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Computerised working memory training in healthy adults: A comparison of two different training schedules

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This study compared a high intensity working memory training (45 minutes, 4 times per week for 4 weeks) with a distributed training (45 minutes, 2 times per week for 8 weeks) in middle-aged, healthy adults. The aim was to clarify whether a computerised working memory training is effective and whether intensity of training influences training outcome. To evaluate the efficacy and possible transfer effects, a neuropsychological test battery assessing short- and long-term memory, working memory, executive functions and mental speed was applied at baseline and at retest. Our results indicate that the distributed training led to increased performance in all cognitive domains when compared to the high intensity training and the control group without training. The most significant differences revealed by interaction contrasts were found for verbal and visual working memory, verbal short-term memory and mental speed. These results support the hypothesis that cognitive

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enhancement by cognitive intervention is effective in healthy individuals, and that a distributed training schedule is superior to a high intensity intervention.

Keywords: Working memory; computerised training; Cognitive rehabilitation; Brain plasticity; Training intensity.

INTRODUCTION

In contrast to short-term memory that enables storage of information for short periods of time, working memory refers to the ability to retain, control, regulate and actively maintain task-relevant information. It is regarded to be one of the key functions for a wide range of other cognitive functions (Baddeley, 2003). Performance differences in healthy adults observed in a variety of cognitive tasks might therefore be able to be interpreted in terms of the capacity of working memory processes.

Many studies have focused on working memory processes, and recently a very comprehensive review article demonstrated that the working memory system responds to training on different levels; on the functional neuroanatomical level in terms of increases in activation in task-relevant brain regions, as well as on the dopamine receptor level by a decrease in the dopamine D1 receptor binding potential (Klingberg, 2010). However, a still unanswered question is to what extent the training has to be performed to be as effective as possible. Research conducted so far has produced inconsistent data. Some of the inconsistencies may result from the variety of trained tasks and outcome measures studied, or be due to differences in the amount of training sessions applied.

Working memory training can induce behavioural improvements with task repetition, such as reduction in reaction time or alteration in accuracy. For example Garavan, Kelley, Rosen, Rao, and Stein (2000) as well as Olesen, Westerberg, and Klingberg (2004) found improved performance in their younger healthy adults. In contrast, the participants in the study by Landau, Schumacher, Garavan, Druzgal, and D'Esposito (2004) did not show any behavioural improvement.

Some studies indicated that working memory training could lead to effects that go beyond a specific training effect. In the study by Olesen et al. (2004), participants improved significantly by showing a decrease in error rate and reaction time in various non-trained neuropsychological tests. In a study by Westerberg and Klingberg (2007) younger healthy participants improved in a reasoning task following visuo-spatial working memory training.

Jaeggi, Buschkuehl, Jonides, and Perrig (2008) showed a transfer effect by finding significant improvements in fluid intelligence in healthy participants after a demanding *n*-back training task. Moreover their analyses indicated that the gain in fluid intelligence was responsive to the amount of training.

In a pilot study by Penner, Kobel, Stoecklin, Opwis, and Calabrese (2007) with elderly healthy participants, improvements in working memory and attention outcome measures were found after computerised working memory training with BrainStim (Penner, Kobel, & Opwis, 2006). Also, the study conducted by Vogt et al. (2009) on patients with multiple sclerosis found that training using BrainStim led to improvements in some indicators of working memory and mental speed. In summary, working memory training has been shown to result in improved performance in the practised task as well as in tasks conceptually associated to this cognitive domain (Klingberg, 2010).

However, there is no consensus yet with regard to the optimal time frame for cognitive interventions although it is known from studies on learning processes that distributed learning is superior to massed learning. Several distributed learning phases have been shown to be more effective even in the context of long-term storage (Baddeley & Longman, 1978). It is thought that a longer delay between training sessions increases learning success because it allows for recreation and for a deeper elaboration of information (Mumford, Costanza, Baughman, Threlfall, & Fleishman, 1994). In contrast, massed learning can lead to exhaustion, loss of motivation and decrease of attention (Terry, 2003).

In the context of training studies, the range of training duration varies from one day or less (Garavan et al., 2000; Landau et al., 2004), to five sessions in two weeks (Carretti et al., 2007), to four sessions in four weeks (Penner et al., 2007) up to five sessions in five weeks and more (Westerberg & Klingberg, 2007; Olesen et al., 2004). Only one study so far has compared different working memory training schedules in healthy participants. In the study by Jaeggi et al. (2008) four training groups performed working memory training ranging from 8 to 19 sessions of daily training (except for weekends) within 8 to 19 days, representing a high-intensity training approach.

