characteristic of theta during encoding and retrieval (parietal), and during the performance of central executive and attentional control (frontal). Theta synchronization was accompanied by lower-1 alpha synchronization in the occipital brain areas and an early left parietal desynchronization (ERD). Given the attentional function of the lower-1 alpha, the ERD/ERS topography would suggest inhibition processes in the occipital area probably suppressing task irrelevant information in the visual cortex and in that way allowing for faster WM processing, as was indicated by earlier occurring patterns of theta synchronization being topographically similar to the ones observed in individuals prior to WM training. This is in line with research relating the level of intelligence with brain activity (Jaušovec & Jaušovec, 2004). It was found that high intelligent individuals, while solving a WM task, displayed greater theta synchronization in the early phases of task completion as compared to low intelligent individuals. It is further interesting to note that the WM training influenced those two areas of the brain that are assumed to constitute a highly important network involved in complex information processing – frontal and parietal. According to the parieto-frontal integration theory by Jung and Haier (2007), the fidelity of neuronal transmissions in these areas is a key characteristic distinguishing high versus low intelligent individuals.

Neuroelectric activity in the lower-2 and upper alpha band after WM training showed increased desynchronization (ERD). In the lower-2 alpha band this desynchronization after WM training occurred earlier and was more intense, located in the left and right parietal areas, as opposed to a more left hemispheric parietal ERD prior to training. In the upper alpha band, after WM training an early right parietal ERD (1000 ms) intensified spreading to a left parietal and bipolar frontal ERD pattern (6000 ms). Prior training less intense and more scattered ERD patterns in the upper alpha band were observed.

Even though research on the relations between NIRS and EEG measures (Koch, Steinbrink, Villringer, & Obrig, 2006) suggests that electrophysiological resonance between an individual's alpha frequency and stimulation is not mirrored by the vascular response (probably because there is no straightforward translation of neuronal excitation and inhibition into respective increases or decreases in vascular response), the training induced changes in upper alpha ERD/ERS are to some extent similar to the distribution of oxygenated hemoglobin changes in frontal brain areas. After WM training about equal concentrations of oxy-hemoglobin in the left and right frontal areas could be observed. This equalization in oxy-hemoglobin concentrations was due to increases in left hemisphere and decreases in right hemisphere oxy-hemoglobin concentrations. A similar mixture of increases and decreases in fronto-parietal brain areas after different types of WM trainings was also reported by some studies using functional magnetic resonance imaging (e.g., Moore, Cohen, & Ranganath, 2006; Olesen, Westerberg, & Klingberg, 2003; for a review see, Klingberg, 2010).

The only significant change in neuroelectric activity observed in respondents of the active control group was an increase in theta synchronization. Because it is well documented that with increasing WM load, theta power increases (Gevins & Smith, 2000; Klimesch, 1999) this could point to more intense WM processes in respondents of the control group. The same is true for the observed changes in frontal oxy-hemoglobin concentrations. After training the same but more intensified pattern in right/left frontal brain activity was observed as compared with the hemodynamic patterns prior to training. This would further suggest that the respondents of the control group tried hard on the tests but could not solve more tasks than before training.

The neuroelectric as well as hemodynamic patterns observed in individuals after WM training suggest that the training has influenced the working memory's retention as well as processing components guided by the central executive. The changes in the upper alpha band ERD would further suggest that also processes related to long term memory were influenced. This could be expected, given that both systems WM and LTM interact on several levels of processing (Baddeley, 2010). This relation has been elaborated in Cowan's embedded processes model of WM, in which only the control function of the central executive is assigned to WM, whereas all other processes are part of LTM (Cowan, 1999). The model corresponds well with the neuroelectric and hemodynamic patterns of brain activity observed in the present study.

In conclusion, the results obtained, beside the mentioned limitations due to sample structure and size, lend further support to the hypothesis that working memory training can improve fluid intelligence which is also reflected in changed brain activity. These changes could further be indicative of training-induced flexibility in the neural systems that underlie working memory.

References

Amin, Z., Epperson, C. N., Constable, R. T., & Canli, T. (2006). Effects of estrogen variation on neural correlates of emotional response inhibition. *NeuroImage, 32*, 457–464.

Andrev, C. (1999). Quantification of event-related coherence (ERCoh). In G. Pfurtscheller & F. H. Lopes da Silva (Eds.). *Handbook of electroencephalography and clinical neuropsychology. Event-related desynchronization* (Vol. 6, pp. 119–137). Amsterdam: Elsevier.

