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Exercising during learning improves vocabulary acquisition: Behavioral and ERP evidence

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ABSTRACT

Numerous studies have provided evidence that physical activity promotes cortical plasticity in the adult brain and in turn facilitates learning. However, until now, the effect of simultaneous physical activity (e.g. bicycling) on learning performance has not been investigated systematically. The current study aims at clarifying whether simultaneous motor activity influences verbal learning compared to learning in a physically passive situation. Therefore the learning behavior of 12 healthy subjects (4 male, 19–33 years) was monitored over a period of 3 weeks. During that time, behavioral and electrophysiological responses to memorized materials were measured. We found a larger N400 effect and better performance in vocabulary tests when subjects were physically active during the encoding phase. Thus, our data indicate that simultaneous physical activity during vocabulary learning facilitates memorization of new items.

Marcus Tullius Cicero (106 B.C.–43 B.C.) used to say that *it is exercise alone that supports the spirits, and keeps the mind in vigor*. Most likely he would not have suspected that his statement is still relevant more than 2000 years later. In fact, the influence of exercise not only on physical health but also on cognition is a topic that has re-entered the limelight in the last 10 years. The application of new neuropsychological methods enables to track neuroplasticity changes as a function of exercise. As a consequence, several animal studies have shown a strong influence of physical activity on synaptic plasticity and in particular on the genesis of new neurons in the adult mammalian brain [30,31,14,15,9,29,2]. In addition, there is cumulating evidence on a biochemical level that physical exercise leads to an increased release of several neurotrophic factors [20,9,2] which in turn should mediate the effects of exercise and cognition.

Recently, several studies have confirmed the close relationship between physical activity and cognitive abilities not only in animals but also in humans (e.g. [4,3,11]). Thus, regular exercise has been shown to prevent cognitive decline in elderly [4,11] which results in improved performance in reasoning tasks, working memory tasks, reaction time, or vocabulary measurements in physically active elderly compared to same age non-active participants [34].

However, studies on the relationship of exercise and cognition in elderly vary in duration, type of physical activity, and intensity. Nonetheless, they all indicate that physical activity positively influences cognition [11,16] as shown in functional magnetic resonance imaging (MRI) and event-related potentials (ERP) studies. For instance, Hillman et al. [13,12] showed that the amplitude of the P3b is increased in physically active compared to non-active participants indicating efficient allocation of attentional resources and faster cognitive processing during stimulus encoding in the former group [11]. On the other hand, MRI studies provide evidence for increase in prefrontal and temporal gray matter volume [4]. However, not only the aging, but also the young brain profits from physical activity. Hence, several studies provide evidence for a positive correlation of exercise, learning, and intelligence in children as well as young adults [24,19,12,27].

In sum, all the previous results point in the same direction: Physical activity pushes brain activity, which in turn makes it an ideal candidate to improve learning. However, studies investigating the effect of different learning situations (physically active vs passive) systematically are rather rare. One of them has been published recently by Winter et al. [33]. The authors investigated whether physical activity prior to vocabulary learning accelerates the learning process in young athletic men. They demonstrated that short but intensive training prior to a learning session results in the best learning outcome. Hence, the study of Winter et al. convincingly probed the effect of a single physical intervention on verbal learning. In the current experiment we aim to extend the results of Winter et al. by (i) verifying whether the described effect is specific

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to athletic men, by (ii) looking at the long-term effect of regular physical activity (in contrast to a single bout), by (iii) investigating whether physical activity *during* learning does also accelerate the learning process, and by (iv) conducting a cross-language N400 priming experiment prior to and after the training to track for changes in brain plasticity.

We address these aims for the following reasons: firstly, the beneficial effect of the physical intervention as reported by Winter et al. may be specific to young athletic men as they may be particularly motivated to pass the physical intervention. In turn, motivation and not exercise may be the primary factor that mediates the learning outcome. Less athletic participants, however, should be less motivated to pass a physical training. To test the effect of exercise and not of motivation (which has also been shown to be a modulating factor in learning [28]) we decided that subjects should not be particularly interested in physical activity but should not be obese. Secondly, we aimed to investigate the long-term effect of regular physical activity and tracked participants' learning curve over 3 weeks. Referring to the first research question our assumptions were twofold: If the positive effect of physical activity as described by Winter and colleagues is simply a matter of motivation due to the new environment (physical activity prior to learning), this effect should diminish after a few training sessions. If the benefit of physical activity is due to mediating physiological factors, as e.g. increased regional blood flow [8] or higher levels of learning mediating hormones (e.g. [32]), the beneficial effect of learning should be stable during the 3 weeks.