Since there is so far no data available recommending an optimal dosage of cognitive intervention, the present study aimed to compare, in healthy adults, high intensity training (16 sessions, 4 times per week for 4 weeks) with distributed training (16 sessions, 2 times per week for 8 weeks) assessed with the computerised working memory training tool BrainStim (Penner et al., 2006). The decision to compare 16 sessions of training over a 4-week or an 8-week period was taken on review of the literature with mean duration and training frequencies as in the chosen design. Moreover, practicability, compliance, and adherence, also in terms of further clinical application, were also taken into account when deciding on training duration and frequency.

Based on results from previous studies that demonstrated cognitive improvements in domains other than just working memory after training, e.g. mental speed (Jaeggi et al., 2008) or executive functions (Westerberg and Klingberg, 2007), a comprehensive test battery examining short- and long-term memory, working memory, executive function and mental speed was applied before and after the training. In addition, performance of the two intervention groups (4 weeks of training vs. 8 weeks of training) was also compared to a matched control group which only performed the test battery at baseline and at the end of week 4, without training.

METHODS

Participants

Thirty-six healthy adults participated in the study. Twenty-four participants were female, 12 were male. Mean age was 38.72 years ($SD = 14.67$ years, range = 20–70 years), mean educational level = 3.97 ($SD = 0.67$, range: 2–5) (0 = no school diploma, 1 = junior school, 2 = apprenticeship, 3 = secondary level, 4 = advanced level, 5 = university degree). Volunteers with any neurological disease or psychiatric illness were excluded from the study. Subjects, who did not have to belong to any specific social or professional category, were recruited by study flyers and posters presented at the University of Basel or by intranet notices. All participants gave their written informed consent to participate in the study, which was approved by the local ethics committee. Subjects were not paid for participation to ensure that motivation was not affected by monetary issues. Travel costs were refunded. All subjects completed the training.

Study design

Participants were allocated based on their demographic data to either one of the two intervention groups (16 training sessions within four or eight weeks) or to the control group without training, so that age, sex and educational level were comparable between the groups. Participants in the intervention groups were requested to train at home according to a predefined schedule. Once started, it was prohibited to temporarily suspend the training. Volunteers in the high intensity training group received 45 minutes of training 4 times per week for 4 weeks; participants in the distributed training group underwent 45 minutes of training 2 times per week for 8 weeks. Each training module was applied for 15 minutes.

All volunteers (training groups and control group) underwent a comprehensive cognitive test battery three times in total. The test battery at the start was performed twice at an interval of two weeks and the averaged scores were taken as the baseline measure to avoid mere learning effects due to repeated exposure to the test battery. The retest was performed within 1–2 days after completion of the training (for the high intensity training group after 4 weeks, for the distributed training group after 8 weeks and for the control group without training after 4 weeks). All participants received the same instructions by a trained psychologist to control for interaction effects between experimenter and subjects.

Training tool BrainStim

The training tool BrainStim (Penner et al., 2006) was designed according to Baddeley's model of working memory (Baddeley, 1986, 2000; Baddeley & Hitch, 1974) and consists of three modules. The module *City Map* trains spatial orientation by either visual or verbal instructions to be remembered, followed by finding the path using arrows along a virtual city map. In the version with visual inputs, the arrows pointing a route through the virtual city map have to be memorised. In the version with verbal instructions, inputs such as "turn left after the library" are presented and have to be remembered. The module *Find Pairs* trains visual object memory and the updating function of the central executive component. The aim is to remember the location of cards that have been turned over and back again and find pairs of cards with the same image (similar to the card game called memory). In the third module *Memorise Numbers*, numbers are presented for a short period of time. The digits, increasing in number while the task becomes more difficult, have to be remembered during an arithmetic distraction task. All stimuli in each module are presented in a completely randomised fashion to avoid recognition effects. BrainStim adapts the level of difficulty to participants' performance (accuracy) to ensure optimal training conditions. If the participant fails to answer or is able to answer a certain amount of tasks correctly, BrainStim adapts level of difficulty accordingly. Written information is given to the subject on the computer screen whenever the level of difficulty is changed. In addition, BrainStim gives auditory feedback by means of a melodic fanfare whenever a training unit has been completed successfully, and by means of a low-pitched sound immediately after an error. As the amount of memorised information increases with ascending levels of difficulty, the achievement in the tasks is to not rely only on repetition or practice but also on the ability to develop strategies to improve working memory capacity. Log files (measuring time of assessment, accuracy, reaction times and levels of achieved difficulty), recorded automatically, allow verification of correct completion of training and data collection on the training procedure.