Baddeley, A. (1992). Working memory. *Science, 255*, 556–559.

Baddeley, A. (2010). Working memory. *Current Biology, 20*, 136–140.

Berman, K. F., Schmidt, P. J., Rubinow, D. R., Danaceau, M. A., Van Horn, J. D., Esposito, G., et al. (1997). Modulation of cognition-specific cortical activity by gonadal steroids: A positron-emission tomography study in women. *Proceedings of the National academy of Sciences of the United States of America, 94*, 8836–8841.

Burgess, A. P., & Gruzelier, J. H. (1999). Methodological advances in the analysis of event-related desynchronization data: Reliability and robust analysis. In G. Pfurtscheller & F. H. Lopes da Silva (Eds.). *Handbook of electroencephalography and clinical neuropsychology. Event-related desynchronization* (Vol. 6, pp. 139–158). Amsterdam: Elsevier.

Buschkuehl, M., & Jaeggi, S. M. (2010). Improving intelligence: A literature review. *Swiss Medical Weekly, 140*, 266–272.

Colom, R., Abad, F. J., Quiroga, M., Chun, S. P., & Flores-Mendoza, C. (2008). Working memory and intelligence are highly related constructs, but why? *Intelligence, 36*, 584–606.

Colom, R., Haier, R. J., Head, K., Álvarez-Linera, J., Quiroga, M., & Chun, S. P. (2009). Gray matter correlates of fluid, crystallized, and spatial intelligence: Testing the P-FIT model. *Intelligence, 37*, 124–135.

Court, J. H., & Raven, J. (1995). Manual for Raven's progressive matrices and vocabulary scales. Section 7: Research and references: Summaries of normative, reliability, and validity studies and references to all sections. Oxford, England: Oxford Psychologists Press/San Antonio, TX: The Psychological Corporation.

Cowan, N. (1999). An embedded-processes model of working memory. In A. Miyake & P. Shah (Eds.), *Models of working memory* (pp. 62–101). Cambridge: Cambridge University Press.

Craik, F. I. M. (2006). Brain–behavior relations across the lifespan: A commentary. *Neuroscience and Biobehavioral Reviews, 30*, 885–892.

Crone, E. A., Wendelken, C., Donohue, S., van Leijenhorst, L., & Bunge, S. A. (2006). Neurocognitive development of the ability to manipulate information in working memory. *PNAS, 103*, 9315–9320.

Doppelmayr, M., Klimesch, W., Hödlmoser, K., Sauseng, P., & Gruber, W. (2005). Intelligence related upper alpha desynchronization in a semantic memory task. *Brain Research Bulletin, 66*, 171–177.

Draganski, B., Gaser, C., Busch, V., Sheerer, G., Bogdahn, U., & May, A. (2004). Neuroplasticity: Changes in grey matter induced by training. *Nature, 427*, 311–312.

Driemeyer, J., Boyke, J., Gaser, C., Büchel, C., & May, A. (2008). Changes in gray matter induced by learning—Revisited. *PLoS One, 3*, e2669.

Duncan, J. (2001). An adaptive coding model of neural function in prefrontal cortex. *Nature Reviews Neuroscience, 2*, 820–829.

Egner, T., & Gruzelier, H. J. (2003). Ecological validity of neurofeedback: Modulation of slow wave EEG enhances musical performance. *NeuroReport, 14*, 1221–1224.

Fabbri, F., Henry, M. E., Renshaw, P. F., Nadgir, S., Ehrenberg, B. L., Franceschini, M. A., et al. (2003). Bilateral near-infrared monitoring of the cerebral concentration and oxygen-saturation of hemoglobin during right unilateral electro-convulsive therapy. *Brain Research, 992*, 193–204.

Fantini, S., Franceschini, M. A., & Gratton, E. (1994). Semi-infinite geometry boundary problem for light migration in highly scattering media, a frequency domain study in the diffusion approximation. *Journal of the Optical Society of America B: Optical Physics, 11*, 2128–2138.

Fink, A., Grabner, R. H., Bendedk, M., Reishofer, G., Hauswirth, W., Fally, M., et al. (2009). The creative brain: Investigation of brain activity during creative problem solving by means of EEG and fMRI. *Human Brain Mapping, 30*, 734–748.

