



## Better than sleep: Theta neurofeedback training accelerates memory consolidation



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### ABSTRACT

Consistent empirical results showed that both night and day sleep enhanced memory consolidation. In this study we explore processes of consolidation of memory during awake hours. Since theta oscillations have been shown to play a central role in exchange of information, we hypothesized that elevated theta during awake hours will enhance memory consolidation.

We used a neurofeedback protocol, to enhance the relative power of theta or beta oscillations. Participants trained on a tapping task, were divided into three groups: neurofeedback theta; neurofeedback beta; control. We found a significant improvement in performance in the theta group, relative to the beta and control groups, immediately after neurofeedback. Performance was further improved after night sleep in all groups, with a significant advantage favoring the theta group. Theta power during training was correlated with the level of improvement, indicating a clear relationship between memory consolidation, and theta neurofeedback.

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### 1. Introduction

Improving memory has been a long-time quest. A large body of evidence points to night sleep as playing a central role in consolidation of memory (e.g. Dudai, 2004; Rauchs, Desgranges, Foret, & Eustache, 2005; Stickgold, 2005). More recent evidence points to day-time-naps as supporting memory consolidation (Korman, Doyon, et al., 2007). The central question in this study is whether consolidation of memory occurs during awake hours, and if so, what conditions support consolidation without day sleep. We consider the potential role of theta rhythms engaged in the hippocampal/PFC (prefrontal cortex) interplay in consolidation of memory and report empirical results on the effect of enhanced theta oscillations on memory consolidation.

It is widely accepted that memory consolidation process happen off-line, after the initial hippocampus encoding event. Consolidation relies on the re-activation of neuronal circuits that were implicated in the initial encoding (Albouy et al., 1995). Recent accumulating research provides consistent support for the central role of sleep in memory consolidation, suggesting that some forms of declarative and hippocampus-mediated memories are consolidated across periods of sleep (Censor et al., 2006; Diekelmann

& Born, 2010; Karni, Tanne, Rubenstein, Askenasy, & Sagi, 1994; Stickgold, 2005; Walker, 2005). A meta-analysis of sleep and delayed procedural memory-consolidation, showed correlations of 0.56–0.95 between sleep and memory consolidation, “explaining an average across studies of 69% of the variance” (Stickgold, 2005, p. 1277). Another meta-analysis (Stickgold, 2005, p. 1273) of night sleep and memory consolidation across varying tasks showed T1ing improvement following night-sleep, and no similar effects during an equivalent period of being awake. These sleep-dependent processes of memory enhancement continue for at least 24–96 h (Stickgold, 2005).

Experimental evidence suggests that motor memory formation occurs in two subsequent phases (Albouy et al., 1995; Dudai, 2004; Karni et al., 1994; Luft & Buitrago, 2005). The first is initial encoding of experience during training that occurs within the first minutes-to-hours after training, and is characterized by rapid improvement in performance. This initial encoding occurs in all memory systems studied so far. The second phase is memory consolidation, and involves a series of systematic changes at the molecular level, that occur after training. This second phase requires longer time. During consolidation, memories are reorganized and hippocampus-dependent initial memories may become hippocampal-independent (Albouy et al., 1995; Maquet, 2008). Processes of reactivation of memories lead to renewed consolidation each time reactivations occur, enhancing the first consolidated memory representation, and converting it into a long-lasting stable

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memory trace (Dudai, 2004). Delayed additional gains occur after the second phase, even without additional practice (Karni et al., 1994).

Of the two stages above, it is the delayed gains in memory consolidation, that have been found to be highly dependent on night sleep (Albouy et al., 1995; Fischer, Hallschmid, Elsner, & Born, 2002; Karni et al., 1994, 1998; Maquet, 2001; Stickgold & Walker, 2005; Stickgold, Hobson, Fosse, & Fosse, 2001; Walker & Stickgold, 2004). For instance, both speed and accuracy of sequential motor tasks such as the Finger Tapping Task (FTT) (e.g. Karni et al., 1994; Korman, Raz, Flash, & Karni, 2003), were significantly improved after night sleep. Short day sleep might be effective too (Mednick, Nakayama, & Stickgold, 2003). Just a 90-min day nap led to delayed gains of about 10% improvement in motor performance, followed by additional improvement of about 10% after a night sleep (Korman et al., 2007). Which unique sleep-specific processes contribute to memory consolidation, and which sleep stage/processes are responsible for motor memory consolidation, are still open questions. Overnight memory improvements showed a strong relationship with NREM sleep (Walker, Stickgold, et al., 2005) and with early sleep (Fischer, Nitschke, Melchert, Erdmann, & Born, 2005; Gais, Plihal, Wagner, & Born, 2000). Also, it seems that sleep spindles might have an important role in motor memory consolidation (Nishida & Walker, 2007; Schabus et al., 2004). Stage II NREM is characterized by slow (4–8 Hz) theta rhythm oscillations (Mizuseki et al., 2009), hinting at a potential role of theta oscillations in sleep-dependent motor memory consolidation.

Neural oscillations, in general, have been assumed to play a central role in cognitive processes. Specific oscillatory rhythms and synchronicity are correlated with changes in specific cognitive processes, (Herrmann, Munk, & Engel, 2004; Keizer, Verment, & Hommel, 2010; Zoefel, Huster, & Herrmann, 2011), and separate frequency bands have different roles in enhancement of distinctly different cognitive processes, such as mental rotation (Hanslmayr, Sauseng, Doppelmayr, Schabus, & Klimesch, 2005; Klimesch, Sauseng, & Gerloff, 2003), object detection (Engel, Fries, & Singer, 2001; Salari et al., 2012) mediating attention (Lakatos, Karmos, Mehta, Ulbert, & Schroeder, 2008; Schroeder & Lakatos, 2009), working memory and memory consolidation (Klimesch, 1999; Jaušovec & Jaušovec, 2012). States of phase synchronization are considered a mechanism of increased communication between regions (Fell & Axmacher, 2011; Varela, Lachaux, Rodriguez, & Martinerie, 2001; Womelsdorf et al., 2007).