Cognitive test battery

The cognitive test battery included different tests to evaluate working memory, short- and long-term memory, mental speed and executive functions. Working memory (WM) was measured by different indicators:

(1) the block span backward (visuo-spatial WM) and the digit span backward (verbal WM) of the Wechsler Memory Scale (WMS-R; Haerting, Markowitsch, Neufeld, Calabrese, & Deisinger, 2000). Scores from correct items as measured by accuracy were taken. (2) The 2-back task and the 3-back task, adapted from the computerised test battery for attentional assessment (TAP; Zimmermann & Fimm, 1992) were included to measure WM functions such as online monitoring, updating and manipulation of memorised information. Numbers from 1–9 were presented in a pseudo-randomised sequence on a computer screen. The participant had to indicate whether or not each item in the continuous stream of stimuli matched the one presented two (2-back) or three (3-back) positions back in the series. The cues were presented using E-prime software (Psychology Software Tools). Reaction time and number of correct items were recorded. (3) Sustained attention, information processing speed and WM were measured using the 3-second version of the Paced Auditory Serial Addition test (PASAT) of the Brief Repeatable Battery of Neuropsychological Tests (BRB-N; Rao, 1990). A pseudo-random series of 60 auditively presented numbers from 1 to 9 have to be added in pairs, such that each number is added to the one that directly precedes it. Numbers of correctly calculated pairs were recorded. Short-term memory (STM) was evaluated by using the block-span forward (visuo-spatial STM) and the digit-span forward (verbal STM) from the WMS-R. In both tests number of correct items were calculated. For visual long-term memory (LTM) the Spatial Recall Test from the BRB-N was assessed, measuring visuo-spatial learning by the number of recalled responses. The Symbol Digit Modalities Test (SDMT; Smith, 1973) was applied to assess mental speed. Using a reference key, the examinee is given 90 seconds to pair specific numbers with given symbols. Numbers of correct items were calculated. Executive functions were measured by using the Regensburger Word Fluency Test (RWT; Aschenbrenner, Tucha, & Lange, 2000). Scores for correct items under the semantic condition were taken to measure verbal fluency. For figural fluency, cognitive flexibility and planning, the 5-point Test (Regard, Strauss, & Knapp, 1982) was used. Number of correct items and strategy points were counted.

RESULTS

Participants

All participants completed the training. Overall compliance and motivation was high. Table 1 lists sex, age, education and baseline characteristics of the three participant groups. The groups were compared using a Kruskal-Wallis one-way analysis of variance. There were no significant differences

TABLE 1
Demographical and baseline characteristics of participants in the two training groups and the control group

	Participants						
	High intensity training (n = 12)		*Distributed training (n = 12)*		*Without training (n = 12)*		*p Value*[t]
Sex:							
Men	4		4		4		
Women	8		8		8		
Age (years) M (*SD*)	36.50	12.63	39.83	17.89	41.62	14.90	0.84
Education[+] M (*SD*)	4.08	.91	4.08	.51	3.69	.63	0.27
Working memory							
Block span backward	8.54	2.30	7.71	0.91	9.08	1.58	0.33
Digit span backward	7.20	2.38	7.25	0.81	6.45	2.05	0.28
2-back task reaction time	834.52	263.72	659.48	140.18	796.01	297.39	0.34
2-back task correct responses	55.04	3.45	55.95	3.96	55.58	2.74	0.41
3-back task reaction time	869.15	280.50	729.73	63.88	897.08	288.67	0.28
3-back task correct responses	52.16	2.52	50.67	2.84	52.58	2.38	0.19
PASAT	53.04	5.81	53.20	8.59	49.58	9.81	0.53
Short-term memory							
Block span forward	9.33	1.64	8.67	1.23	8.62	1.38	0.53
Digit span forward	8.08	1.97	7.62	1.24	7.54	2.29	0.48
Long-term memory							
Spatial recall test	24.29	4.75	25.33	3.76	24.70	3.07	0.77
Mental speed							
SDMT	59.54	11.83	61.37	15.57	58.58	11.12	0.96
Executive functions							
5-point test correct responses	38.33	7.85	38.87	11.07	42.41	12.55	0.74
5-point test strategy points	23.20	8.25	22.70	11.68	28.25	9.88	0.45
RWT semantic condition	40.91	6.08	41.41	7.00	44.58	12.11	0.89

Note. [t]Kruskal-Wallis comparison. [+]Education: 0 = No school diploma, 1 = Junior school, 2 = Apprenticeship, 3 = Secondary level, 4 = Advanced level, 5 = University degree. PASAT = Paced Auditory Serial Addition Test; SDMT = Symbol Digit Modalities Test; RWT = Regensburger Word Fluency Test.

between the groups in relation to sex, age, or educational level. Baseline screening in the test battery also showed no significant differences between the groups.

