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Motor Learning in Lucid Dreams: Prevalence, Induction, and Effectiveness

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Introduction

Two hours each night we spend actively dreaming. Our body lays motionless, yet our eyes start to move rapidly, our breath rhythm intensifies, and the heart starts to beat more irregularly. Our brain becomes highly active and we enter a reality akin to the usual waking one. We move with our dream body, interact with other characters in the dream, trying to achieve something, solve some problem or a situation. Usually we are getting emotional, frequently frustrated. We act and react as if awake, although the world we are in is not the real one. It looks very much the same, but exists only in the inside not the outside of ourselves. Yet sometimes a strange thought can strike our dreaming mind – something is not right here... A sudden flash of awareness penetrates the illusion – I must be dreaming! This is the point where everything changes. Endless opportunities arise. A perfectly real simulation of the waking reality is at our disposal, where the only constraints are the ones that we set for ourselves. We can break the physical laws - fly, rush into the outer space, jump from huge cliffs, dive deep into the ocean, create any scenarios or environments we only can think of. All the sensations are just as real, but we are completely safe – we cannot injure our physical sleeping body – so we can experiment here as much as we like. This is a perfect environment not only for having fun, but also for learning. We can acquire new skills, polish existing ones and try things that are rather dangerous in our ordinary waking reality.

The purpose of the present investigation was to explore the potentials for motor learning in this special state of consciousness – so called lucid dreams (dreams in which the dreamers are aware that they are dreaming): its prevalence among athletes, facilitating methods and effectiveness. The contents of this dissertation are structured in the following way. The *first chapter* introduces the concept of mental practice in sports, reviews the evidence for its effectiveness and presents main theories explaining its effects. Further, the empirical evidence showing the correspondence between imagined and executed actions is discussed, which supports the theoretical view of a functional equivalence between covert and overt motor actions. The *second chapter* presents the basics of human sleep and the relation of sleep to memory consolidation, especially in terms of procedural (motor) memory. It also introduces the basics of dreams and dream research. The *third chapter* presents the phenomenon of lucid dreaming, its incidence and frequency rates, underlying physiology and psychology. The *fourth chapter*, the core of the present investigation, focuses on the application of lucid dreams in sports and, specifically, in motor learning. Anecdotal accounts and previous research is discussed and the present empirical work is introduced. The first study (**Paper 1**) surveyed the frequency of lucid dreaming and lucid dream practice in athletes. In the second study (**Paper 2**), a systematic review was conducted to examine the empirical evidence for all different methods for lucid dream induction that have been suggested in the literature. Then a sleep laboratory study followed to test one of the prospective methods suggested in the literature but not yet examined – an induction of lucid dreams via transcranial brain stimulation (**Paper 3**). Lastly, an online study was carried out in which the effectiveness of motor practice was compared to actual physical practice and mental practice in wakefulness (**Paper 4**). Finally, the *last chapter* provides an overall discussion of the findings and directions for future research.

1. Mental practice in sports

Mental practice is the cognitive rehearsal of a physical activity in the absence of overt physical movements (Richardson, 1967a). In contrast to other cognitive training methods in sports, it involves an imaginative representation of body movements. An athlete can use mental practice in a variety of contexts: preparing for a competition, during a competition (e.g. before making a kick, a serve, or a shot), or when there is no possibility to perform actual practice (e.g. when travelling or recovering from an injury). It is a well-established technique in sports science and practice (Morris, Spittle, & Watt, 2005) and widespread among elite athletes, with the prevalence numbers ranging from about 70% (Ungerleider & Golding, 1989) up to 99% (Orlick & Partington, 1988). Mental practice can be used for the acquisition of motor skills or as a means of action preparation (Magill, 2003). It can be carried out by using an internal (first-person) or external (third-person) perspective. The findings on which of the perspectives is more beneficial are somewhat ambiguous. Some studies show greater benefits of internal perspective (e.g. Epstein, 1980; Mahoney & Avener, 1977), others – of external perspective (e.g. Hardy & Callow, 1999; White & Hardy, 1995), whereas some other studies did not find any differences between the two perspectives (e.g. Gordon, Weinberg, & Jackson, 1994; Mumford & Hall, 1985). Recently also a distinction was made between internal visual, external visual and kinesthetic imagery (Roberts, Callow, Hardy, Markland, & Bringer, 2008). The latter was considered more of a feature of internal imagery in some earlier studies (e.g. Mahoney & Avener, 1977).

1.1. Effectiveness of mental practice

Since 1930s, when Sackett (1934, 1935) showed that “symbolic rehearsal” of a task improves subsequent performance, a numerous studies on the effects of mental rehearsal with different motor tasks have been conducted. Mental practice has been shown to improve performance in a variety of sports, including darts (Mendoza & Wichman, 1978), basketball (Hall & Erffmeyer, 1983), volleyball (Shick, 1970), tennis (Surburg, 1968), field hockey (Smith, Holmes, Whitemore, Collins, & Devonport, 2001) and many others. Mental practice can have an effect on a number of different aspects of motor performance, for example: increase muscular strength (Ranganathan, Siemionow, Liu, Sahgal, & Yue, 2004; Yue & Cole, 1992), endurance (Kelsey, 1961), flexibility (Guillot, Tolleron, & Collet, 2010), improve balance (Fansler, Poff, & Shepard, 1985), increase movement speed and accuracy (Smith & Harrison, 1962), consistency of movement tempo and relative timing (Vogt, 1995).

One of the first literature reviews to assess the effects of mental practice was done by Richardson (1967a). Eleven studies with significantly positive findings regarding improvements following mental practice were found, seven studies with positive trends, three with negative findings and one equivocal; thus, indicating that mental practice is indeed associated with improved performance.

In 1983, Feltz and Landers carried out the first extensive meta-analysis to more robustly examine the effectiveness of mental practice on motor skills learning and performance. Their review included 60 studies from which 146 effect sizes were obtained (some studies measured the effects of more than one task or condition). The overall effect size was found to be M = .48 ± .67, suggesting that mentally practicing a motor task indeed improves subsequent performance. Feltz and Landers (1983) also found that tasks with cognitive elements had larger effect sizes (M = 1.44) as compared to motor tasks (M = .43) or strength tasks (M = .20), and published studies had larger effect sizes (M = .74) than unpublished studies (M = .32). No gender differences were found as well as any significant differences between novices and experienced subjects. The relationship between practice duration and effect size was found to be neither linear nor curvilinear but rather third degree polynomial: either very short practice sessions (under 1 min or less than 6 trials) or much longer (15-25 min or 36-46 trials) seemed to be the most effective. The relationship appeared to be also task-specific: Improvements in cognitive tasks were associated with very short practice durations, whereas motor and strength tasks required longer practice durations.

A decade later, Driskell, Copper, and Moran (1994) conducted another meta-analysis which involved more strict operational definition of mental practice (excluding composite studies of mental and physical practice, modeling, relaxation, etc.) and mandatory comparison with a control group. A total of 35 studies with 100 hypothesis tests (3214 subjects) were included. Their combined results indicated that mental practice (62 hypothesis tests) result in significant improvements that are small to moderate in magnitude (r = .255, d = .527) but are lower than improvements from physical practice (moderate to strong in magnitude: r = .364, d = .782; 38 hypothesis tests). Further, they found that mental practice was more effective for tasks that involved cognitive elements and that the positive effect of the practice declines with the time (after two weeks the effects are reduced to a half of their original magnitude). The experience with the task was also found to play some role: While there were no differences between experienced and novice participants in overall combined effects, novice subjects seemed to have stronger effects of mental practice for cognitive rather than physical tasks, while the experienced subjects equally benefited from mental practice regardless of the task type. The number of practice trials appeared not to be related to the effectiveness; however, there was a negative relationship between the duration of mental practice and the magnitude of effect, indicating that longer practice periods (over 20 min) can lead to weaker effects.

Altogether the evidence from meta-analyses suggests that mental practice has a positive and significant effect on performance. The findings from sports have recently been extended to other disciplines, such as education, medicine, music and psychology (Schuster et al., 2011). To explain how mental practice works several theories have been suggested.

1.2. Theories of mental practice

One of the earliest explanations of how mental practice works was proposed by Sackett (1934, 1935). According to his symbolic rehearsal theory, a symbolic representation of the action is gained which can be subsequently rehearsed and these patterns coded in memory. Therefore this theory suggests that only those actions that involve cognitive elements can benefit from mental practice and symbols representing the movements must be acquired prior mental rehearsal. While meta-analyses showed that mental practice is indeed more effective for tasks that involve cognitive elements (cf. Driskell et al., 1994; Feltz & Landers, 1983), this theory does not explain how performance can be improved in such tasks as muscular strength and endurance (cf. Kelsey, 1961; Ranganathan et al., 2004; Yue & Cole, 1992).