Several lines of evidence suggest that theta oscillations play an important role in formation of memory: theta oscillations are typical of hippocampal activity, upon memory encoding, generating oscillations which can propagate to other brain structures (even relatively distant), supporting memory consolidation and are thought to play a critical role in the induction of long-term plasticity, associated with memory consolidation (Chauvette, 2013; Kropotov, 2008). Theta rhythms are correlated with episodic and semantic memory (Buzsáki, 2005; Guderian & Duzel, 2005; Kahana, 2003) and are involved in learning and memory within the mPFC (medial prefrontal cortex) and hippocampal system (Anderson, Rajagovindan, Ghacibeh, Meador, & Ding, 2010; Benchenane et al., 2010; Steinvorth, Wang, Ulbert, Schomer, & Halgren, 2010). Frontal-midline theta seems to be correlated with processing of memory in general, and specifically with working memory and/or sustained attention (Mitchell et al., 2008); Theta coordination in the limbic system in mice is reported to influence inter-individual differences in memory consolidation of aversive experiences (Popa, Duvarci, Popescu, Léna, & Paré, 2010). Fear memory consolidation and retention in humans shows enhanced theta phase synchronization between the hippocampus and amygdala during the retrieval of the fear memory (Moses et al., 2007; Nishida, Pearsall, Buckner, & Walker, 2009). Theta synchronization between the hippocampus

and remote areas must then happen, in the processes of memory consolidation depending on the type of memory.

Several studies point to theta synchronization as a mechanism underlying communication between the hippocampus, the ventromedial prefrontal cortex and remote memory areas, during consolidation. The underlying mechanism is still not clear. One attempt to explain the mechanism of memory consolidation is known as the “system-level memory consolidation theory” (Nieuwenhuis & Takashima, 2011). This model suggests that the hippocampus is strongly activated in the first stages of memory-related neocortical formations, but gradually new forms of memory become independent of hippocampal activations, and consolidation correlates with increased activation in the human subgenual ventromedial prefrontal cortex (vmPFC). The vmPFC, similar to the anterior cingulate cortex, seems to link the neocortical representational areas in remote memory (Maquet, 2008; Nieuwenhuis & Takashima, 2011). According to this approach, the hippocampus and vmPFC access distributed representations. Whether it is transferred from the hippocampus to the neocortex, or whether the trace is replicated repeatedly to consolidate the memory trace, is not clear (Battaglia, Benchenane, Sirota, Pennartz, & Wiener, 2011). The system-level memory consolidation view, implies exchange of information in a network of brain areas. The center is the hippocampus and the communicating areas include the neocortex and structures such as the amygdala and the striatum (Battaglia et al., 2011; Maquet, 2008). The interaction between the hippocampus and striatum resembles the interaction between the hippocampus and neocortex (Battaglia et al., 2011). This exchange is theorized to be linked to theta oscillations: hippocampal cells fire preferentially at a specific theta phase (Mizuseki et al., 2009; Klausberger et al., 2003), and so do areas in the medial temporal lobe and other areas that exchange information with the hippocampus. Thus theta is assumed to regulate information exchange between the hippocampus and striatum (for a review see Battaglia et al., 2011). This exchange of information extends to relatively distant sensory and associative areas of parietal cortex, which are also entrained by theta (and gamma) oscillations (Sirota et al., 2008). Exchange of information is based on a dynamical evolving schema, in which synchronized discharge of cell assemblies across brain structures are orchestrated by theta to encode information. Recent results further support the central role of the hippocampus–striatum exchange in motor memory consolidation, and suggest that the interplay between the striatum and the hippocampus during motor training conditions subsequent motor sequence memory consolidation, which is further supported by reorganization of cerebral activity in hippocampo–neocortical networks after sleep (Albouy et al., 2013). The ventral striatum is involved in learning beyond memory consolidation and was found to be related to individual variations in learning performance (Vink, Pas, Bijleveld, Custers, & Gladwin, 2013). Note that the results cited here are based mainly on human studies, simply since in animals, theta can reliably be measured from the hippocampus, but in humans it cannot, and the relation between animal theta originating from the hippocampus and human theta recorded at the scalp is not obvious.

Following these findings, we adopt a system-level memory consolidation view, suggesting a two level process of memory: first formation in the hippocampus, then formation of neocortical structures that are hippocampus independent. Theta is suggested to regulate exchange of information between the hippocampus and the neocortical areas for memory consolidation. We hypothesize that enhanced theta supports exchange of information between the hippocampus and neocortical areas during consolidation of memory, hence will be reflected in indicators of memory consolidation. In the current study we used a neurofeedback paradigm for training subjects to manipulate the power of theta and compare with two control groups: one manipulating beta (instead of theta)

and the other with no neurofeedback processes. We study the differences in: (a) motor performance before/after users increase power of theta or beta, (b) after night-sleep and increased power of theta/beta, (c) Differences in the 'time window of enhancement' i.e. for how long is an enhancement effect still reflected in measures, after theta neurofeedback? and (d) Correlation between power of theta and level of performance. Our experimental design follows that of day-nap effects on consolidation of memory (Korman et al., 2007). They found that a 1-h nap enhances consolidation processes and lead to improved performance immediately after day sleep and additional improvement after night sleep. We used a similar design and replaced day-nap by neurofeedback training (NFT) protocols, described in detail below.