Training tool BrainStim

Log files recorded during training (measuring duration of training, accuracy, reaction times and levels of difficulty achieved by individuals) revealed that participants in both intervention groups (distributed training and high

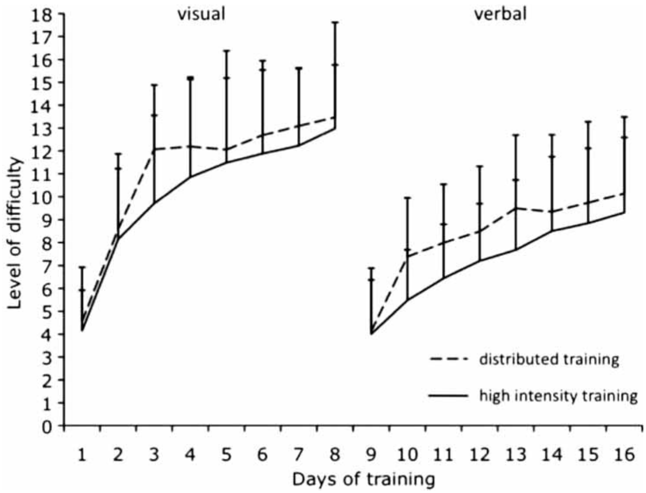

Figure 1. Averaged achieved performance of the participants in the two different training groups (high intensity and distributed training) in the module City Map. City Map with visual instructions is represented by days 1–8 of training; City Map with verbal instructions is represented by days 9–16 of training. Level of difficulty = level reached after a defined number of consecutively correct responses. Days of training = number of accomplished training sessions. Error bars indicate standard deviation. Maximum level of difficulty was 15.

intensity training) were able to master increasing levels of difficulty in all three modules as training progressed. Figures 1 to 3 show the averaged performance of participants in the two training groups and the highest level possible in the three modules. In the module Memorise Numbers the increase in performance for both groups was comparable as the two training graphs showed a similar ascent. In the module City Map with visual and verbal instruction and in the module Find Pairs the average achievement of the participants in the distributed training was up to one level higher as training progressed compared to participants in the high intensity training. Additionally, participants in the distributed training in the module City Map with verbal instructions demonstrated faster mastering of difficulty levels at the beginning of training.

Visual inspection of the individual training curves revealed that training effects were not based on outliers but were similar between subjects.

Cognitive test battery

Table 2 shows means, standard deviations and effect sizes of the test battery for all three participant groups at baseline and after training (for participants without training, after 4 weeks, respectively). Since the number of

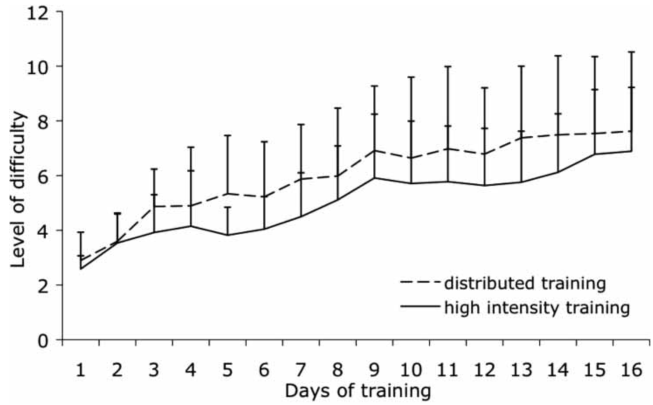

Figure 2. Averaged achieved performance of participants in the two different training groups (high intensity and distributed training) in the module Find Pairs. Level of difficulty = level reached after a defined number of consecutively correct responses. Days of training = number of accomplished training sessions. Error bars indicate standard deviation. Maximum level of difficulty was 9.