Gevins, A., & Smith, M. E. (2000). Neurophysiological measures of working memory and individual differences in cognitive ability and cognitive style. *Cerebral Cortex, 10*, 830–839.

Gordon, T. (1974). *Teacher effectiveness training*. New York: Peter H. Wyden Publisher.

Gruzelier, J. (2009). A theory of alpha/theta neurofeedback, creative performance enhancement, long distance functional connectivity and psychological integration. *Cognitive Processing, 10*(Suppl. 1), S101–S109.

Haier, R. J. (1993). Cerebral glucose metabolism and intelligence. In P. A. Vernon (Ed.), *Biological approaches to the study of human intelligence* (pp. 317–332). Norwood, NJ: Ablex.

Haier, R. J., Colom, R., Schroeder, D. H., Condon, C. A., Tang, C., Eaves, E., et al. (2009). Gray matter and intelligence factors: Is there a neuro-g? *Intelligence, 37*, 136–144.
Horovitz, S. G., & Gore, J. C. (2004). Simultaneous event-related potential and near-infrared spectroscopic studies of semantic processing. *Human Brain Mapping, 22*, 110–115.
Jaeggi, S. M., Buschkuehl, M., Jonides, J., & Perrig, W. J. (2008). Improving fluid intelligence with training on working memory. *PNAS, 105*, 6829–6833.
Jaušovec, N., & Jaušovec, K. (2004). Differences in induced brain activity during the performance of learning and working-memory tasks related to intelligence. *Brain and Cognition, 54*, 65–74.
Jensen, A. R. (1969). How much can we boost IQ and scholastic achievement? *Harvard Educational Review, 39*, 1–123.
Jensen, A. R. (1981). Raising the IQ: The Ramey and Haskins study. *Intelligence, 5*, 29–40.
Jensen, O., & Mazaheri, A. (2010). Shaping functional architecture by oscillatory alpha activity: Gating by inhibition. *Frontiers in Human Neuroscience, 4*, 1–8.
Johnson, W., & Bouchard, T. J. Jr., (2007). Sex differences in mental ability: g Masks the dimensions on which they lie. *Intelligence, 35*, 23–39.
Jung, R. E., & Haier, R. J. (2007). The Parieto-Frontal Integration Theory (P-FIT) of intelligence: Converging neuroimaging evidence. *Behavioral and Brain Sciences, 30*, 135–187.
Keizer, A. W., Verment, R. S., & Hommel, B. (2010). Enhancing cognitive control through neurofeedback: A role of gamma-band activity in managing episodic retrieval. *NeuroImage, 49*, 3404–3413.
Klimesch, W. (1999). EEG alpha and theta oscillations reflect cognitive and memory performance: A review and analysis. *Brain Research Reviews, 29*, 169–195.
Klimesch, W., Freunberger, R., Sauseng, P., & Gruber, W. (2008). A short review of slow phase synchronization and memory: Evidence for control processes in different memory systems? *Brain Research, 1235*, 31–44.
Klimesch, W., Sauseng, P., & Hanslmayr, S. (2007). EEG alpha oscillations: The inhibition-timing hypothesis. *Brain Research Reviews, 53*, 63–88.
Klimesch, W., Schimke, H., & Schwaiger, J. (1994). Episodic and semantic memory: An analysis in the EEG-theta and alpha band. *Electroencephalography and Clinical Neurophysiology, 91*, 428–441.
Klingberg, T. (2010). Training and plasticity of working memory. *Trends in Cognitive Sciences, 14*, 317–324.
Koch, S. P., Steinbrink, J., Villringer, A., & Obrig, H. (2006). Synchronization between background activity and visually evoked potential is not mirrored by focal hyperoxygenation: Implications for the interpretation of vascular brain imaging. *Journal of Neuroscience, 18*, 4940–4948.
Maguire, E. A., Gadian, D. G., Johnsrude, I. S., Good, C. D., Ashburner, J., Frackowiak, R. S. J., et al. (2000). Navigation-related structural change in the hippocampi of taxi drivers. *PNAS, 97*, 4398–4403.
Mihelič, A. (1972). *Baterija testov sposobnosti BTI Priročnik*. Ljubljana: Zavod SR Slovenije za produktivnost dela.
Moody, D. E. (2009). Can intelligence be increased by training on a task of working memory? *Intelligence, 37*, 327–328.