## 2. Methods

### 2.1. Participants

Thirty-eight volunteers, half males, half females, aged between 25 and 35, participated in the study for payment. Participants were right-handed ( $R > 0.7$  by Edinburgh Handedness Inventory), had no medical conditions and no medications and reported more than 6 h of regular sleep per night before and during the week of the experiment, and had no sleep disruptions. Musicians and professional typists were excluded. Subjects were unaware of the goals of the experiments.

### 2.2. Protocols

We use a brain computer interface system to provide users with feedback on their neural oscillations. This is the basis for neurofeedback training (NFT), and is defined as the process whereby individuals learn how to control the amplitude, frequency, synchrony, or other derived measures of the electrical activity of their own brain (Gruzelier, 2009; Kropotov, 2008). NFT, as an operant conditioning method to control one's own brain activity, is applied here for training participants to enhance the power of their theta waveband. NFT with a restricted number of electrodes has been shown to be effective and a wide range of experimental studies have applied NFT paradigms with single or double active electrodes (Barnea, Rassis, & Zaidel, 2005; Gruzelier, Egner, & Vernon, 2006; Hammond, 2007; Keizer et al., 2010; Vernon, 2005). NFT with single/double electrodes have been widely used and reported in the context of microsurgical skills, artistic and dance performance which were improved by training for theta/alpha ratio over parietal electrodes (Pz) (Gruzelier, 2009; Gruzelier et al., 2006). Gruzieler (2009) associated increased parietal theta (recorded from the Pz channel) with increased activity in the hippocampus. Parietal theta synchronization was also found to be correlated with retrieval (Jacobs, Hwang, Curran, & Kahana, 2006; Sauseng, Klimesch, Schabus, & Doppelmayr, 2005). Thus we use theta and beta NFT protocol over Pz, and compared the effect of theta NFT with beta NFT. Beta-waves are fast waves (15–22 Hz) with low amplitudes that are associated with alertness, attention and action. Beta and theta waves are viewed as non-overlapping in their frequency, and are drastically different, in the associated functionality. Hence beta NFT serves as a good control for theta. We expected a positive effect on learning after theta, but not (or to a lesser extent) in the beta group.

A widely used paradigm is SHAM protocols. We deliberately chose not to use the SHAM protocols due to the effect of learned helplessness (Abramson et al., 1978; Seligman, 1975). Learned helplessness occurs when users learn that nothing they did had any effect on success. Studies on both humans and animals show that previously learned helplessness leads to passive behavior, which is carried over to later events. It has been shown that learned helplessness may manifest itself as depression and anxiety (Hiroto & Seligman, 1975) Thus, it seems that SHAM protocols, may create an artificially low score, which may distort the results, and show a difference between the SHAM group and the experimental group, which may be due to the learned helplessness rather than the effect of theta.

### 2.3. Participants

#### 2.3.1. Design and setup

**Neurofeedback training:** The spectral distribution of the ongoing oscillatory brain activity was measured with an EEG electrode at Pz following Gruzelier's papers on peak performance (Egner & Gruzelier, 2003, 2004) and on theta/alpha protocols used by Peniston, Marrinan, Deming, and Kulkovsky (1993).

A visual feedback, indicating the estimated intensity, was displayed to the user visually, providing a base-line for the user to adapt to. Using a brain-computer interface (BCI) we calculated, in real-time, with negligible latency, the brain measures, and modified the visual display accordingly. A conditioning process allowed subjects to develop strategies of reaching and maintaining a desired electrophysiological state of the brain (Egner & Gruzelier, 2003, 2004). Participants were divided into three groups. Participants of each group went through a single NFT/control procedure: the first went through NFT session to increase theta waves (theta group);

**Table 1**  
Grouping and treatment.

Group	Treatment
Experimental – theta NFT	45 min of theta NFT
Control beta NFT	45 min of beta NFT
Control	45 min of watching movies

the second group was trained to increase beta (beta group) and a third (control) group watched movies for an equal period of time (Table 1 and Fig. 1).

All participants were tested immediately after motor training, immediately after NFT, after 24 and 48 h, and a week after the initial session. We measured the number of successfully completed sequences of FTT (Fig. 2), in four repetition of the performance-test, for each group, in each condition.

We expected changes in performance, reflected in number of accurate sequences, in all groups due to the effect of training during the test, and effects of sleep. If indeed theta oscillations have a role in memory consolidation, we expect improvement in performance following NFT in the theta group, but not in beta or control groups. In addition, we expected that this advantage in performance improvement would be stable for a while after the NFT session. Based on previous studies, we expected a small number of errors by all the subjects. Due to a ceiling effect, we expected no changes in accuracy.

Informed consent and approval from the ethics committee of the Technion (Israel Institute of Technology) was obtained before the experiment. Details on the ethics rules and procedures at the Technion can be viewed at <http://www.admin.technion.ac.il/Manlam/defaultEng.htm>.

### 2.4. Procedure

Each participant went through a performance test (T1) prior to the motor training session. Then went through a motor training session, followed by another test (T2). Participants went through a neurofeedback training (or watching movies), session followed by an additional performance test (T3). All participants were also tested after 24 h (T3), 48 h (T4) and a week after training and NFT (T5). The control group performed the same tests, in the same order. Instead NFT, the control group watched 2 short movies. Watching movies normally keeps motor actions to a minimum, and hence maintains a similar bodily state to the experimental group. All other conditions were kept identical: subjects in the control group sat on an identical chair with electrodes attached to the scalp (as if working), watching the movie on the monitors, similar to the conditions of the experimental groups.