A somewhat different – psychoneuromuscular – explanation was put forward by Richardson (1967b). The explanation is based on early psychophysiological studies (e.g. Jacobson, 1930, 1932) which found that during mental practice very small innervations of the muscles that are involved in the actual movement occur. Richardson proposed that due to this small kinesthetic feedback together with imagined visual feedback, corrections can be made and neuromuscular coordination can be facilitated. Yet the overall findings regarding increased EMG activation in respective muscle groups during mental practice are rather ambiguous: some studies did find increases in EMG activity, other studies did not (overview: Guillot, Lebon, & Collet, 2010). Further, studies failed to find an association between increases in EMG activity and improvements in performance during mental practice (e.g. Smith, Collins, & Holmes, 2003; Yue & Cole, 1992). Also this theory does not explain why the highest gains for mental practice are with the tasks that involve cognitive elements (cf. Driskell et al., 1994; Feltz & Landers, 1983).

Hecker and Kaczor (1988) suggested applying a cognitive bioinformational theory, proposed by Lang (1979), to the domain of mental practice in sports. According to this bioinformational theory (originally developed for emotional imagery), images can be understood as propositional structures stored in the brain and are organized into two main categories: stimulus and (behavioral) response (which includes both physiological and emotional reactions). Lang proposed that learning and behavioral change occurs from linking stimulus and response propositions and mental imagery can strengthen these links. Support for this theory comes from studies which showed that, for example, internal imagery produces more EMG activity than external imagery (Hale, 1982), both EMG activity and improvements in performance are greater when response rather than stimulus propositions are emphasized in the script (Bakker, Boschker, & Chung, 1996; Smith et al., 2001), increases in heart rate are higher when imagining a familiar situation than unfamiliar (Hecker & Kaczor, 1988), experienced athletes gain more from mental practice than novices (Feltz & Landers, 1983). This evidence gives credibility for the application of bioinformational theory in sports, yet more empirical support, especially in the applied sport setting, is needed (cf. Morris et al., 2005).

Further, some theories have been suggested that emphasized the effects of mental practice on a psychological state. Schmidt (1982), for example, proposed that imagery could provide a preparatory set to achieve an optimal arousal level for good performance. This “attention-arousal set” view is in part supported by findings of respective muscular innervations during mental practice (e.g. Jacobson, 1930, 1932), yet has not been empirically examined and hence its critical evaluation is not possible (Hecker & Kaczor, 1988). Mental practice has been also suggested to increase self-efficacy and confidence which can lead to improved performance, however the empirical evidence failed to show that self-efficacy/efficacy mediates the relationship and thus might rather be an independent outcome of mental practice (Morris et al., 2005).

A theoretical view which seems to be most strongly grounded in empirical evidence is a neurophysiological explanation of functional equivalence. This view was put forward by Finke (1980), who argued that visual imagery is functionally equivalent to visual perception, i.e. mental imagery activates the same information-processing mechanisms of visual perception at many different levels. Jeannerod (1994) proposed that this functional equivalence can be generalized to mental representations in other modalities, and, specifically, to motor imagery. Thus mentally imagined movements would share the same neural mechanisms with actual physical movements and would have similar functional outcomes, which would explain the effectiveness of mental practice: On a neurophysiological level mental practice is equivalent to actual physical practice, just the movement execution is inhibited, and learning can occur due to the motor programming process (cf. Schmidt, 1975). The empirical evidence for functional equivalence is very sound and is reviewed in the next section.

1.3. Neural basis of motor imagery

Decety (1996) proposed three lines of evidence to support the notion that imagined and executed actions share the same neural structures: measuring central nervous activity (e.g. cerebral blood flow), monitoring autonomic responses and using mental chronometry. The converging evidence would show that the same brain areas are involved in planning actual movements, peripheral effectors are innervated according to the level of effort, and temporal dynamics is preserved.

In a pioneering study, Roland, Larsen, Lassen, and Skinhøj (1980) found that mental simulation of the movement resulted in increased regional cerebral blood flow (rCBF) most strongly in the supplementary motor area (SMA), whereas actual movement increased rCBF not only in SMA but also in the primary motor area (M1), thus implying the involvement of SMA in motor action programming. Subsequent studies (e.g. Decety et al., 1994; Lotze et al., 1999; Roth et al., 1996) confirmed the involvement of SMA and the premotor cortex in motor imagery, which have now been considered as the predominant areas of motor imagery (overviews: Jeannerod, 2001; Lotze & Halsband, 2006). The involvement of M1 in motor imagery is more controversial (Munzert, Lorey, & Zentgraf, 2009). While some PET studies did not find increased M1 activity (e.g. Decety et al., 1994; Roland et al., 1980) during motor imagery, many fMRI studies did find (e.g. Lotze et al., 1999; Roth et al., 1996; overview: Munzert et al., 2009), although typically to a lesser extent (e.g. 30% as compared to actual execution, Roth et al., 1996). Considering all evidence together, the current consensus is that M1 is involved in motor imagery (Lotze & Halsband, 2006; Munzert et al., 2009). Thus imagined actions seem to involve the same brain regions as executed actions, although they do not completely overlap (see Lotze & Halsband, 2006).

According to Guillot and Collet (2005a), three different physiological categories with six variables can be measured to monitor autonomic nervous activity (ANS): electrodermal (skin conductance and skin potentials), thermo-vascular (skin blood flow and skin temperature) and cardio-respiratory (heart rate and respiration). Decety, Jeannerod, Germain, and Pastene (1991) found that mental simulation of movement at increasing speed resulted in proportional increase of heart rate and pulmonary ventilation (cardio-respiratory parameters of mental running at 12 km/h were comparable to actual walking at 5 km/h). These findings were replicated in subsequent studies, which also find increases in respiratory rate and that the effects are independent from the experience with the task, i.e. whether a participant is a novice or a professional athlete (Calabrese, Messonnier, Bijaoui, Eberhard, & Benchetrit, 2004; Fusi et al., 2005). Further studies showed corresponding effects on other ANS parameters – skin conductance/resistance, skin potential, skin temperature and blood flow, systolic and diastolic blood pressure (Beyer, Weiss, Hansen, Wolf, & Seidel, 1990; Deschaumes-Molinaro, Dittmar, & Vernet-Maury, 1992; Oishi, Kasai, & Maeshima, 2000; Wang & Morgan, 1992). Moreover, ANS responses during mental practice seem to be associated with improvements in performance (Roure et al., 1999).

Finally, it is important to consider the temporal dynamics of motor imagery (reviews: Guillot & Collet, 2005b; Guillot, Hoyek, Louis, & Collet, 2012). An early study by Decety, Jeannerod, and Prablanc (1989) found that walking time to the target in actual and mental performance was nearly equivalent, yet when the participants were asked to carry a 25-kg weight on their shoulders, actual walking time remained the same but mental walking time increased by 30%. Further, Decety and Jeannerod (1995) discovered that the time needed to mentally walk to a target (a gate) is affected both by its width and distance (speed-accuracy trade-off) and that Fitt's law (cf. Fitts, 1954) is preserved. Whereas many studies confirmed similar durations for actual and imagined movement times, underestimations and overestimations were also found in several studies (overview: Guillot & Collet, 2005b). Many different factors seem to influence timing of motor actions, including movement duration, movement complexity and perceived difficulty, expertise level, age, imagery type and perspective, instructions, and others (review: Guillot et al., 2012).

Altogether, the converging lines of evidence support the notion that imagined and executed actions to some extent share the same neural structures. Taking a step further, Jeannerod (2001) put forward a theory of neural simulation of action which postulates that, in general, covert actions are actual actions, except for the fact that they are not executed. Therefore this theory predicts a neural similarity between the state in which an action is simulated (so called "S-state") and the state of execution of this action. S-states include intended actions, imagined actions and actions in dreams (see section 3.2).

2. Sleep, memory consolidation, and dreams

About a third of their time human beings spend in sleep. While the functions of sleep largely remain unknown, there is substantive evidence showing that sleep plays a crucial role in memory formation (Stickgold, 2005). There are different types of memories, which are most often divided into two classes: declarative and non-declarative (Squire, 2004). Declarative memories are explicit memories that can be consciously recollected, such as memories of facts (semantic memories) or events (episodic memories). Non-declarative memories are implicit and usually used without conscious recollection, such as procedural and motor skills (e.g. riding the bicycle). While sleep is important for formation of both types of memories, the evidence is much stronger for its involvement in formation of procedural skills (Stickgold, 2005). Before looking into the role of sleep in motor memory consolidation, the basics of sleep will be briefly discussed.