Moore, C. D., Cohen, M. X., & Ranganath, C. (2006). Neural mechanisms of expert skills in visual working memory. *Journal of Neuroscience, 26*, 11187–11196.
Morrison, A. B., & Chein, J. M. (2011). Does working memory training work? The promise and challenges of enhancing cognition by training working memory. *Psychonomic Bulletin & Review, 18*, 46–60.
Neubauer, A. C., & Fink, A. (2009). Intelligence and neural efficiency. *Neuroscience and Biobehavioral Reviews, 33*, 1004–1023.
Nyborg, H. (2005). Sex-related differences in general intelligence g, brain size, and social status. *Personality and Individual Differences, 39*, 497–509.
Olesen, P., Westerberg, H., & Klingberg, T. (2003). Increased prefrontal and parietal brain activity after training of working memory. *Nature Neuroscience, 7*, 75–79.
Otnes, R. K., & Enochson, L. (1978). *Applied time series analysis*. New York: John Wiley.
Owen, A. M., Hampshire, A., Grahn, J. A., Stenton, R., Dajani, S., Burns, A. S., et al. (2010). Putting brain training to the test. *Nature, 465*, 775–779.
Pantev, C., Ross, B., Fujioka, T., Trainor, L. J., Schulte, M., & Schultz, M. (2003). Music and learning-induced cortical plasticity. *Annals of the New York Academy of Sciences, 999*, 438–450.
Pascual-Leone, A. (2001). The brain that plays music and is changed by it. *Annals of the New York Academy of Sciences, 930*, 315–329.
Pfurtscheller, G. (1999). Quantification of ERD and ERS in the time domain. In G. Pfurtscheller & F. H. Lopes da Silva (Eds.). *Handbook of electroencephalography and clinical neuropsychology. Event-related desynchronization* (Vol. 6, pp. 89–105). Amsterdam: Elsevier.
Pfurtscheller, G., & Aranibar, A. (1977). Event-related cortical synchronization detected by power measurements of scalp EEG. *Electroencephalography and Clinical Neurophysiology, 42*, 817–826.
Pietschnig, J., Voracek, M., & Formann, A. M. (2010). Mozart effect–Shmozart effect: A meta-analysis. *Intelligence, 38*, 314–323.
Rauscher, F. H., Shaw, G. L., & Ky, K. N. (1993). Music and spatial task performance. *Nature, 365*, 611.
Raven, J. C. (1990). *Advanced progressive matrices: Sets I, II*. Oxford: Oxford Univ Press.
Repovš, G., & Baddeley, A. (2006). The multi-component model of working memory: Explorations in experimental cognitive psychology. *Neuroscience, 139*, 5–21.
Rideout, B. E., & Laubach, C. M. (1996). EEG correlates of enhanced spatial performance following exposure to music. *Perceptual and Motor Skills, 82*, 427–432.
Sauseng, P., Griesmayr, B., Freunberger, R., & Klimesch, W. (2010). Control mechanisms in working memory: A possible function of EEG theta oscillations. *Neuroscience and Biobehavioral Reviews, 34*, 1015–1022.
Shipstead, Z., Redick, T. A., & Engle, R. W. (2010). Does working memory training generalize? *Psychologica Belgica, 50*, 245–276.
Sternberg, R. J. (2008). Increasing fluid intelligence is possible after all. *PNAS, 105*, 6791–6792.
Sternberg, R. J., Ferrari, M., Clinkenbeard, P., & Grigorenko, E. L. (1996). Identification, instruction, and assessment of gifted children: A construct validation of a triarchic model. *Gifted Child Quarterly, 40*, 129–137.
Surmeli, T., & Ertem, A. (2010). Post WISC-R and TOVA improvements with QEEG guided neurofeedback training in mentaally retarded: A clinical case series of behavioral problems. *Clinical EEG Neuroscience, 41*, 32–41.
Thatcher, R. W., Toro, C., Pflieger, M. E., & Hallet, M. (1994). Human neural network dynamics using multimodal registration of EEG, PET and MRI. In R. W. Thatcher, M. Hallet, & T. Zeffiro (Eds.), *Functional neuroimaging: Technical foundations* (pp. 259–267). Orlando, FL: Academic Press.
Wechsler, D. (1981). *Wechsler adult intelligence scale — Revised*. San Antonio, TX: Psychologica Corporation.
Zoefel, B., Huster, R. J., & Herrmann, C. S. (2011). Neurofeedback training of the upper alpha frequency band in EEG improves cognitive performance. *NeuroImage, 54*, 1427–1431.