### 2.5. Description of the motor task

FTT – Finger Tapping Task, task (Fig. 2) has been extensively used in previous studies of night sleep effects on memory consolidation (see for example Karni et al., 1994; Korman et al., 2003).

Each finger was assigned a number (Fig. 1). Participants were instructed to touch the thumb of their left (non-dominant) hand with the fingers of the same hand in the sequence: 4,1,3,2,4.

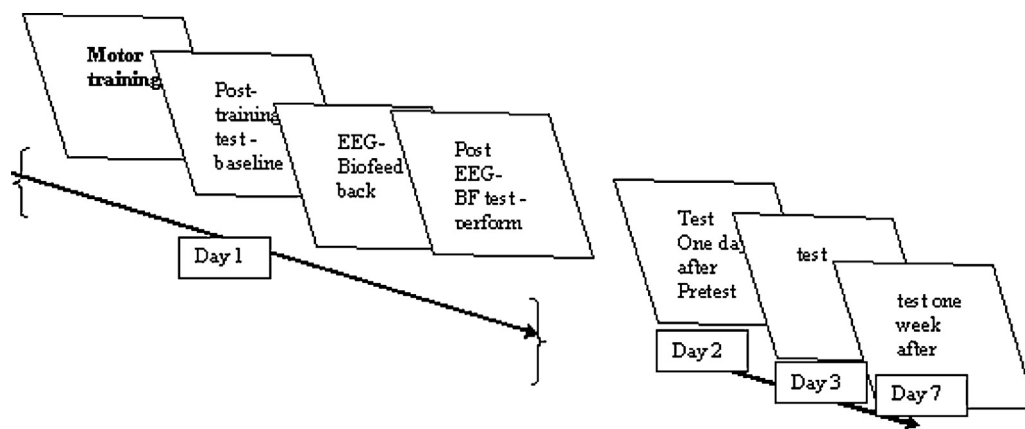
Participants performed the instructed movements while sitting comfortably. The arm was supported by a pillow. Visual feedback was not provided, i.e. the subjects could not see their fingers.

**Performance test:** Participants were cued to start the task by an auditory cue. They were instructed to continuously tap the sequence as rapidly and accurately as possible until given a stop signal. Each test consisted of four blocks of 30 s with a 50-s rest period between the blocks. Participants were instructed that occasional errors should not be corrected and to continue without disruption. The tests were recorded by a video camera, for future analysis.

**Motor training:** 160 repetitions of the assigned sequence (4,1,3,2,4) were divided into 10 training blocks. Each sequence was cued by an auditory signal at a rate of 0.4 Hz, so that the subject had 2.5 s per sequence after the cue. Training blocks were separated by 30 s breaks.

**NFT (neuro feedback training):** Each participant went through one session of NFT. Each session consisted of 10 rounds of 3 min each, a total of 30 min. EEG was recorded and the relevant frequency components were extracted.

Participants were asked to accelerate the car/robot 'by thought'. The feedback was provided when specific conditions (theta up or beta up) were satisfied for a minimum of 3 s. An auditory beep and a visual display of the speed of a car in a game like environment were presented on the screen for reinforcement. The participants received a feedback beep and saw their score each time the relevant wave-band (ratio) was raised. When the amplitude of the wave band did not change, no positive feedback was provided, i.e. the car did not accelerate, and the score did not rise. When the desired waveband decreased, or the undesired increased, participants received a negative feedback, i.e. the car decelerated proportionally, and the score went down proportionally.



**Fig. 1.** Experimental design: a first test, T1 was administered on the first day, prior to any manipulation. A second test, T2, was after motor training, and before the NFT session. A third test, T3, was administered after the NFT session. Additional tests (T3, T4, and T5) were performed on the second, third and seventh day, respectively. The control group watched movies for about 30 min, instead of an NFT session.

## 2.6. EEG measurement

We used the Deymed TruScan 32 EEG system for NFT. Sampling rate of signal acquisition was 256 Hz, and the band was filtered to extract delta (0–4 Hz), theta (4–8 Hz), alpha (8–12 Hz), low-beta (beta in the following) (12–15 Hz) and high beta 18–22 Hz components. We enhanced the theta band and suppressed the beta band in the theta group. In the beta group, we enhanced the beta band and suppressed the theta band. The intensity of the 18–22 Hz increases during motion. Thus we suppressed high beta (>18) during all NFT sessions in both experimental groups, to avoid positive feedback due to motion, and elimination of motion artifacts.

An active scalp electrode was placed at Pz, according to the standard of the 10–20 system. The reference electrode was placed on the right ear, and the ground electrode was placed on the left earlobe. Impedance was kept below 5 k $\Omega$ , and artifact-rejection thresholds were set individually for each participant so as to interrupt feedback during eye and body movements that produced gross EEG fluctuations. Threshold of 100  $\mu$ V was applied for artifacts.

## 2.7. Measures

### 2.7.1. Performance

The level of performance in each block is the number of successful sequences which were completed within 30 s. Each test consists of four trials. Performance in each test is the averaged number of successfully completed sequences in the four.

Performance during the second test (immediately after motor training) was defined as baseline performance.

### 2.7.2. Relative band power

In order to overcome the large inter-individual variance in absolute band power, through the entire statistical analysis we used values of the relative band power measures, i.e. theta/beta ratio. The ratio was calculated by dividing the average amplitude of theta by the average amplitude of beta during each session. In addition, we measured the change rate for every wave-band during the NFT session (slope) in order to analyze the correlations between changes in EEG and performance.