2.1. Basics of sleep

In behavioral terms, sleep can be defined as a reversible behavioral state of perceptual disengagement from and unresponsiveness to the environment (Carskadon & Dement, 2000). Since the pioneering discovery of rapid-eye movement (REM) sleep (Aserinsky & Kleitman, 1953), sleep has been divided into two states: REM sleep and NREM (non-rapid eye movement) sleep. Both states are present in virtually all mammals and birds and are physiologically distinct from one another and from wakefulness. NREM sleep can be further divided into different substages: Stage 1, Stage 2, Stage 3 and Stage 4 NREM sleep which can be relatively unambiguously defined according to the electroencephalographic (EEG) patterns (Rechtschaffen & Kales, 1968). Recently Stages 3 and 4 of NREM sleep due to minute physiological differences between them were combined into a single state NREM 3 or N3 (Iber, Ancoli-Israel, Chesson, & Quan, 2007). Standard sleep recording (polysomnography) includes EEG (electrode placement: F_4-M_1, C_4-M_1, O_2-M_1, F_3-M_2, C_3-M_2, O_1-M_2, according to the international ten-twenty system, Jasper, 1958), electrooculogram (EOG) and chin electromyogram (EMG).

Stage NREM 1 (N1) is marked by conjugate sinusoidal slow eye movements, low amplitude predominantly theta (4-7 Hz) brain activity, and vertex sharp waves (Iber et al., 2007). NREM 1 typically occurs at sleep onset (the first sleep epoch after wakefulness) and usually accounts for 2-5% of total sleep time. Muscular twitches and hypnic jerks, as well as hypnogogic hallucinations can be experienced during N1. When awakened from this sleep, people often report that they were still awake.

NREM 2 (N2) is characterized by K complexes (negative sharp waves with duration of ≥0.5 seconds, usually maximal in amplitude on frontal derivations) and sleep spindles (a train of distinct waves of 11-16 Hz frequency with a duration of ≥0.5 seconds, usually maximal in amplitude on central derivations) (Iber et al., 2007). It is the most prevalent sleep stage during the night, constituting of 45-55% of total sleep time. The arousal thresholds in N2 sleep are similar as in REM sleep (Rechtschaffen, Hauri, & Zeitlin, 1966).

NREM 3 (N3), also called slow-wave sleep (SWS) or deep sleep, is distinguished by the presence of 20% or more of high voltage (≥75µV) 0.5-2 Hz waves (Iber et al., 2007). N3 takes about 15-20% of total sleep time and is more prevalent in the first part of the night. It is the stage of sleep associated with the highest arousal thresholds. Parasomnias, such as sleep walking or sleep terrors, most often occur during N3 sleep (American Academy of Sleep Medicine, 2001).

REM sleep is marked by irregular rapid eye movements, low amplitude mixed frequency EEG and low chin EMG tone (with short irregular bursts of EMG activity) (Iber et al., 2007). REM sleep usually accounts for 20-25% of total sleep time, is predominant towards the end of the night, and associated with the most vivid dream experiences (see section 2.3).

Wakefulness in polysomnographic recordings is also characterized by irregular rapid eye movements (as well as by reading eye movements – a slow phase followed by a rapid phase in the opposite direction) but associated with normal or high chin EMG tone and EEG alpha (8-13 Hz) rhythm. It usually constitutes less than 5% of total sleep time.

Sleep occurs in NREM-REM sleep cycles of about 90-110 min duration throughout the night (N1-N2-N3-N2-REM). Deep sleep (N3) predominates during the first third of the night, whereas REM sleep is most prevalent during the last third. This is also associated with circadian rhythms – REM sleep, for example, is closely linked with body temperature (Czeisler, Zimmerman, Ronda, Moore-Ede, & Weitzman, 1980). Brain activity differs across NREM-REM sleep cycle: NREM sleep is marked by a decreased overall brain activity, while during REM sleep the brain becomes highly active (Braun et al., 1997; Maquet et al., 1996, 1997).

2.2. Procedural memory consolidation in sleep

Different studies demonstrated that sleep is crucial for motor learning. When learning a new motor task, post-test improvements are seen after a night’s sleep, but not after an equivalent period of waking time (Fischer, Hallschmid, Elsner, & Born, 2002; Huber, Ghilardi, Massimini, & Tononi, 2004; Walker, Brakefield, Morgan, Hobson, & Stickgold, 2002).

An early study by Karni, Tanne, Rubenstein, Askenasy, and Sagi (1994) found that performance of a visual discrimination task improved after a night sleep, yet the improvements were lost when REM sleep of the night was disrupted, whereas the disruption of slow-wave sleep (N3) did not affect improvement. Subsequent studies confirmed the involvement of REM sleep in memory consolidation for visual discrimination skills, but showed that SWS is likely also to be involved (Gais, Plihal, Wagner, & Born, 2000; Stickgold, Whidbee, Schirmer, Patel, & Hobson, 2000).

In motor skills domain, a study by Buchegger, Fritsch, Meier-Koll, and Riehle (1991) showed that participants who acquired a new motor skill (trampolining) had a significant increase in subsequent REM sleep. Plihal and Born (1997) found that improvements in mirror-tracing skills were more associated with the late sleep (where REM sleep is predominant), while improvements in declarative memory were associated with the early sleep (where SWS is predominant). Similarly, Tucker at al. (2006) demonstrated that a day-time nap without REM sleep enhanced declarative but not procedural (mirror-tracing) memory. On the other hand, Erlacher and Schredl (2006) did not find any effects of learning a new motor task (snakeboard riding) on REM sleep parameters. With a finger-tapping task, Fischer et al. (2002) found that improved performance was associated with a greater amount of REM sleep, although another study by Walker et al. (2002) found improvements to be associated with the proportion of N2 sleep across the night. Further, Smith and MacNeill (1994) showed that the performance on a pursuit rotor task is impaired due to N2 rather than REM sleep loss. On the other hand, Huber et al. (2004) found improvements on a rotation-adaptation task to be related to the increases in slow-wave activity.

Thus, nearly all sleep stages (except of N1) have been shown to be involved in procedural and motor memory formation (Walker & Stickgold, 2004). Considering the evidence altogether, SWS seems to facilitate declarative, hippocampus-dependent memory, whereas REM sleep appears to facilitate hippocampus-independent non-declarative (procedural, emotional) memory (Diekelmann & Born, 2010). REM sleep, in particular, seems to be associated with initial phases of motor learning, when the task appears to be completely new and unfamiliar (Blischke & Erlacher, 2007).

Using position emission tomography (PET), Maquet et al. (2000) showed that those participants who practiced a visuomotor serial reaction task had the same brain activation patterns (located in occipital and premotor cortices) reappearing during subsequent REM sleep, while no such activity was seen in those participants who did not practice the task. Furthermore, these increases in regional cerebral blood flow during REM sleep were directly related with the extent of improvements in performance (Peigneux et al., 2003). Moreover, in another study Louie and Wilson (2001) implanted microelectrodes into the rat hippocampus and recorded the activity of multiple neurons during the wake motor task and subsequent REM sleep. It was found that temporally sequenced firing rate patterns of wake behavior are reproduced during REM episodes at an equivalent timescale. Finally, a recent study using a virtual navigation task and human subjects found that those participants who dreamt about the task (during NREM sleep) showed greater improvements in subsequent performance than participants without task-related dream mentation, while task-related thoughts in wakefulness did not predict improved performance (Wamsley, Tucker, Payne, Benavides, & Stickgold, 2010). Despite the fact that dreams in this study were collected from NREM sleep (in three cases from the sleep onset and once after awakening from N2 sleep), the findings could possibly be extended to other sleep stages, supporting the idea that dream experiences reflect the learning-induced memory reactivation during sleep and this reactivation is associated with improvements with performance (Wamsley & Stickgold, 2011).