Thirdly, we were interested in the effect of simultaneous physical activity on learning. As aforementioned, motor activity results in acute secretion of learning mediating hormones, and hence simultaneous learning may be maximally efficient. On the one hand, it is conceivable that simultaneous movement and learning may interfere with the encoding of new vocabulary.

Lastly, we were interested in the neural substrates underlying different training effects. Thus, we conducted an N400 priming experiment prior and after the whole learning period. Beyond behavioral performance (vocabulary tests), ERPs permit to track cognitive processes as they unfold in time and thus they identify mechanisms underlying the beneficial effects of simultaneous physical activity on vocabulary learning.

These four issues are addressed in the current experiment that combines electrophysiological and behavioral measurements as a function of the learning outcome.

In the current experiment we tested 12 participants (8 female) with a mixed factorial design and asked them to learn French vocabulary. Participants were selected thoroughly to control for confounding factors. Hence, all participants were native German speakers and students at the University of Leipzig. Exclusion criteria were left-handedness, practicing of any endurance sport including regular walks as well as any neurological or psychiatric impairment. We controlled very carefully for participants' previous knowledge of French. In doing so, we consequently excluded all participants that had previously learned French at school or in private lessons. Further exclusion criteria were extensive journeys to France (more than 2 weeks).

Subjects were pseudo-randomly assigned to one of two groups, a *Spinning* group (simultaneous bicycling and learning), and a *Passive* group (no physical intervention). The respective group conditions will be explained in more detail in the following. Participants in both groups were paralleled according to age (mean *Spinning*: 25.2 years; mean *Passive*: 25.1 years), gender (i.e., 2 male and 4 female participants in each group), and working memory capacity, i.e., all participants were low-span readers according to the Reading Span Test (equal or lower than 3.0). The Reading Span Test was originally developed by Daneman and Carpenter [6]. For the current experiment we used a German adaptation of the Reading Span Test [26].

At the beginning of the study, all of the participants were instructed to avoid changes in their physical activity level for the duration of the experiment (3 weeks).

Within the 3 weeks, participants were asked to learn 80 French words (40 nouns and 40 verbs). Participants underwent 3 individual trainings sessions per week resulting in 9 learning sessions in total. Each learning session lasted 30 min during which participants listened to the 80 words twice. Thus, all 80 vocabulary pairs were presented in French–German order before they were presented again in German–French order. Within the French–German and the German–French block the order of vocabulary pairs was randomized for each learning session. Within the 3 weeks of training participants listened each item 18 times in total. Stimuli were presented auditorily via headphones (Sennheiser HD 202). The loudness level was adjusted to the individual preference and kept constant across all learning sessions. Both French and German items were spoken by a female German native speaker, who was a non-professional speaker but had a phonetic–linguistic background. All stimuli were normalized to an intensity level of 75 dB using the software PRAAT. The stimulus onset asynchrony (SOA) of French–German vocabulary pairs amounted to 2 s. The SOA between successive vocabulary pairs was 6 s. Thus, the onset of the next item was maximally predictable. We excluded action verbs to ensure that better performance of the cycling group was not semantically induced [22].

In the *Spinning* group participants were instructed to cycle in synchrony to vocabulary presentation. This was possible when subjects cycled at a speed of 60 rounds per minute (RPM), a pace that is usually recommended to beginners in fitness centres. To acquaint participants with this tempo, 42 sinusoidal tones with a frequency of 0.5 Hz were presented before the actual vocabulary presentation was started. In the *Spinning* group we controlled for the participants' heart rate (mean: 103.5, SD: 20.9) and blood pressure (mean: 130/78; SD: 13.4/11.3) three times in each training session. Participants were instructed to exercise at a medium exertion level, i.e., they should breathe a little faster and feel a little warmer.

In the *Passive* group participants listened to the same acoustic stimuli (sinusoidal tones followed by the vocabulary list). Instead of being physically active, subjects were sitting at a table and passively listening to the to-be-memorized words, imitating a traditional classroom situation. The environment was kept constant across group conditions, i.e., the room of the *Spinning* and the *Passive* group was equipped identically except for the bicycle in the room of the *Spinning* group.

After every third learning session participants performed a vocabulary test to assess their learning progress. Here, all participants (*Spinning* and *Passive* group) were sitting at a table and listened to all of the French items while they were asked to write down the German translation. Response time was limited to 8 s. Participants performed three vocabulary tests in total.