## 2.8. Statistical analysis

We set the baseline of performance as the results on the test after motor training, T2. We comprised the improvement between the groups on each test after the NFT session, as reflected by the relative change relative to the baseline. The baseline is the performance on the test after motor training and before NF (T1). The change ratio was calculated by the formula  $(T_x - T_1)/T_1 \times 100$ , where  $x = 2, 3, 4, 5$ .

We used GLM repeated measures and post hoc Tukey to reveal changes between the tests in each group and to compare these changes between the groups.

## 3. Results

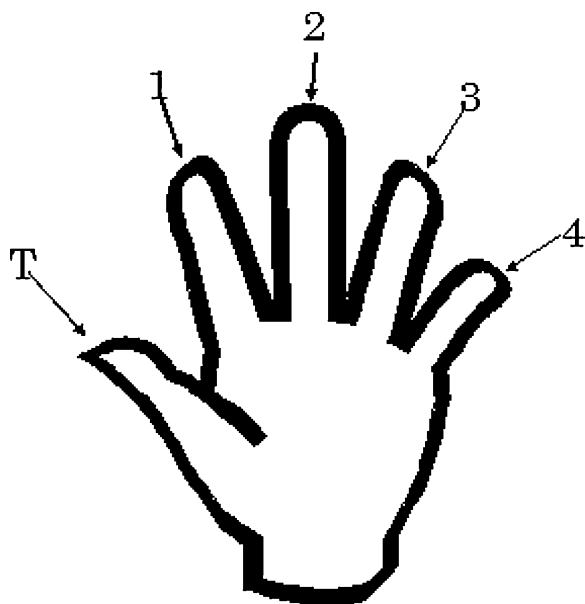
### 3.1. Changes in performance

GLM Repeated measures analysis was performed for the three aggregated groups, to identify differences within every block and between the blocks. We found significant differences [ $F(3,31) = 43.7, p < 0.01$ ] between the blocks in the first test in all groups, with significant improvement from block to block [ $M_1 = 15.3, M_2 = 17.4, M_3 = 18.9, M_4 = 19.8$ ]. Within the following tests (T1, T2, T3, T4, T5) the differences between blocks were not significant (Fig. 3).

Performance of all the groups was identical in first test, and remained so in the second test after motor training.

As expected, significant differences were found between performance in every test [ $F(4,30) = 69.4, p < 0.01$ ] in the whole sample, such that every new tested performance was better than the previous [ $M_1 = 17.9, M_2 = 22.5, M_3 = 25, M_4 = 26.4, M_5 = 27.3$ ].

Groups did not differ in their initial performance and post-motor-training performance (T0 vs T1) – all three groups overlapped in the pre/post training test (see Fig. 4). One-way ANOVA analysis was performed to reveal possible differences between the groups in the first test, the second test and in the rate of change from the first to the second test. As expected, there were no differences between the groups in the first test [ $F(2,31) = 0.05, n.s.$ ], the second test [ $F(3,21) = 0.1; n.s.$ ] and no difference in the rate of change from the first to second test [ $F(3,21) = 0.5; n.s.$ ].



**Fig. 2.** Description of the motor task: participants were asked to perform a sequence of finger movements – touching each finger by the thumb in a given sequence 4–1–3–2–4.

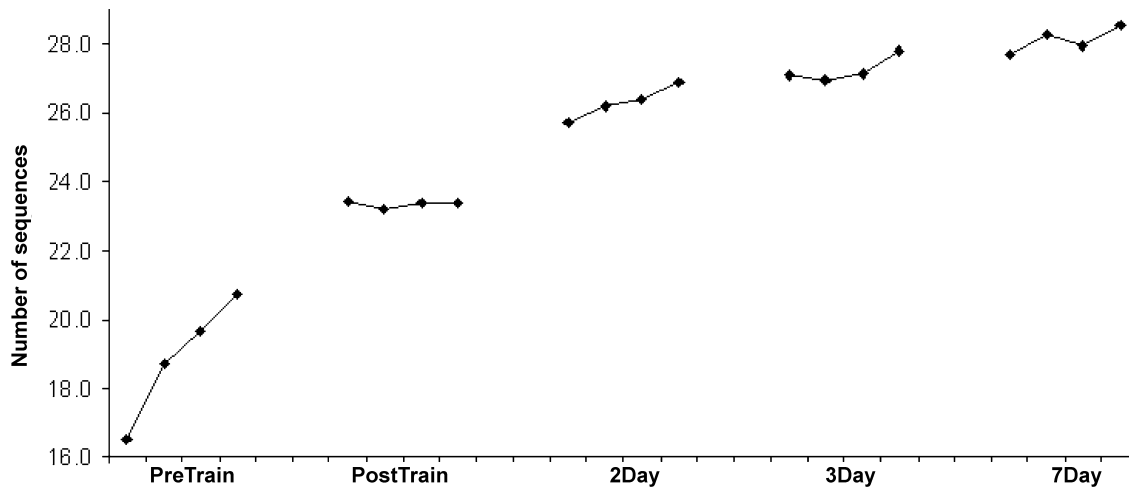


Fig. 3. Performance of the aggregated groups. Each point represents a single block. The test consists of four blocks.