2.3. Dreams

In general, dreaming can be defined as mental activity occurring during sleep, while a dream (or a dream report) is the recollection of mental activity which has occurred during sleep (Schredl, 2008b). Dream reports can be collected from a spontaneous recall in a natural (e.g. home) environment or following deliberate awakenings in a sleep laboratory (cf. Schredl, 2008a). In the sleep laboratory setting, dreaming has been strongly associated with REM sleep since its discovery: Initial experiments showed that upon awakenings from REM sleep dreams are recalled in 74-80% of cases, while only 7-9% of awakenings from NREM sleep result in dream recall, leading to a suggestion that a dream recalled during NREM sleep might only be a persisted memory from a previous REM period (Aserinsky & Kleitman, 1953; Dement & Kleitman, 1957). This view “dreaming = REM sleep” prevailed for a while, until Foulkes (1962) showed than when a person is asked to report any mental content which “was going through the mind”, the recall rate from NREM sleep is much higher and not that much different comparing to REM sleep (recall rates in his study: NREM 74% vs. REM 87%). The differences between REM and NREM dreams, however, do exist: In a meta-analysis of 34 studies, Nielsen (1999) found the average recall rate 82±9% for REM sleep and 43±21% for NREM sleep. REM dream reports are typically longer, more bizarre, more perceptually vivid, more emotionally charged and with more motor activity, while NREM dream reports contain more thought-like mentation and representation of current concerns (Hobson, Pace-Schott, & Stickgold, 2000).

To explain the ambiguity between dreaming and REM vs. NREM sleep different theoretical models have been proposed. Hobson et al. (2000) suggested that wakefulness, REM sleep and NREM sleep are distinct mental states with different levels of cortical activation, input source and aminergic-cholinergic neuromodulation. Solms (2000) considering the evidence from brain lesions proposed that REM sleep and dreaming are controlled by different brain mechanisms and while there is a substantial correlation between the two, in fact, they are dissociable states. Nielsen (2000) put forward another hypothesis, proposing that there might be externally unnoticeable “covert” REM processes during NREM sleep, which could be responsible for dreamlike mental activity in NREM sleep.

People differ in their ability to recall dreams: For example, women seem to have better dream recall than men (Schredl & Reinhard, 2008). Empirical research supports the so-called continuity hypothesis of dreaming which states that waking experiences are reflected in dreams, i.e. dreaming is in continuity with waking life (Schredl, 2003). Sport students, for example, dream more about sports than psychology students do and the time spent in sports activities is directly related to the percentage of sports dreams (Erlacher & Schredl, 2004a; Schredl & Erlacher, 2008).

3. Lucid dreams

A special type of nocturnal dreams are lucid dreams – dreams in which the dreamer is aware that he or she is dreaming and often can deliberately influence the dream content (LaBerge, 1985a). Although the phenomenon was already known to Aristotle (trans. 2007), scientific research on lucid dreaming spans only over the last three decades, since its verification in a sleep laboratory (Hearne, 1978; LaBerge, 1980b; LaBerge, Nagel, Dement, & Zarcone, 1981). Lucid dreaming is mainly considered to be a REM sleep phenomenon (LaBerge, 1990) and is more likely to occur during later REM periods than earlier ones (LaBerge, 1985b). Although lucidity during NREM sleep is also possible (Stumbrys & Erlacher, 2012): most likely to be observed during N1 sleep, somewhat less likely during N2 sleep and yet to be observed during N3 sleep. Lucid dreams are most often initiated from the dream state, but sometimes can also be initiated from the waking state when retaining conscious awareness while falling asleep (LaBerge, Levitan, & Dement, 1986).

3.1. Incidence and frequency

While lucid dreams are still relatively little known, they are not that infrequent among general population, although the estimates vary. In a representative survey of Austrian population (N = 1000) by Stepansky et al. (1998), 26% of respondents reported that they had lucid dreams (64% reported no lucid dreams, 10% did not answer). A recent survey of a German representative sample (N = 919) by Schredl and Erlacher (2011) found much higher incidence rates: 51% of respondents reported that they had at least one lucid dream in their life, 20% experienced lucid dreams once a month or more frequently, and 5% had one or more lucid dreams per week. Mean lucid dream frequency was found to be 0.65 (SD = 2.14) lucid dreams per month, which corresponded to a rough estimate of 7.5% as compared to overall dream recall frequency (mornings with dream recall per week: M = 2.00, SD = 2.14). Similar incidence rates were found by Snyder & Gackenbach (1988), who undertook a review of different surveys that were published up to that time and provided a “conservative estimate” that about 58% of the population had experienced a lucid dreams at least once in their lifetime and 21% report lucid dreams once a month or more often (hence they are referred as frequent lucid dreamers).

Some specific samples appear to have lucid dreams more often, for example, university students. In a German university student sample (containing mostly psychology students; N = 439) surveyed by Schredl and Erlacher (2004), 82% of participants reported at least one lucid dream and 37% were frequent lucid dreamers. Blackmore (1982a, 1982b) in three different samples of university students in England and the Netherlands (*N* = 114, 157, & 189) found the prevalence of lucid dreaming to be 73%-79%, while Yu (2008) in a Chinese student sample (*N* = 348) found the prevalence rate of 92%. Interestingly, Erlacher, Schredl, Watanabe, Yamana, and Gantzert (2008) found much lower lucid dream prevalence rate in a Japanese student sample (*N* = 153) as compared to other countries: Only 47% of Japanese students reported at least one lucid dream experience and only 17% were frequent lucid dreamers. This suggests that cross-cultural differences regarding lucid dream frequency may also exist.

Most of these studies used self-questionnaires and rating scales to assess lucid dream frequency. A recent study by Stumbrys, Erlacher, and Schredl (2013a) showed that lucid dream frequency can be indeed reliably measured with a frequency scale: Re-test reliability of an 8-point scale over a 4-week interval in a sample of 93 sport students was found to be $r = .89$ ($p < .001$). Thus lucid dream frequency seems to be relatively stable over the time (at least in a short while). Another approach for assessing lucid dream frequency is to count lucid dreams in the dream diaries. Within university student samples, the frequency of lucid dreams as compared to all recalled dreams seems to be very low, only about 0.3-0.7% (Barrett, 1991; Zadra, Donderi, & Pihl, 1992). Yet it might be as high as 13% if the dreams are collected once weekly (Gackenbach & Curren, 1983). In a sample of 1666 dream reports collected from dream seminar attendees in six different countries (Argentina, Brazil, Japan, Russia, Ukraine, and USA), Krippner and Faith (2001) found 1.7% lucid dream incidence rate, ranging from 0% (males and females in Japan, females in Ukraine) to 3.3% (males in Russia).

3.2. Physiology

During REM sleep, in which lucid dreams most often occur (cf. LaBerge, 1990), skeletal muscles of the sleeping body are actively suppressed by neural structures in the brain stem (so called muscular atonia), keeping dreamers from actually acting out their movements in their dreams (Hobson et al., 2000). One evident exception is eye movements, which in part correspond with shifts of gaze in dream imagery (scanning hypothesis, cf. Roffwarg, Dement, Muzio, & Fisher, 1962). By using a prearranged pattern of specific eye movements (typically a sequence of left-right eye movements), the dreamers can give a volitional signal once they become lucid in a dream or accomplish a particular action in the lucid dream (LaBerge et al., 1981). Interestingly, a fixation of a gaze on a stationary point in the dream environment leads to a termination of the dream and awakening (Tholey, 1983a).

Compared to non-lucid REM dreaming, lucid REM dreaming is associated with elevated physiological activation – higher REM density, increases in respiration, heart rate and skin potential (LaBerge et al., 1986). H-reflex suppression, however, is greater in lucid dreams than non-lucid dreams, suggesting that the lucid dreaming state might not be closer to awakening than ordinary REM sleep (Brylowski, Levitan, & LaBerge, 1989).

In terms of the brain activity, early studies found higher EEG alpha activity during REM sleep to be associated with prelucid (i.e. when the dreamer starts to develop a critical attitude by questioning the reality of the dream), as well as lucid dreaming (Ogilvie, Hunt, Tyson, Lucescu, & Jeakins, 1982; Tyson, Ogilvie, & Hunt, 1984). Further, a 4-channel EEG study found an increased beta-1 activity (13-19 Hz) over both parietal regions during REM lucid dreaming (Holzinger, LaBerge, & Levitan, 2006). Recently, a 19-channel EEG study was conducted, which found an increased brain activity in all frequencies, when comparing lucid versus non-lucid REM sleep, especially in the frontal and frontolateral regions, peaking at around 40 Hz (Voss, Holzmann, Tuin, & Hobson, 2009). Another recent study measured brain activity in fMRI scanner during lucid dreaming and found that several areas that are normally deactivated during REM sleep where reactivated, including the bilateral precuneus, cuneus, parietal lobules, and prefrontal and occipito-temporal cortices (Dresler et al., 2012).