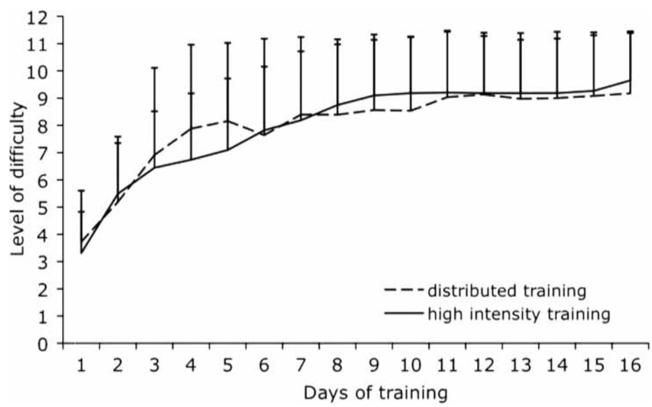

Figure 3. Averaged achieved performance of participants in the two different training groups (high intensity and distributed training) in the module Memorise Numbers. Level of difficulty = level reached after a defined number of consecutively correct responses. Days of training = number of accomplished training sessions. Error bars indicate standard deviation. Maximum level of difficulty was 19.

participants in each group was too small to allow for multiple comparisons, the first step of our analysis consisted of a descriptive approach. Pre/post-effect sizes were calculated using Cohen's *d* (mean change in the variable of interest over the standard deviation of the differences between baseline

TABLE 2

Means, standard deviations and effect sizes for pre- and posttesting in the different cognitive tests of participants in the three groups (high intensity training, distributed training and without training)

Participants									
	High intensity training (n =12)			*Distributed training (n =12)*			*Without training (n = 12)*		
	Baseline	*After 4 weeks*		*Baseline*	*After 8 weeks*		*Baseline*	*After 4 weeks*	
Test battery	*M(SD)*	*M(SD)*	*d*	*M(SD)*	*M(SD)*	*d*	*M(SD)*	*M(SD)*	*d*
Working memory									
Block span backward	8.54 (2.30)	8.42 (2.19)	0.08	7.71 (0.91)	9.5 (1.44)	0.97	9.08 (1.52)	8.58 (2.19)	0.35
Digit span backward	7.20 (2.38)	7.66 (2.34)	0.33	7.25 (0.81)	8.16 (2.03)	0.46	6.45 (2.05)	6.58 (3.11)	0.08
2-back task reaction time	834.52 (263.72)	716.67 (183.64)	0.70	659.48 (140.18)	554.79 (129.13)	1.20	796.01 (297.39)	740.17 (322.25)	0.41
2-back task correct responses	55.04 (3.45)	56.670 (4.11)	0.83	55.95 (3.96)	58.00 (2.33)	0.73	55.58 (2.74)	57.17 (1.81)	0.57
3-back task reaction time	869.15 (280.50)	785.53 (204.21)	0.43	729.73 (221.31)	634.47 (205.29)	0.98	897.08 (288.67)	760.93 (327.16)	0.87
3-back task correct responses	52.16 (2.52)	52.67(3.45)	0.28	50.67 (2.85)	52.00 (4.09)	0.40	52.58 (2.38)	52.17(4.91)	0.10
PASAT	53.04 (5.82)	54.25 (7.02)	0.28	53.21 (8.59)	56.67 (3.77)	0.50	49.58 (9.81)	50.33 (10.64)	0.12
Short-term memory									
Block span forward	9.33 (1.64)	9.50 (2.64)	0.09	8.67 (1.23)	9.25 (1.81)	0.52	8.62 (1.38)	8.75 (1.81)	0.09
Digit span forward	8.08 (1.97)	8.33 (2.18)	0.23	7.62 (1.24)	8.92 (2.19)	0.70	7.54 (2.29)	7.33 (2.90)	0.13
Long-term memory									
Spatial recall test	24.29 (4.75)	26.75 (4.35)	0.75	25.33 (3.76)	28.25 (2.8)	0.77	24.70 (3.07)	25.67 (4.59)	0.23
Mental speed									
SDMT	59.54 (11.83)	64.25 (12.88)	1.27	61.37 (15.57)	74.75 (20.33)	1.45	58.58 (11.12)	62.08 (14.24)	0.73
Executive functions									
5-point test correct responses	38.33 (7.85)	40.91 (7.59)	0.53	38.87 (11.07)	44.33 (10.77)	1.09	42.42 (12.55)	44.75 (12.92)	0.49
5-point test strategy points	23.21 (8.25)	24.58 (3.11)	0.22	22.71 (11.86)	28.75 (12.20)	0.89	28.25 (9.88)	30.83 (10.79)	0.38
RWT semantic condition	40.91 (6.08)	42.58 (6.4)	0.27	41.41 (7.01)	43.83 (9.45)	0.55	44.58 (12.11)	42.83 (9.29)	0.25

Note. M = mean, *SD* = standard deviation, *d'* = Cohen's *d'*. PASAT = Paced Auditory Serial Addition Test; SDMT = Symbol Digit Modalities Test; RWT = Regensburger Word Fluency Test.