### 3.2. Changes in performance in each group

To check changes in performance after NF in the theta group, GLM repeated measures analysis was performed. We combined the performance (averaged number of completed sequences) in the T2 test and T1 test. The post training, ‘T1’, test was used as a baseline for performance. The factors for GLM were – ‘Group’ (theta, beta or control) and ‘Time’ (before/after NF). As expected, the GLM model was significant [ $F(1,31)=6.4$ ;  $p < 0.05$ ], i.e. there was an effect of time (before NF or after NF) on performance. In addition, an interaction between ‘group’ and ‘test’ was found [ $F(1,31)=13.489$ ;  $p < 0.001$ ], indicating that the improvements measured at the different times were group dependent. Post hoc Tukey analysis revealed significant improvement in the theta group [ $F(1,11)=82.6$ ;  $p < 0.001$ ], but not in the beta group [ $F(1,11)=1.12$ ; n.s.] and control [ $F(1,9)=0.03$ ; n.s.] groups. The improvement in the theta group after NF was about 2 additional sequences [ $M(\text{postrain})=22.03$ ;  $M(\text{T2})=23.83$ ;  $\text{SEM}=1.9$ ], an 8.7% increase in comparison with the performance after T0ing-test. In the beta group there was a minor non-significant decrease in performance [ $M(\text{postrain})=22.72$ ;  $M(\text{T2})=22.29$ ;  $\text{SEM}=1.96$ ]. There was also a minor non-significant increase in performance in the control group [ $M(\text{postrain})=22.77$ ;  $M(\text{T2})=22.83$ ;  $\text{SEM}=1.7$ ]. The

dynamics of performance over time during the week of the experiment is shown in Fig. 4.

### 3.3. Differences between the groups in improvement rates

Improvement rate in each test is defined as the ratio of performance in the specific test and the baseline (T1 test). At every time-point there is a specific change in the ratio for every group. To reveal the differences between the groups in improvement rate at every time point, GLM repeated measure analysis was performed (T2, T3, T4, T5; theta, beta, Control).

The GLM model was found to be significant [ $F(3,29)=31.17$ ;  $p < 0.001$ ]. In accordance with our assumption, there was a significant effect of time on delayed gains [ $F(3,31)=70$ ;  $p < 0.001$ ]. Moreover, an interaction between group and time was found [ $F(6,56)=4.1$ ;  $p < 0.01$ ], indicating that the improvement attained at the different time points was group dependent. There were significant differences between groups in achieved delayed gains [ $F(2,31)=12.13$ ;  $p < 0.001$ ] (delayed gains are the number of additional sequences in comparison to the previous test). Post hoc Tukey analysis revealed that differences between groups were due to NFT protocol, the theta and beta groups [ $p < 0.001$ ] and between the

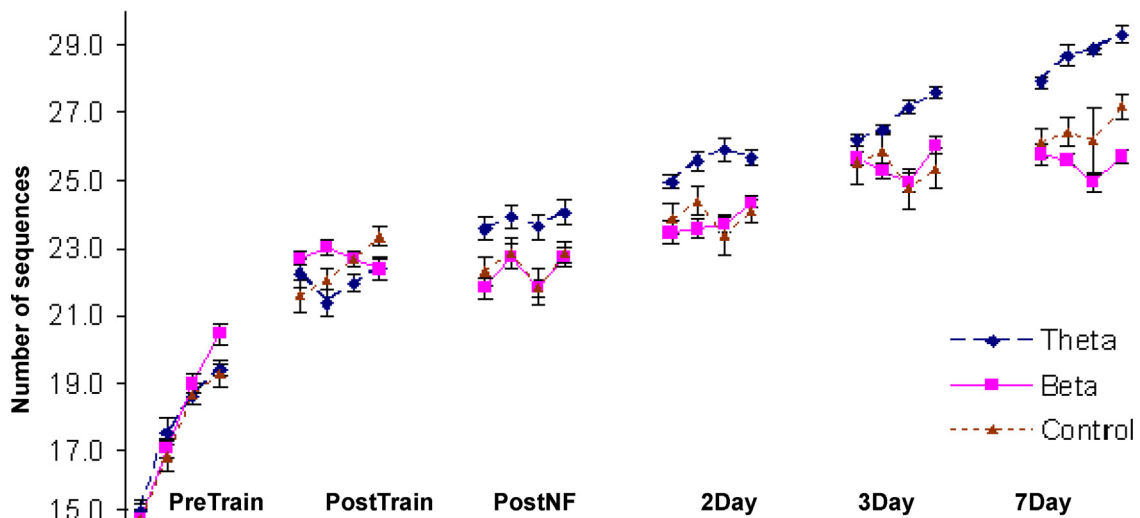
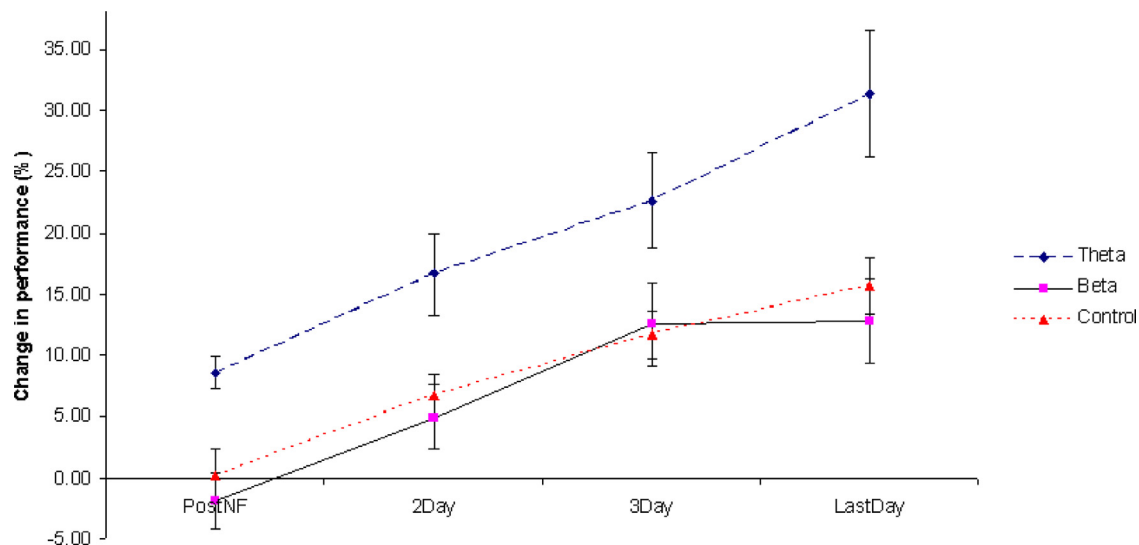


Fig. 4. Performance in each group during the week of experiments. Each point represents averaged number of sequences completed in 30 s. Four connected points represent the four blocks of one test.