When a person performs an action in a lucid dream, corresponding changes can be observed in the physiological activity of the sleeping body. For example, voluntary control of respiratory rate in lucid dreams is reflected in matching changes in actual respiration (LaBerge & Dement, 1982). Dreamed sexual activity and orgasm in lucid dreams were found to be associated with the similar physiological pattern as waking orgasmic experience – increased vaginal EMG, vaginal pulse amplitude, levels of skin conductance and respiratory rate (LaBerge, Greenleaf, & Kedzierski, 1983). Dreamed physical activity (doing squats in a lucid dream) resulted in increased heart rate and (partially) respiration (Erlacher & Schredl, 2008a). Despite of general muscular atonia during REM sleep, corresponding EMG activity can also be measured in some muscle groups. For example, hand clenching in a lucid dream results in corresponding muscular twitches on the wrist (LaBerge et al., 1981). Fenwick et al. (1984) measured EMG activity in different muscle groups while movements were carried out in a lucid dream and found greater corresponding activity in flexor muscles, somewhat lower in extensor limb muscles, and it was never present in axial muscles, which suggests a clear hierarchy of the motor inhibition in the upper and lower extremities during REM sleep. Also dream speech was found to be related to respiration patterns (Fenwick et al., 1984). Motor actions in lucid dreams seem also to activate the same brain patterns as in the case of physically accomplished actions in wakefulness. Erlacher, Schredl, and LaBerge (2003) in an EEG study found a decrease of EEG alpha power over the motor areas during hand clenching in a lucid dream, suggesting the involvement of the cortical motor regions in dreamed actions. These findings were confirmed by a recent fMRI/NIRS study which found that dreamed hand clenching activated similar regions in the sensomotory cortex as actual hand clenching, but the activation was weaker – about 50% as compared to actual execution, yet somewhat stronger as compared to wakeful imagination (Dresler et al., 2011).

By using eye signals from a dreamer, it is possible to measure the exact time intervals required for different actions in lucid dreams. In a pilot study LaBerge (1985a) found that counting from one to ten in a lucid dream takes about the same time as in wakefulness. Erlacher and Schredl (2004b) asked lucid dreamers to count to five, do a sequence of squats, then count to five again, and also did not find significant differences between counting intervals in lucid dreams and wakefulness, yet doing squats took about 40% more time in a lucid dream compared to wakefulness. In a subsequent study, Erlacher, Schädlich, Stumbrys, and Schredl (2014) examined if the task modality, length, or complexity, might be an influencing factor for the prolonged durations in lucid dreams. Three different conditions were performed both in lucid dreams and wakefulness: counting to 10, 20, and 30; walking 10, 20, and 30 steps; and a gymnastic routine. It was found that performing a motor task in a lucid dream indeed takes more time than in wakefulness. The differences in time, however, were observed only for the absolute durations (i.e. the total time required to perform the task) but not for the relative durations (i.e. there was no a disproportional time effect when accomplishing longer tasks). More complex actions did not lead to more prolonged durations.

Considering the evidence for correspondences between (lucid) dreamed actions and executed actions in the central nervous activity, autonomic responses and time aspects, Erlacher and Schredl (2008b) proposed that actions in dreams, similarly as imagined actions in wakefulness (cf. Decety, 1996), also appear to share the same neural structures with executed actions, which supports the theory of neural simulation of action by Jeannerod (2001).

3.3. Psychology

A number of studies explored personality variables and individual differences that might be associated with the ability to lucid dream. Frequent lucid dreamers appear to be more field independent in their cognitive style (i.e. are more analytical when approaching a problem, noticing features separately from the context), more internal on locus of control (i.e. experience themselves as being in control of their life), have a higher need of cognition, thinner boundaries (i.e. greater interconnection between various mental states and processes) and rate themselves as more creative (Blagrove & Hartnell, 2000; Blagrove & Tucker, 1994; Gackenbach, Heilman, Boyt, & LaBerge, 1985; Galvin, 1990; Hicks, Bautista, & Hicks, 1999; Patrick & Durndell, 2004; Schredl & Erlacher, 2004; Zink & Pietrowsky, 2013). Within the Big Five personality traits, they appear to be more open to experience, yet seem somewhat less agreeable (Schredl & Erlacher, 2004; Watson, 2001; Yu, 2012).

When comparing lucid to non-lucid dreams, lucid dreams are marked by higher levels of insight, control, thought, memory, dissociation, and positive emotions, but do not differ in their realism and negative emotions (Voss, Schermelleh-Engel, Windt, Frenzel, & Hobson, 2013). Experienced volition in lucid dreams is comparable to one in wakefulness and is higher than experienced volition in non-lucid dreams (Dresler et al., 2014). Lucid dreams, however, are not always completely lucid: Cognition and memory are quite often impaired and irrational thoughts persist (Barrett, 1992). For example, lucid dreamers are not always successful in recalling their waking memories in lucid dreams (Erlacher, 2009; Stumbrys, Erlacher, Johnson, & Schredl, 2014).

Perception in lucid dreams is also appears to be very similar to the waking perception with both being quite different from the waking imagination. In a study by LaBerge and Zimbardo (2000), participants were asked to draw a circle with their eyes by tracking movements of the finger in three different conditions: awake with eyes open (actual perception), awake with eyes closed (waking imagination) and while lucid dreaming. The circles drawn in lucid dreams much more resembled the circles drawn during the actual perception, showing predominantly slow tracking eye-movements, whereas circles drawn in the waking imagination were rather different and were distinguished by saccadic eye movements with significantly higher velocities.

4. Motor learning in lucid dreams

The ability to be aware in the dream state and deliberately perform actions while physically asleep opens up opportunities to use lucid dreams for sports practice, for example, to consciously rehearse specific motor tasks without waking up (Tholey, 1990). This lucid dream practice thus is similar to mental practice in wakefulness: Movements are rehearsed with a representation of the body on a cognitive level without overt physical movements (Erlacher, 2007).

As with mental practice in wakefulness and imagined actions (cf. Decety, 1996), motor actions performed in lucid dreams also appear to share underlying neural mechanisms with executed actions (Erlacher & Schredl, 2008b), which sets the foundation for motor learning – a set of processes associated with practice or experience leading to relatively permanent changes in the capability for movement (Schmidt & Lee, 2005). Functional equivalence during lucid-dreamed movements in central nervous activity (cf. Dresler et al., 2011), relative timings (cf. Erlacher et al., 2014), as well as peripheral effectors (cf. Erlacher & Schredl, 2008a) enables to strengthen neural networks involved in motor programming via rehearsal in lucid dreams and improve motor performance.

4.1. Previous research

Several anecdotal accounts have been presented in the literature about professional and amateur athletes who claimed that their waking performance was improved due to their practice in lucid dreams. Tholey (1990), for example, presented a case of a martial artist who studied for years the “hard” martial art systems (karate, taekwondo, and jujitsu) and then unsuccessfully tried to learn the "soft" system of aikido (experiencing difficulties because of his hard-wired “hard” movements). He started to practice aikido in his lucid dreams and after a week of such practice amazed his instructor with almost a perfect defence. Other examples included a snow skier who mastered jetting in one week after taking initial learning in lucid dreams or an internationally successful equestrian who was perfecting his riding skills in lucid dreams (Tholey, 1990). Some further anecdotal evidence was presented by LaBerge and Rheingold (1990), including the cases of lucid dreamers who were able to learn some special running and skating techniques in their lucid dreams or improve their tennis play. Recently, Erlacher (2007) collected several reports from amateur athletes, for example, a spring board diver, who practiced complex twists and somersaults in her lucid dreams by slowing down the whole sequence to focus on important details of the dive, or a snowboarder, who lucidly practiced several tricks on his board which he could not do in waking life, and the practice in lucid dreams helped him to get better.

The scientific research on the effects of lucid dream practice is rather scarce. Tholey (1981) conducted a qualitative study where six proficient lucid dreamers were asked in their lucid dreams to perform and practice movements and complex sport skills, such as skiing on gymnastics, with which they were already familiar from their waking life. According to the participants' reports, they did not encounter any difficulties while performing complex sport skills in lucid dreams and the movements were accompanied by a pleasant feeling in the dream. The participants also had an impression that following their lucid dream practice, their movements improved both in the dream state and waking life.

Further, Erlacher and Schredl (2010) conducted a pilot study (field experiment) with a pre-post design in which the participants were asked to practice a simple motor task – to toss 10-cent coins into a cup, positioned at the distance of two meters, as many times as possible out of 20 attempts. Twenty participants tried to practice the task in a lucid dream on a single night and seven of them succeeded. Their performance was compared to a group which accomplished actual physical practice (n = 10) and a control group without practice (n = 10). There were significant increases in hitting the target from pre-test to post-test for both lucid dream practice and physical practice groups, but no improvements were found for the participants who did not practice the task. Although the improvements achieved by lucid dreaming practice were somewhat lower than the ones achieved by actual physical practice, the differences were not statistically significant.