Next to behavioral measurements, we recorded the electrophysiological response to new items before and after the learning period to track for changes in brain plasticity. We conducted a cross-language N400 priming ERP (event-related potentials) experiment [1] prior to and after the 3-week training to obtain a sensitive measurement to track learning differences between groups that may not be detected by behavioral measures alone. Here, participants were tested in a dimly illuminated sound-attenuating booth, were seated in a comfortable reclining chair, and were instructed to move and blink as little as possible. They listened to French–German and German–French word–word and word–pseudoword pairs and performed a lexical decision task on the second word of each word pair. In order to permit the lexical decision task we created French and German pseudowords that corresponded in syllable number

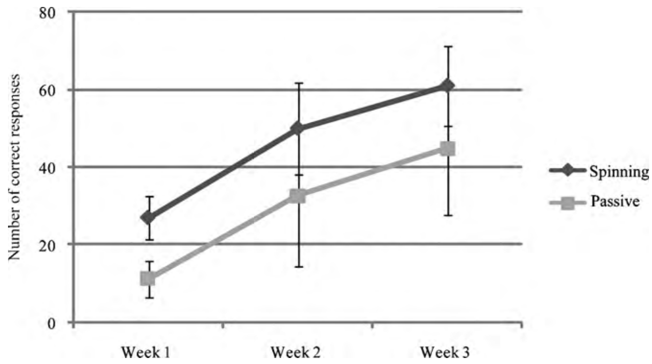

Fig. 1. Behavioral performance plotted separately for each week.

and complexity. During the experiment, each trial was introduced by a visual cue (asterisk) on the centre of a computer screen. After 500 ms the first word of a pair was presented. The following interval between the first and the second word in each trial was kept constant, namely 500 ms. Immediately after the offset of the second stimulus, participants were asked to perform the lexical decision. The next trial started 500 ms after the participant's response (button press, counterbalanced for correct and incorrect). All 320 experimental pairs (40 per condition) were presented auditory via two loud speakers in pseudorandomized order. The experimental trials were presented in eight blocks of approximately 5 min each. After the fourth block participants were offered a break. An N400 effect was expected for French–German mismatching, e.g. *gateau–Hund (English translation: cake–dog), compared to French–German matching, e.g. chien–Hund (English translation: dog–dog) word pairs that should be modulated as a function of learning type (*Spinning* vs *Passive*). The N400 is a negative component which is most pronounced at centro-parietal electrodes and typically elicited around 400 ms after the presentation of a critical item [5]. This component is affected by a large number of manipulations including frequency of a particular item, close probability, repetition, and semantic priming. If learning was successful, the acoustic presentation of the French word should prime the corresponding German item and hence reduce the N400. Mismatching word–word pairs on the other hand should induce a larger N400 as participants' lexical retrieval was misleading. Hence the difference in the electrophysiological response to matching compared to mismatching items should increase as a function of successfully memorized vocabulary.

We computed two-tailed *t*-tests for each vocabulary test to test for group differences in performances at test day. We did not find a significant main effect of group, probably due to a lack of power, however, planned comparisons showed that members of the Spinning group performed significantly better than members of the Passive group at each day of testing (week 1: *Spinning* vs *Passive*: $t(1,5) = 6.47$, $p = .001$; week 2: *Spinning* vs *Passive*: $t(1,5) = 4.46$, $p < .01$; week 3: *Spinning* vs *Passive*: $t(1,5) = 3.95$, $p = .01$), see Fig. 1.

The EEG was recorded from 29 scalp sites by means of Ag/AgCl electrodes mounted in an elastic cap (Electro-Cap Inc., n.d.) according to the 10–20 International System (cf. [21]). The sternum served as ground, the left mastoid as on-line reference (recordings were re-referenced to averaged mastoids off-line). Electrode impedances were kept below 5 kΩ. In order to control for eye movements, a horizontal and a vertical EOG was recorded. EEG and EOG signals were digitized on-line with a sample frequency of 250 Hz. An anti-aliasing filter of 67.5 Hz was applied during recording.