**Fig. 5.** Differences in performance before and after, with/out neurofeedback training. Differences in performance are measured as the ratio of performance at each specific test and the baseline (the T1 test).

theta and control groups [ $p < 0.01$ ]. The differences between the beta and control groups were small and non-significant.

In the theta group, there was a significant improvement immediately after the NFT session, as we described earlier, while in the beta and control groups, there were minor decreases and increases respectively in performance. The differences in improvement between the theta, beta and control groups were significant [ $F(2,31) = 13.2$ ,  $p < 0.001$ ]. Post hoc analysis revealed differences between the theta and beta groups [ $p < 0.01$ ] and between the theta and control groups [ $p < 0.01$ ], while the difference between the beta and control groups was non-significant.

After 24 h (first night) there were improvements in all groups. The amount of improvement after the first night was similar in all groups, with a small advantage for the theta group. The theta group improved by 8% (1.7 delayed gains), while the beta and control groups improved by 6.75% and 6.4%, respectively (1.5 delayed gains). The difference in overall improvement was significant [ $F(2,31) = 9$ ;  $p < 0.01$ ], while theta [ $M = 16$ ;  $SEM = 3.2$ ] improved more than the beta group ( $M = 4.9$ ;  $SEM = 1.67$ ) [ $p < 0.01$ ], and the control group ( $M = 6.9$ ;  $SEM = 2.15$ ) [ $p < 0.05$ ]. The difference between beta and the control groups was not significant.

After the second night, there were similar improvements in all groups – the theta group improved by 5.8% (1.3 delayed gains), beta by 7.6% (1.7 gains) and the control group by 5% (1.2 gains). The overall improvement in performance, between the baseline (after training) until the 7th day, was significant [ $F(2,31) = 4.9$ ;  $p < 0.01$ ], with the theta group [ $M = 21.9$ ;  $SEM = 3.9$ ] improving more than beta ( $M = 12.6$ ;  $SEM = 1.95$ ) [ $p < 0.01$ ] and control groups ( $M = 12$ ;  $SEM = 1.8$ ) [ $p < 0.01$ ]. The difference between the beta and control groups was not significant. All improvements were calculated relative to the baseline, i.e. after the training test.

During the last test session, a week after training and NF, the overall picture unexpectedly changed. As in the previous tests, there was an improvement in the theta group by an additional 8.5% (1.8 delayed gains). However, in the beta and control groups only small non-significant improvements were observed: beta 0% (0.1 gain), control 4% (0.6 gains). Interestingly, all subjects from the theta group showed improvement in the last test. All of them achieved one or more additional delayed gain. In contrast, only five subjects (out of 14) from the beta group improved in the last test. In the control group, all participants improved in the last test although the gains were mostly small (0.1–0.9). Improvement rate

is calculated by the formula:  $(\text{Test} - T1)/T1 \times 100$  and is shown in Fig. 5.

#### 3.4. Correlation between theta intensity and level of improvement in performance

We expected that the theta wave band plays a role in motor performance. If so, there should be a positive correlation between changes in theta and improvement in motor performance. The absolute power of theta or beta is not valid for comparisons and correlations in this study, due to high inter-individual variability. So, we used measures of relative band power, i.e. the theta/beta ratio, calculated by dividing the average power of theta by the average power of beta. The range of theta/beta in the theta group is 1.85–3.15 average of 2.42, and 1.7–2.6, average of 2.02 in the beta group. Pearson correlation analysis was performed between theta and changes in performance (in percentages) for every test. The analysis was performed for all the subjects. The results revealed a medium but non-significant correlation of improvement on the test after NFT with theta/beta ratio [ $R = 0.31$ ;  $n = 19$ ; n.s.]. However, we found significant and strong correlations of improvement with theta/beta ratio on every subsequent test: second day [ $R = 0.644$ ;  $n = 19$ ;  $p < 0.01$ ]; third day [ $R = 0.661$ ;  $n = 19$ ;  $p < 0.01$ ] and last day [ $R = 0.64$ ;  $n = 19$ ;  $p < 0.01$ ].

We cannot control the quality and amount of sleep, but we can report that all the subjects had regular sleep during nights. Thus it makes sense to relate the effects to sleep, rather than to time, to explain the gains. Identical time period without sleep does not lead to delayed gains (Karni et al., 1998; Korman et al., 2007).

#### 4. Summary and discussion

We showed that memory consolidation can be enhanced, by using relatively short theta NFT sessions. Night sleep further contributes to enhanced consolidation. Implications are both practical and theoretical. The first hints at a potential technology for enhanced consolidation of memory, a possible ‘shortcut’ of enhanced memory in educational, social, clinical and training applications. Memory, being a cornerstone of cognitive performance, has the potential power to enhance cognitive functionality.