Thus motor learning in lucid dreams seems to be feasible and appears to be effective. Yet several questions remain unclear. How prevalent is lucid dream practice in athletes and how many of them do actually have lucid dreams which could make such practice possible? How lucid dreams can be efficiently induced, making lucid dream practice more accessible? How effective lucid dream practice is, as compared to actual physical practice and mental practice in wakefulness? These questions formed the basis of the present investigation.

4.2. Study 1: Prevalence of lucid dreams and lucid dream practice in athletes

In the first study (Paper 1: Erlacher, Stumbrys, & Schredl, 2011-2012), 840 German athletes (483 male / 357 female) from a variety of sports (including both team sports and individual sports) were surveyed about their experiences with lucid dreams. In average, the participants were 21.6 ± 6.3 years of age, practicing their sport for 11.1 ± 5.8 years, with 11.1 ± 6.6 hours of practice per week. About 57% of athletes stated that they experienced a lucid dream at least once and 24% reported that they have lucid dreams once a month or more frequently and therefore can be considered as frequent lucid dreamers (cf. Snyder & Gackenbach, 1988). These findings thus show that lucid dreaming has similar prevalence rate in athletes as in general population (cf. Schredl & Erlacher, 2011), however the rough estimate of the percentage of lucid dreams as compared to all recalled dreams in athletes was found to be nearly twice as big as in general population (14.5% vs. 7.5%). About 9% of athletes who had lucid dreams (5% of the total sample) used their dreams to practice sports skills and the majority of those who practiced (77%) had an impression that their performance improved following their practice in lucid dreams.

While most of athletes had some lucid dream experiences, only few have used lucid dreams for their sport practice. To make lucid dream practice more available, it is important to have efficient techniques that athletes could use for lucid dream induction.

4.3. Studies 2 & 3: Inducing lucid dreams

Since the onset of lucid dream research, it was demonstrated that the ability to lucid dream can be facilitated (LaBerge, 1980a). A plethora of different techniques for lucid dream induction have been suggested in the literature (e.g. Gackenbach, 1985-1986; LaBerge & Rheingold, 1990; Price & Cohen, 1988; Tholey, 1983b), however a considerable number of these techniques were based on personal or anecdotal accounts and lacked empirical evaluation. The second study (Paper 2: Stumbrys, Erlacher, Schädlich, & Schredl, 2012) aimed to systematically review all published evidence on lucid dream induction and present an empirically-based classification of different induction methods. A comprehensive literature search was carried out in a number of electronic bibliographic databases and (lucid) dreaming specific resources (e.g. dreaming-dedicated scientific journals, references, personal collections). One hundred and thirty one citations were identified via database search and 22 via hand search in specific resources. Thirty-seven manuscripts reporting 35 studies (11 sleep laboratory and 24 field studies) were included in the final analysis. The methodological quality of the studies was assessed with the Downs and Black's (1998) checklist and was found to be rather low. Three classes of methods were used for lucid dream induction: cognitive techniques (26 studies), external stimulation (11 studies) and miscellaneous (1 study – drug application). Cognitive techniques aimed to increase the frequency of lucid dreams by training cognitive skills, such as prospective memory, self-reflection, or intention, while external stimulation intended to trigger lucid dreams either by presenting a cue during REM sleep (which could get incorporated into the dream) or by a specific activation (e.g. vestibular). Drug application aimed to alter cholinergic levels of the brain. None of the induction techniques were verified to induce lucid dreams reliably, consistently, and with a high success rate, although some did look promising. A few methods were found that were not yet tested empirically. One of such prospective but untested methods was brain stimulation, which seemed to warrant empirical examination.

The third study (Paper 3: Stumbrys, Erlacher, & Schredl, 2013b) thus aimed to manipulate the brain activity during REM sleep to increase dream lucidity. The hypothesis for this experiment was derived from two recent studies that showed increased activation in the prefrontal brain regions during lucid dreaming (Dresler et al., 2012; Voss et al., 2009) and from the suggestion by Hobson et al. (2000) that reactivation of the dorsolateral prefrontal cortex (DLPFC), which is normally deactivated during REM sleep, might be linked to dream lucidity. Nineteen participants spent three consecutive nights in a sleep laboratory. The first night served as an adaptation and screening (for sleep disorders and sensitivity to stimulation) night, while the second night and the third night were experimental nights: In a randomized and counterbalanced order, on one of those nights the participants received 1 mA anodal transcranial direct current stimulation (tDCS) over the DLPFC for 10 min during each REM period (starting from the second) and on the other night they received sham stimulation. One minute after the stimulation, the participants were awakened and asked for their dream reports and to rate their dream metacognition and lucidity. Dream reports were later permutated and scored by an external judge for lucidity and bizarreness. According to the participants' self-reports, tDCS delivered over the DLPFC during REM sleep resulted in increased dream lucidity. The judge scored dream reports from a tDCS night also as more lucid and somewhat more bizarre as compared to dream reports from a sham night. The effects, however, were not strong and pronounced only in frequent lucid dreamers. Further, tDCS quite often disrupted REM sleep and resulted in awakenings. Thus, while the study provides support for the involvement of the DLPFC in lucid dreaming, due to small effects, practical applications for lucid dream induction might be rather limited. Future studies, however, can try to target different brain regions, such as the precuneus – the area which was found to be the most strongly activated during lucid dreaming in a recent fMRI study (Dresler et al., 2012), or higher stimulation intensities (e.g. 2 mA) with topically applied local anesthetic creams.

The development of efficient techniques for lucid dream induction thus still remains one of the biggest challenges for lucid dream research.

4.4. Study 4: Effectiveness of lucid dream practice

The final fourth study (Paper 4: Stumbrys, Erlacher, & Schredl, submitted) aimed to replicate the findings from Erlacher and Schredl (2010) with a different (serial reaction) motor task and compare the effectiveness of lucid dream practice not only to physical but also to mental practice in wakefulness. Further, it was aimed to match the times of different practice conditions, in order to avoid the interference of memory consolidation effects during sleep (cf. Fischer et al., 2002; Walker et al., 2002). Online experiment was completed by 68 participants divided into four groups: lucid dream practice group, mental practice group, physical practice group and control (no practice) group. Finger-tapping was used as a motor task: The task required pressing four keys on a computer keyboard with a non-dominant hand producing a sequence of five elements "as quickly and accurately as possible" for a period of 30 s. All participants completed the pre-test in the evening and the post-test in the morning, while the participants in three practice groups also practiced the task either in a lucid dream, or – at a corresponding time after awakening from sleep – physically or mentally. At the post test, significant improvements were seen for all three practice groups but not for the control group. In lucid dream practice group, the performance improved by 20% (effect size d = 0.91), in physical practice group by 17% (d = 1.57), while in mental practice by 12% (d = 1.16). All these effect sizes are considered large (≥ 0.8) according to Cohen (1992). Slight insignificant improvement was also observed in control group (5%, d = 0.39). Post-hoc analysis showed that the improvements in lucid dream practice group and physical practice group were significantly greater than in control group. No significant differences were found between other groups.

Thus motor practice in lucid dreams was replicated to be effective in improving performance. Considering also the findings from the previous study (Erlacher & Schredl, 2010), the improvements following lucid dream practice seem to be similar or slightly lower as compared to actual physical practice, and similar or slightly higher as compared to mental practice in wakefulness. However more studies are needed, especially in a sleep laboratory environment, which can ensure more controllable experimental conditions.

Summary and conclusions

The aim of the present investigation was to explore the potentials for motor learning in lucid dreams: prevalence and frequency rates among athletes, methods for facilitation and effectiveness. It was found that lucid dream frequency in athletes is similar as in general population, however the percentage of lucid dreams as compared to all recalled dreams in athletes was found to be nearly twice as high as in general population. Yet only few athletes used lucid dreams for their sport practice. This shows that lucid dream practice is little known and more publicity is needed among sport scientists, physical educators, coaches, athletes and general public. Work with children and adolescents might be especially fruitful, as lucid dreams seem to be more pronounced in young children and the incidence rates drop at the age of 16, which is likely to be linked to brain maturation (Voss, Frenzel, Koppehele-Gossel, & Hobson, 2012).