and post-test; Cohen, 1988). In the high intensity training group, medium ($d > 0.5$) to large effect sizes ($d > 0.8$) were found for the 2-back task (WM), spatial long-term memory, mental speed and for one of the executive functions, indicating some positive training effects. In the distributed training group medium to large effect sizes were found for nearly all indicators of working memory (block span backward, 2-back task, 3-back task, PASAT), the two measures of short-term memory, the spatial long-term memory task, mental speed and for all measures of executive functions, indicating general and broad positive training effects. In contrast, in the group without training, medium to large effect sizes could only be found for two working memory indicators and for mental speed while all other tests revealed small to no effect sizes or slight deterioration in performance in the post-test. Detailed information about performance change between pre- and post-tests is given in Table 2.

In addition, Figure 4 gives a qualitative and visual illustration of training effects found in our study by effect sizes of pre/post mean differences. Negative values imply a decrease in performance in the post-test compared to baseline while positive values reflect an increase. As can be seen, a decrease in performance was only found in the non-trained control group concerning the tests block span backward, 3-back correct responses, digit span forward and RWT semantic condition.

In the second step of our analysis, a 3 x 2 mixed ANOVA with the three participant groups as between-subjects factor and baseline-post-test results as within-subjects factor was applied. Interaction-contrasts were performed to explore whether the difference between baseline and post-test results was larger in the two training groups than in the control group and whether this difference was larger in the high intensity training group compared to the distributed training group (see Table 3). An alpha level of .05 was adopted for all statistical tests. The interaction-contrasts of the differences between baseline and post-test results when comparing the high intensity training group to the control group revealed no significant results. Analysis of differences between baseline and post-test results when comparing the distributed training group to the control group revealed significant improvements in three of the WM indicators (block span backward, digit span backward, 3-back task accuracy), one of the STM indicators (digit span forward) and mental speed (SDMT). When comparing the distributed training group to the high intensity training group significant differences between pre- to post-test results were also found in the above-mentioned tests, indicating a superiority of the distributed training (see Table 3 for details).

TABLE 3
Interaction-contrasts to test if the difference between baseline- and post-test results is larger a) in the training groups compared to the control group, and b) in the high intensity training compared to the distributed training group

	Contrasts					
	(BL-PT)x(CG-HIT)a		*(BL-PT)x(CG-DT)a*		*(BL-PT)x(HIT-DT)b*	
Test battery	*t*	*Partial eta-square*	*t*	*Partial eta-square*	*t*	*Partial eta-square*
working memory						
Block span backward	0.60	0.01	2.85**	0.20	2.25**	0.13
Digit span backward	0.54	0.01	2.22**	0.13	1.68*	0.08
2-back reaction time	1.15	0.04	0.00	0.00	1.15	0.04
2-back accuracy	0.03	0.00	1.29	0.05	1.33	0.05
3-back reaction time	0.68	0.01	1.10	0.04	0.42	0.01
3-back accuracy	0.65	0.01	2.18**	0.13	1.53**	0.07
PASAT	0.20	0.00	1.26	0.05	1.07	0.03
Short-term memory						
Block span forward	0.07	0.00	0.77	0.02	0.70	0.01
Digit span forward	0.78	0.02	2.84**	0.20	2.06**	0.11
Spatial recall test	1.11	0.04	1.05	0.03	0.06	0.00
Mental speed						
SDMT	0.46	0.01	2.10**	0.12	1.64*	0.08
Executive functions						
5-point test correct responses	0.14	0.00	0.02	0.00	0.16	0.00
5-point test strategy points	0.48	0.01	0.62	0.01	0.13	0.00
RWT semantic condition	1.31	0.05	0.54	0.01	0.76	0.02

BL = baseline; PT = post-test; CG = control group; HIT = high intensity training; DT = distributed training; all tests performed with DF = 33; $^{*}p < .05$; $^{**}p < .01$

DISCUSSION

Application of cognitive brain training in terms of effective CNS treatment is still controversial (Owen et al., 2010). However, as long as there are studies showing evidence of beneficial effects on healthy subjects and patients with different pathologies it is worthwhile directing our focus on this research field.