From a theoretical point of view this supports the system level consolidation theory. Processes of memory consolidation according

to the system-level theory imply that the neocortical representational areas are initially hippocampus dependent. With time, the connections between these neocortical areas are strengthened, leading to hippocampus independent consolidated representation (Dudai, 2004; Nieuwenhuis & Takashima, 2011). Both the initial registration of memories in the hippocampus and the later consolidation processes are linked to synchronized theta oscillations (Buzsáki, 2005; Chauvette, 2013; Guderian & Duzel, 2005; Kahana, 2003; Kropotov, 2008). The system level theory predicts that synchronized elevated theta power leads to consolidation of memory. This provided the motivation for this study. To test the role of theta in memory consolidation we asked whether enhanced theta during awake-hours, affects consolidation of memory. Indeed, results show that enhanced theta is correlated with behavioral changes indicating consolidation of memory.

Using a neurofeedback protocol, we trained subjects to perform a classical motor task, which has been used in memory-consolidation-sleep studies. We showed a significant improvement in performance immediately after NFT in the theta group, but not in the beta or control group. The improvement rate was significantly larger in the theta group in comparison to the beta and control groups in every test after theta-NF. This benefit was stable and even increased during the 7 days of experiments. We found improvements (as expected) after the first and second night and additional improvement in theta-group only after the last test, a week after the NFT.

We further tested the correlation between the relative power of elevated theta during NFT and changes in performance. Indeed, we found a strong and significant correlation between theta/beta during NFT and improvement measured in each test after night sleep, but not with the performance measures immediately after NFT. On average, participants that successfully increased their theta waves during NFT showed greater improvement on the tests after night sleep.

Results show interaction between theta-NFT, night sleep and repeated motor practice during testing, suggesting that the memory trace consolidated through theta NFT, interacts with night sleep. All groups improved after night sleep, which is expected and repeatedly shown in the literature. Yet the more interesting result is that the theta group improved significantly after night sleep, beyond the two control groups. It seems that the theta-NFT session generated an initial memory seed that was further enhanced by sleep. Lacking this initial memory enhanced form, the control groups improved less than the theta group. Surprisingly, the difference in performance of the theta-NFT and control groups increased after a week. We assume that the effect of the initial memory form, immediately after motor training, was 'stronger' and long lasting memory. Additional studies are needed to further define the nature of the impact of theta on memory consolidation and improved motor performance.

Our results support the assumption that theta waves play a role in procedural memory consolidation leading to long-term memory formation. Similar results were reported in studies that found correlations between improvement of motor memory and amount of stage 2 NREM sleep with theta prevalence (Rauchs et al., 2005; Walker, 2005). This is consistent with the findings on the role of theta oscillations in memory formation (e.g. Buzsáki, 2005; Mitchell et al., 2008).

The mechanism underlying the effect of enhanced theta power on memory consolidation is not clear. Diekelmann and Born (2007) suggest that in spite of behavior similarity, stabilization during sleep or time may be based on different neural processes. Stabilization during awake hours is related to synaptic consolidation, whereas stabilization during sleep-time benefits from system-level consolidation. Synaptic consolidation involves strengthening connections in the regions and neural circuits related to the recently

acquired skill. System consolidation may be reflected by redistribution of new memories to different brain regions, leading to enhanced performance (Song, 2009).

We challenge this view and suggest that a system level consolidation can occur during wake hours, given that specific conditions of enhanced theta are met.

Do these results indeed suggest that we managed to manipulate theta oscillations such as to generate a process information exchange across brain regions? No—there is no direct data to show the precise oscillations and precise areas. This will require a different experimental protocol. Nevertheless, this may further point at the hypothesis that synchronized theta oscillations are correlated with exchange of information across the hippocampus and remote areas. We managed to achieve manipulation of memory consolidation by controlling the level of theta oscillations. Beyond that, there might be other factors, unknown to us at this time, that have a role in memory consolidation. Independently, our results are consistent with the system level theory that theta synchronized oscillations across remote areas – such as between the hippocampus and the striatum – enhance the exchange of information, providing a mechanism for memory consolidation.

Additional factors might have an effect on improvement in skills. For example theta NFT, due to its relaxing nature, could lead to improvement in vigilance or attention. Thus, higher vigilance, attention or motivation may lead to better performance in the T2T test, providing an alternative explanation for the increase in difference between the groups. Still, the increased effect lasting for a week remains an encouraging result indicating interaction between consolidation during night sleep and theta-NFT-related day-time consolidation.

This study is based on a small number of electrodes. It will be essential to run this study on a multichannel EEG system for improved localization of distribution oscillations. In addition, single-channel recording provides limited data resulting from the limited number of electrodes and measures. Real-time NFT of single channel systems uses only coarse automatic artifact rejection, which is based on pre-defined amplitude of different band-waves. A multichannel system will require developing algorithms that target noise reduction, i.e. improving the SNR, artifact correction and methods of signal processing embedded in the EEG analysis. Although our sample is sufficiently large that no non-parametric statistics were required, a larger sample may further improve the significance.

Many research questions come up, in light of the theta NFT results, such as what are the precise activations and patterns of flow of information that occur during theta exchange of information, what are the synchronization and localization processes, and especially define a well-established causal mechanism that links theta oscillations with consolidation. Other issues relate to variation across users, contexts and task, age and gender dependency, complexly level of motor/conceptual tasks, (such as surgical or musical tasks), the effect of fatigue, and emotional factors in performance such as stress, joy or depression, and especially changes in the personal ceiling of motor performance with/out theta NFT compared to motor conventional training. More research is needed before these results become applicable to every-day-life technology. However, potentially, these results suggest a method for designing a NFT technology that targets memory consolidation of motor skills. It could be integrated in a gaming mode, in a motor learning session, or in a learning sequence.

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