Individual EEG recordings were scanned for artifacts such as electrode drifting, amplifier blocking, muscle artifacts, eye movements, or blinks by means of a rejection algorithm as well as on basis of visual inspection. Epochs lasted 200 ms before onset of the second item up to 1500 ms after the critical item. All contaminated trials were rejected and the remaining trials (i.e., *session 1*: French–German match: 28.3; French–German mismatch: 29.8; *session 2*: French–German match: 26.0, French–German mismatch: 26.6) were averaged per participant, condition, and electrode site with a 200 ms pre-stimulus baseline. For graphical display only, data were filtered off-line with a 7 Hz low pass filter. All following statistical evaluations were carried out on unfiltered ERP data.

The ERP results (Fig. 2) further support that cycling during encoding enhances vocabulary learning. We conducted a repeated-measures ANOVA with the within-subject factor *condition* (match/mismatch) and the between-subject factor *group* (Spinning/Passive) for each experimental session. Both ANOVAs included right centro-parietal electrodes (C4, CP6, P4, CZ, PZ) in a time window from 350 to 750 ms measured from the onset of the second word in pair.

In the first experimental session, both groups (*Spinning* and *Passive*) failed to show an N400 effect in response to mismatching as compared to matching word pairs as revealed by a non-significant main effect for *condition* ($F(1,10) = .99$, $p > .3$). This result ensures that participants' performance was at the same level at the beginning of the learning period. Hence, the first session was an additional control condition and we checked each data set carefully on a single subject level to ensure that none of the participants has shown an N400 prior to the respective training. In fact we had to exclude one potential participant on the basis of this first EEG session.

However, in the second session, after three weeks of vocabulary learning, members of the *Spinning* group showed a larger N400 effect (mean: $-4.35\,\mu V$) over central and right hemispheric electrode sites in response to the prime-target mismatch condition (*gateau–Hund) compared to the *Passive* group (mean: $-3.21\,\mu V$). Here, the omnibus ANOVA resulted in a significant main effect for *condition* ($F(1,10) = 24.16$, $p < .001$). Planned comparison of this *condition* effect between the *Spinning* and the *Passive* group yielded a significant effect for *condition* only for the *Spinning* group ($F(1,5)$: 22.97, $p < .01$) but not for the *Passive* group ($F(1,5)$: 5.85, $p = .06$) in the post-training session.

In the current study we investigated whether long-term simultaneous physical activity positively influences the memorization of foreign language vocabulary and whether better performance is associated with plasticity changes as evidenced by changes in the N400 amplitude. This ERP component is sensitive to learning induced changes in cortical plasticity [25,17] and proficiency in a second language [18,1]. We hypothesized that members of the *Spinning* group should benefit from the simultaneous physical activity as reflected in performance and ERP responses. Our results are in line with this hypothesis. Members of the Spinning group showed significantly better performance in the vocabulary tests at each testing day. Furthermore they showed a larger N400 effect as compared to those participants who learned vocabulary in the physically passive condition.

The current results are very promising given the fact that a positive influence of simultaneous physical activity on learning has never been demonstrated before. Although previous studies provided evidence for a beneficial effect of high-intensity physical activity on the subsequent learning outcome, it has never been systematically investigated whether simultaneous physical activity further pushes or hinders mnemonic functions. Here, we provide first evidence that simultaneous physical activity positively influences the memorization of new vocabulary, a result that goes hand in hand with plasticity changes as evidenced in an enhanced N400 amplitude compared to the control group. Moreover, in the current study we included female and male participants and we paid attention that participants were not particularly athletic. We thus can generalize the effect reported by Winter et al. [33] from healthy