To make lucid dream practice more available, reliable lucid dream induction techniques are needed. In our systematic review, we found over a dozen different methods that were used for lucid dream induction. Yet none of them were verified to induce lucid dreams reliably, consistently, and with a high success rate. We also tested one of the prospective methods suggested in the literature but not previously empirically examined - brain activation via transcranial direct current stimulation. While we observed increases in dream lucidity following the stimulation, the effects were rather small and pronounced only in frequent lucid dreamers. The question of reliable induction methods, thus, still remains one of the most pertinent issues for lucid dream research, limiting both scientific investigation (where *always* the main challenge is the recruitment of proficient lucid dreamers) and practical applications (making lucid dream practice more widely available). It is also important to note that lucid dreaming appears to be more an ability rather than a skill – while the frequency of lucid dreams can be increased by applying different induction methods, it seems to go back to the baseline levels upon discontinuation of training (Schredl, 2013). Thus continuous induction practice is important. Considering a higher proportion of lucid dreams as compared to all recalled dreams in athletes, one approach for them might be to try to increase their overall dream recall (e.g. starting to keep a dream diary), as the correlation between lucid dream frequency and overall dream recall frequency is one of the most robust findings in lucid dream research (Stumbrys et al., 2014).

Further, we were able to replicate the earlier study and demonstrate – with a different task – that motor practice in lucid dreams is effective in improving performance.

This time we also matched practice times to avoid the interference of memory consolidation processes and made comparisons both with physical practice and mental practice in wakefulness. While it is difficult to draw firm conclusions from only two studies, the effectiveness of lucid dream practice seems to be similar to either physical or mental practice in wakefulness. Yet, in comparison to waking imagination, it offers much more realistic simulation which may offer additional benefits (cf. Tholey, 1990).

Tholey (1990) provided several suggestions for athletes who want to use lucid dreams for their sport practice. His recommendations refer not only to the repetitive training of sport skills but also to other aspects of sport performance. In lucid dreams, athletes can attain mental flexibility (e.g. by varying the actions and reacting to unforeseen situations), acquire new sensory-motor skills, explore more risky actions, practice without a fear of injury or negative judgments by trainers and spectators, experience themselves as both athletes and spectators at the same time, manipulate both phenomenal space and phenomenal time, and develop greater creativity in sports (Tholey, 1990).

Future studies could explore some of these potential applications, for example, the acquisition of completely novel motor skills or the development of greater creativity. Moreover, it would be important to replicate the effects of lucid dream practice in a sleep laboratory environment, which assures more strict compliance with the study procedure. Further comparisons with physical and mental practice are also very interesting: Currently we did not find any significant differences between the three different types of practices, although literature shows that mental practice in wakefulness is somewhat less effective than actual physical practice (cf. Driskell et al., 1994), while lucid dreams provide much more realistic simulation (cf. LaBerge & Zimbardo, 2000) which may, arguably, lead to greater learning effects (cf. Tholey, 1990). Finally, it could only be reiterated that the development of effective methods for lucid dream induction is one of the major tasks currently facing lucid dream research and on which largely depends the advancement of the field.

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**FAKULTÄT FÜR VERHALTENS-
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Promotionsausschuss der Fakultät für Verhaltens- und Empirische Kulturwissenschaften der Ruprecht-Karls-Universität Heidelberg
Doctoral Committee of the Faculty of Behavioural and Cultural Studies, of Heidelberg University

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Appendix: Publications

Paper 1: Erlacher, Stumbrys, & Schredl (2011-2012)

Paper 2: Stumbrys, Erlacher, Schädlich, & Schredl (2012)

Paper 3: Stumbrys, Erlacher, & Schredl (2013)

Paper 4: Stumbrys, Erlacher, & Schredl (submitted)

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FREQUENCY OF LUCID DREAMS AND LUCID DREAM PRACTICE IN GERMAN ATHLETES

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ABSTRACT

Mental practice is the cognitive rehearsal of a motor task in the absence of overt physical movement. A different and rather unknown kind of mental rehearsal is practice in lucid dreams. Within lucid dreams, the dreamer is able to control the ongoing dream content and for athletes it is possible to use the dream state to deliberately practice sport skills while physically asleep. In this study, 840 German athletes from various sports were asked about their experience with lucid dreams. About 57% of the athletes stated that they experienced a lucid dream at least once in their lives, 24% are frequent lucid dreamers (having one or more lucid dreams per month), and 9% of the lucid dreamers used this dream state to practice sport skills, and the majority of those athletes had the impression that the rehearsal within the lucid dream improved their performance in wakefulness. The prevalence rate of lucid dreaming in professional athletes is similar as in general population, however the rough estimate of the percentage of lucid dreams compared to all dreams in athletes was found to be nearly twice as high as in general population (14.5% vs. 7.5%). The possibilities of lucid dream practice for professional sports will be discussed.

Mental practice is the cognitive rehearsal of a motor task in the absence of overt physical movement and in professional sport, mental rehearsal is well established

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(e.g., Hinshaw, 1991-1992). A different and rather unknown kind of mental rehearsal is practice in lucid dreams. In lucid dreams, the dreamer is aware of the fact that he or she is dreaming, is able to control the ongoing dream content, and is free to do what he or she wants (LaBerge, 1985). For athletes, it is possible to use the dream state to consciously practice specific sport skills (Erlacher, 2007). In contrast to mental practice, which is performed during wakefulness, practice in lucid dreams take place while the person is in REM sleep (Erlacher & Schredl, 2008). Several meta-analyses (e.g., Driskell, Copper, & Moran, 1994; Feltz & Landers, 1983) demonstrated that in general mental practice has a positive and significant effect on performance. It seems plausible that practice in lucid dreams would have beneficial effects as well (Tholey, 1990). Lucid dream research suggests that actions carried out in REM (lucid) dreams and wakefulness are comparable (correlations exist for central nervous activity, autonomous responses, time aspects), supporting the notion that dreamed and actual movements share, to some extent, the same central neural structures (Erlacher & Schredl, 2008), similarly as in the case of imagined actions in wakefulness (Decety, 1996). But in contrast to the vast amount of research on mental practice, for practice in lucid dreams the empirical basis is rather small, which can be explained by the fact that lucid dreaming is a rather unknown phenomenon in the scientific sports community.

Tholey (1981) conducted a qualitative study in which six proficient lucid dreamers in their lucid dreams were asked to perform and practice movements and complex sport skills, such as skiing or gymnastics, with which they were already familiar from waking life. According to the participants, they did not encounter any difficulties while performing complex sport skills in their lucid dreams and the movements were accompanied by a pleasant feeling in the dream. The participants also had an impression that following the practice, their movements improved both in their dream state and their waking state. In a quasi-experimental pre-post design study conducted by Erlacher and Schredl (2010b) participants were asked to practice an aiming task in their lucid dreams. Results showed a significant increase in hitting the target from pre-test to post-test for the group which practiced the coin-tossing task in their lucid dreams, but no increase was found for the group that did not practice the task. The improvements achieved by the lucid dreaming practice group were not significantly different from the other group who carried out the actual physical practice. Even though confounding variables such as motivation could not be controlled for by the experimental design used, the results of this study indicate that practice in lucid dreams can enhance performance in wakefulness.

In several anecdotal reports, amateur and professional athletes claimed that they used lucid dreams to improve their waking performance (e.g., Erlacher, 2007; LaBerge & Rheingold, 1990; Mechsner, 1994; Tholey, 1990). Erlacher (2007) reported of several amateur athletes who improved their skills during lucid dreams, for example, a spring board diver who practiced complex twists and somersaults in her lucid dreams by slowing down the whole sequence to focus on important details of the dive, or snowboarder who lucidly practiced several tricks on his board that he could not do in waking life, and the practice in his dreams helped him to get better (see also Erlacher & Schredl, 2010b).

However, it is little known about the prevalence of this kind of mental practice in elite sport. Therefore, the aim of the present study was to estimate the prevalence of lucid dreams in elite athletes. Furthermore, we wanted to find out how many athletes use their lucid dream state for rehearsal and whether those athletes had experienced an improvement on their daytime performance. This descriptive data should provide information on the relevance of the topic for sport psychology.

METHOD

Participants

The sample included 840 German athletes (483 men and 357 women). Their mean age was 21.59 years (*SD* = 6.33), ranging from 11 to 55 years. The athletes were recruited through personal contacts or through their coaches and volunteered to participate in a questionnaire study about sleep and dream habits. Participants were involved in various sports ranging from team sports (e.g., basketball, soccer) to individual sports (e.g., athletics, figure skating). The athletes had been practicing their sport for an average of 11.08 years (*SD* = 5.76) and were practicing an average of 11.06 hours (*SD* = 6.56) per week. The time for practice refers to training time in the athletes' sports and excludes additional time for competitions or other sports. A total of 433 athletes belonged to the German national supported team system (bundesgeförderten Kadersystem). Athletes belonging to this system are or will become professional athletes performing on a high national and/or international level. The remaining 407 athletes had no membership in a supportive organization; however, they were ambitious athletes with a long history of sport (*M* = 10.64, *SD* = 6.19 years) and a high number of hours of practice per week (*M* = 7.70, *SD* = 4.38 hours per week). Ethical approval for the study was granted by the Ethics Committee of the Faculty of Behavioural and Cultural Studies at the University of Heidelberg.