Yet there is no consensus with regard to optimal dosage and frequency of cognitive intervention, thus the present study aimed at evaluating two different training schedules with the computerised working memory training BrainStim (Penner et al., 2006) in healthy participants. Results from the cognitive test battery confirmed a positive effect for enhancing cognitive performance

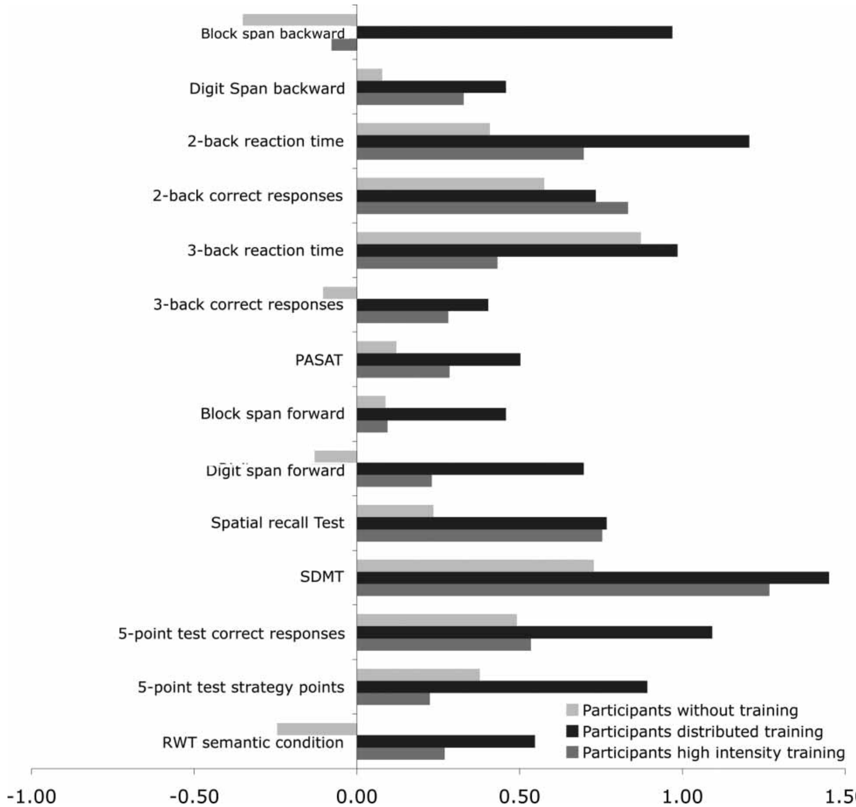

Figure 4. Illustration of changes in cognitive performance when comparing baseline and post-treatment test results for the applied cognitive tests. Performance changes are calculated by effect sizes for the different cognitive test measures and the three participant groups, respectively. Negative values demonstrate deterioration in the post-test performance compared to baseline. Positive values reflect improvement in performance.

in participants in both training groups compared to controls without training. However, by comparing medium to strong effect sizes in the outcome measures, there is a clear tendency that a more distributed training improves performances in more outcome measures than a high intensity training. Participants in the distributed training (8 weeks, 2 times a week for 45 minutes) improved their performance in 12 out of 14 outcome measures by medium to strong effect sizes, while participants in the high intensity training (4 weeks, 4 times a week for 45 minutes) improved with medium to strong effect sizes in five outcome measures. This result is in accordance with study results on learning behaviour. Distributed learning has been shown to be superior to massed learning and it has been suggested that the time interval between learning sessions is responsible for this discrepancy (Baddeley & Longman, 1978). While during distributed learning the CNS has time to consolidate and to recreate, massed learning causes stress, leads to increased exhaustion and decreased motivation (Terry, 2003). More recent results from studies on working memory training also showed a superiority of longer training periods and its effects on training success (Jaeggi et al., 2008; Olesen et al., 2004).

In our study, the strongest effect ($d \geq 1.45$) was found in the distributed training group for a test measuring primarily mental speed (SDMT). This finding goes along with other studies that found increased processing speed after cognitive training (Jaeggi et al., 2008; Olesen et al., 2004). It can be suggested that training with BrainStim facilitates the ability to control attention, as the constant updating of information and representation of new information engages mechanisms of shifting attention by the central executive. In fact, since the training is adaptive, it prevents automatisation of cognitive processes by continuously challenging "online capacities". By persistently doing so, it seems that participants were able to expand their performance to maintain more targets in working memory at once, leading to a faster selection among the stimuli in the task.