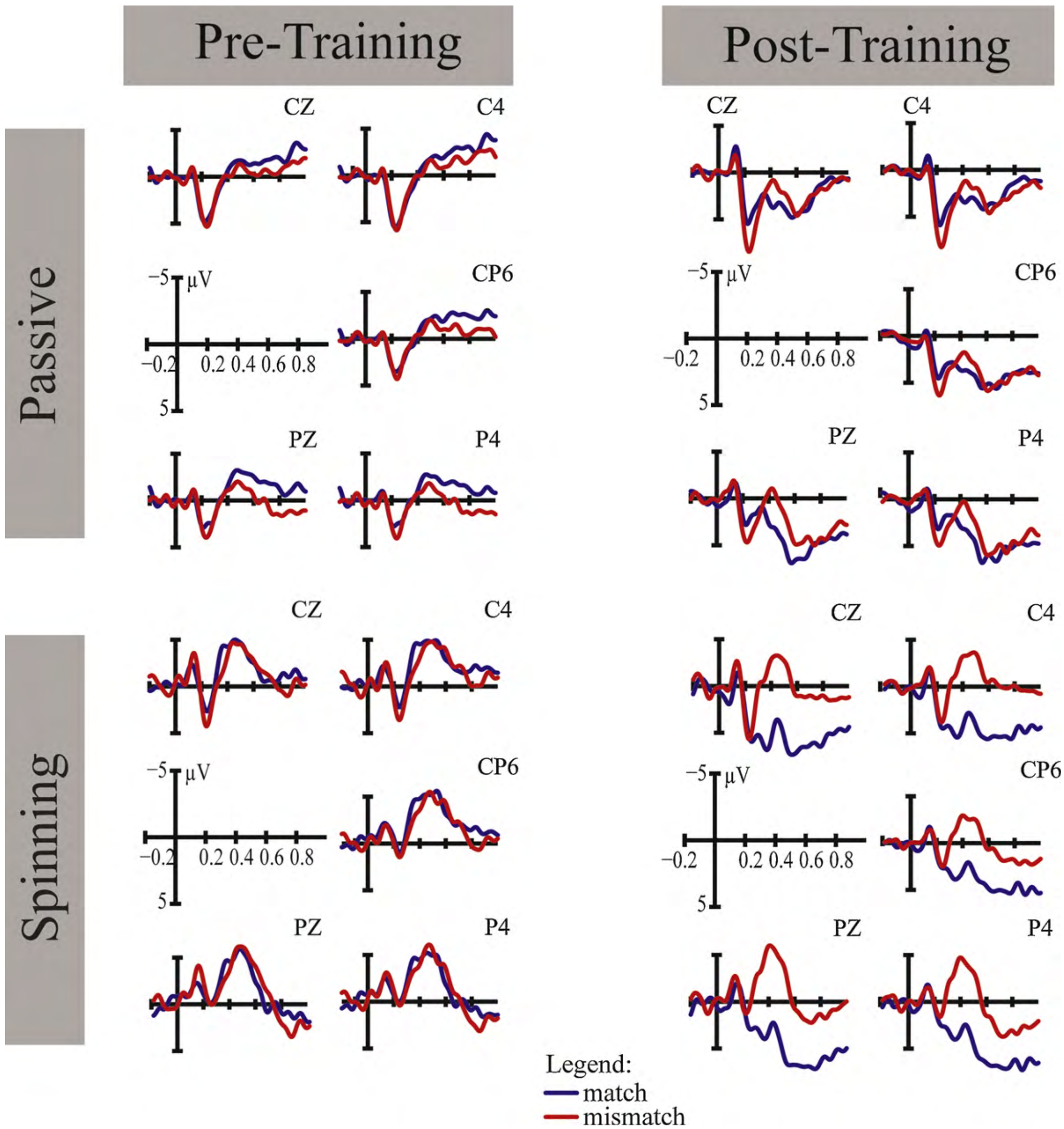

Fig. 2. N400 elicited by the second word in the match and the mismatch condition splitted by group and experimental session. Waveforms show the average for matching and mismatching items from 200 ms prior to the item onset up to 1500 ms prior to the 3 weeks training (right hand site) and after the 3 weeks training (left hand site).

and athletic men to young adults. This implies that motivational aspects, such as the motivation to complete a 30 min bout of exercise, cannot completely explain the positive influence of physical activity on learning. We found significant differences between the two groups even after three weeks of learning, i.e., after nine learning sessions. This persistent finding suggests that the novelty of the new learning experience alone cannot account for the beneficial effect of sport. We therefore exclude pure motivational aspects (i.e., due to the novel learning condition) as a primary cause for this improved learning behavior.

Admittedly, our sample size is rather small. Thus, further experiments are inevitable to substantiate this initial effect. In addition, the modulating biochemical factor that drives improved performance needs to be explored. In this context, the brain derived neurotrophic factor (BDNF) has been extensively discussed as it induces changes in cortical plasticity and is involved in mnemonic processes [10,7]. Thus, enhanced BDNF blood serum levels during learning predict better performance in subsequent test sessions [33]. On the basis of the current study we cannot conclude how physiological dynamics improve performance, but we currently address this open issue by tracking participants' BDNF level in serum in our lab.

To sum up, for the first time we investigated the beneficial influences of simultaneous bicycling positively on vocabulary learning as evidenced by brain imaging and behavioral data. Although the underlying physiological mechanism still need to be further addressed, we conclude that simultaneous physical activity boosts learning capacities even in young adults that are on the peak of their cognitive health [23].

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