Large effect sizes ($d \geq 0.8$) for participants in the distributed training were also found in the block span forward, in the 2-back and 3-back task for reaction times (indicating also an increase in performance in mental speed) and in the 5-point test measuring executive functions. Participants in the high intensity training revealed two large effect sizes, in the SDMT and in the 2-back task for correct responses. This advantage in favour of a distributed training might result from a more continuous stimulation of neuronal circuits responsible for visuo-spatial learning mechanisms. In fact, rodent studies have shown that exercise influenced mRNA expression of brain-derived neurotrophic factor (BDNF) in an intensity-dependent manner. Enhanced neurogenesis in the dentate gyrus of the hippocampus was induced by low-, but not by high-intensity exercise (Lou, Chang, & Chen, 2008). Consistently, gene expression levels in the low-intensity exercise group were greater than in the high-intensity group for nerve growth-associated molecules. Thus, low-intensity, but extended training as practised in the distributed training group might have resulted in optimisation of specific processes such as visual aspects of working memory, processing speed, executive functions and shifting of attention by the aforementioned neurodynamic processes. Comparing these results to performance of participants without training there seems to be more of an intervention effect than only producing a generic improvement due to increased focusing or motivational stimulation. Furthermore, as for all participants baseline testing was done twice to control for possible learning effects and no significant differences in performance between the groups were found, one could assume that improvements in performance may be predominantly ascribed to a specific treatment with BrainStim.

The present work extends beyond already existing cognitive treatment studies by investigating not only two distinct training schedules but also by analysing log files recorded during training. The evaluation of log files recorded during training showed a superiority for the distributed training compared to the high intensity training. Although both intervention groups demonstrated an increase in all three training modules, participants in the distributed training achieved on average one level higher at the end of training in the module City Map with visual and verbal instructions and in the module Memorise Numbers. Moreover, in the module City Map with visual instructions there was also a faster improvement in performance in the first training sessions for the latter group.

When training curves were inspected more carefully it became obvious that the first relevant discrepancy between the distributed and high intensity training group emerged between the third and fourth training sessions and remained almost stable over time. This result very nicely illustrates the advantage of distributed learning. While subjects in the distributed training group had two weeks for consolidating learned information of 4 training sessions, subjects in the high intensity training group had a maximum of one week (4 sessions within 1 week). Obviously, the CNS is less able to use learned information in this short period of time because consolidation is insufficient.

When interaction contrasts were performed to clarify whether the difference between baseline- and post-test results was larger (a) in the training groups compared to the control group, and (b) in the high intensity training compared to the distributed training group, it appeared that regardless of the small sample size, five cognitive tests still revealed a significant increase in performance after the training. These tests referred to verbal and visual working memory, verbal short-term memory and speed. Thus, our results support the assumption of a specific training effect rather than a global one since verbal short-term memory and speed are also components of the working memory system. Moreover, the distributed training group had a disproportionately higher overall training effect compared to the other two groups, indicating not only an advantage of a prolonged training strategy on specific outcomes but also a higher transfer effect on other cognitive domains. The finding that in the interaction contrasts the executive function domain did not become significant, even though effect sizes were strong, might be explained by a high intercorrelation of values between time point one and two in the distributed training group. This means that the effect size is much higher than in the control group but that there is no interaction between these two conditions. The control group without training only showed three medium to strong effect sizes and deterioration in performance from pre- to post-test in four outcome measures.

There are several limitations that need to be addressed regarding our study. The first limitation lies in the lack of long-term effects of training. In fact, our study does not address whether the documented training effects will persist over extended time periods. Further longitudinal studies with follow up tests will have to be performed to investigate the long-term effects of the training programme and to document durability of the results with regard to outcome measures. Second, we do not know from our results whether an even more extended and longer training would have resulted in even better outcomes. Third, the participants' age range was wide in our study and the sample size was too small to run subgroup-analyses to control for age-related training effects. Fourth, there is a need for replicating and extending our findings, possibly on everyday-related abilities. Thus, since our study reports only on primary outcomes which are thought to be of greatest importance, further studies should also contain data on secondary outcomes such as everyday memory variables to evaluate the ecological significance of the intervention.

Fifth, our control group without training was a non-active control group, meaning that they were not confronted with an alternative intervention to be compared to the specific working memory training. Thus, control for potential effects during the waiting period was handled less stringently than in other studies. Sixth, allocation of subjects to the three study groups was not randomised. Instead, subjects were allocated based on their demographic data to make results comparable for age, sex and educational level.

In conclusion, the present study adds some interesting and helpful information on the dosage of cognitive training and its effectiveness. Future therapeutic interventions may apply the computer program BrainStim to patients with neurodegenerative diseases or elderly people with memory complaints. Even if there is a great inter-individual variability in age of onset and the course of cognitive loss, most older adults experience non-pathological impairments in cognitive function and these deficits can often be ascribed to working memory being the function responsible for the reduction in performance associated with ageing. Although non-pathological memory loss may not profoundly affect activities of daily living, mild reductions in cognitive functions can already put them at risk for loss of fluid abilities, thus having a negative impact on people's quality of life and negatively influencing engagement in cognitively stimulating activities and reducing the motivation to learn new skills.

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