Materials

For this study we developed a questionnaire consisting of 38 questions about "Competitive Sports, Sleep, and Dreams." For this analysis we focused on the questions about lucid dreaming, whereas data about sleep before competitions (Erlacher, Ehrlenspiel, Adegbesan, & Galal El-Din, 2011) and dreams with athletic content (Erlacher & Schredl, 2010a) was published elsewhere. In addition to demographic data, the first part of the questionnaire included questions about the participant's sport (e.g., "How long have you been practicing this sport?"; "How much time do you spend training per week on average?"). Then participants were asked how often they experience lucid dreams using an 8-point scale: 0 = never, 1 = less than once a year, 2 = about once a year, 3 = about two to four times a year, 4 = about once a month, 5 = about two to three times a month, 6 = about once a week, 7 = several times a week. To ensure a clear understanding of the phenomenon, a short definition was presented: "During lucid dreaming, one is—while dreaming—aware of the fact that one is dreaming. It is possible to deliberately wake up or to control the dream action or to observe passively the course of the dream with this awareness." For the importance of a clear definition, see Snyder and Gackenbach (1988). Furthermore, an example of a lucid dream was presented within the questionnaire. In order to obtain units in frequency per month, the scales were recoded using the class means (0 → 0, 1 → 0.042, 2 → 0.083, 3 → 0.25, 4 → 1.0, 5 → 2.5, 6 → 4.0, 7 → 18.0) (Schredl & Erlacher, 2004). Then we asked athletes how they developed their ability to have lucid dreams. The answer categories included "spontaneously," "by deliberate practice," or "by methods to relax" (e.g., meditation, Yoga, etc.). Next, athletes were asked if they have ever used lucid dreams to practice their sport while dreaming. If this was confirmed by the athletes, then they were asked if they had an impression that their performance had improved by their practice during the lucid dream. Finally, the athletes were asked to indicate how often they were able to remember their dreams during the past few months on a 7-point scale: 1 = never, 2 = less than once a month, 3 = about once a month, 4 = two or three times a month, 5 = about once a week, 6 = several times a week, 7 = almost every morning. This scale for dream recall frequency has been shown to have high retest reliability ($r = .85$; Schredl, 2004). In order to obtain units of mornings per week, the scale was recoded using the class means (0 → 0, 1 → 0.125, 2 → 0.25, 3 → 0.625, 4 → 1.0, 5 → 3.5, 6 → 6.5).

Design and Procedure

Following the informed consent from the athletes to participate in the study, the questionnaire was administered to the athletes with the assistance of the coaches and the author. All athletes were asked to fill out the questionnaires at their own pace and return the questionnaire to one of the authors. Because this is an explorative study, the focus is on a descriptive level and all parameters were tested two-tailed. Statistical analyses were carried out with the SPSS for Windows (Version 17.0) software package.

RESULTS

Table 1 depicts the frequency of lucid dreams for the athletes. Of all 840 athletes, 475 (56.55%) stated that they had experienced a lucid dream at least once. The majority of the participants have lucid dreams infrequently; however, about

Table 1. Lucid Dream Frequency

Category	Frequency	Relative frequency (%)
Never	365	43.45
Less than once a year	78	9.29
About once a year	69	8.21
About two to four times a year	129	15.36
About once a month	95	11.31
About two to three times a month	59	7.02
About once a week	20	2.38
Several times a week	25	2.98

Note: N = 840

41.89 % of them (or 23.69% of the total sample) can be considered to be frequent lucid dreamers (frequency equal or higher than once per month) in the terminology of Snyder and Gackenbach (1988). The average lucid dreaming frequency was 0.97 (SD = 3.12) lucid dreams per month. Considering that the mean dream recall frequency for this sample was 1.67 (SD = 1.89) mornings with dream recall per week, a rough estimate of the percentage of lucid dreams compared to all dreams is 14.52%.

Among the lucid dreamers, 81 (17.05%) did not specify how they have developed their ability to have lucid dreams, the majority of 375 (78.95%) athletes stated that their lucid dreams evolved spontaneously, 14 (2.95%) applied specific techniques, and 5 (1.05%) evoked their lucid dreams by the methods of relaxation. A total of 44 athletes, this is 5.24% with respect to the total sample and 9.26% with respect to the lucid dreamers, reported that they have used lucid dreams to practice their sport while dreaming and 34 of them (77.27%) stated that they had the impression that their performance was improved by the practice during the lucid dream.

We performed a regression analysis with the frequency of lucid dreams (0 = *never* to 7 = *several times a week*) as the dependent variable, all the following variables were entered simultaneously: dream recall frequency, gender, age, years of sport career, practice hours per week, and sport group. Table 2 shows that dream recall frequency was the only statistically significant predictor. Athletes with a high dream recall frequency were more likely to experience more lucid dreams. The correlation coefficient between lucid dreaming frequency and dream recall frequency was $r = .32$ ($p < .001$).

Table 2. Summary of Regression Analysis for Variables Predicting the Occurrence of Lucid Dream Frequency

Variables entered	Standardized estimate	*T*	*p*
Dream recall frequency	.317	9.60	< .001
Gender	–.042	–1.06	.29
Age	–.028	–.83	.40
Years of sport career	.030	.77	.44
Practice hours per week	.056	1.51	.13
Sport group (individual vs. team sport)	.037	1.02	.31

Note: Adjusted $R^2 = .106$; $N = 840$

DISCUSSION

The results indicate that about 57% of the athletes stated that they experienced a lucid dream at least once in their lives and about 24% are frequent lucid dreamers (having one or more lucid dreams per month) in the terminology of Snyder and Gackenbach (1988). About 9% of the athletes who had lucid dreams have used their dreams to practice sports skills, and the majority of them (about 77%) had an impression that their performance improved following their sport practice in lucid dreams.

The study shows that lucid dreaming has a similar high prevalence rate in the elite athletes as in the general population. Schredl and Erlacher (2011) found that in a recent representative German population sample ($N = 937$), 51% of the participants had a lucid dream at least once and about 20% were frequent lucid dreamers. However, interestingly enough, the rough estimate of the percentage of lucid dreams compared to all dreams in the professional athletes (14.5%) is nearly twice as big as it was found in general population (7.5%; Schredl & Erlacher, 2011). This higher rate of lucid dreaming in athletes perhaps might be explained by the possible differences in spatial and vestibular skills. Snyder and Gackenbach (1988) speculated that the vestibular system plays a role in lucid dream frequency and refer to studies which show that, for example, lucid dreamers have better static balance abilities than infrequent lucid or non-lucid dreamers, are more responsive to caloric irrigation than non-lucid dreamers, etc. In general, athletes are more likely to have a better trained vestibular system than non-athletes because of their continuous involvement in their sports practice. Furthermore, an association between lucid dreaming and good physical orientation/balance was also found by Hunt (1989).

Dream recall frequency was the only variable that predicted the occurrence of lucid dreams in the athletes ($r = .32$, $p < .001$). This relation is consistent with the findings of other studies (e.g., Doll, Gittler, & Holzinger, 2009; Schredl & Erlacher, 2004). No relation was found with demographic parameters (gender, age), nor with sport-specific parameters such as type of sport practiced (individual vs. team sport), number of years practiced, or time spent training per week (see Table 2).

Some methodological issues must be considered when interpreting the results. The sample used in this study was not a representative sample; however, the athletes were recruited from a variety of sport disciplines, including both individual and team sport. Besides, the majority of the athletes were performing at a high (national and international) level. Furthermore, the sample included German athletes only and it might be difficult to generalize the findings to other countries as there seems to be some cross-cultural differences in lucid dream frequency (Erlacher, Schredl, Watanabe, Yamana, & Ganzert, 2008). Lucid dreams percentage was assessed using a rough questionnaire measurement. Such retrospective technique might be biased by memory effects or by difficulties in understanding the lucid dream phenomena. Therefore, it is suggested to provide dream examples to ensure that the participants have a correct understanding of the term lucid dreaming (Snyder & Gackenbach, 1988). However, the definition of lucid dreaming provided in this study seems to be very valid in eliciting lucid dreams: in an online study with the same definition of lucid dreaming, 87% of the lucid dream examples provided were rated as lucid dreams by an external judge, only 1.3% were rated as non-lucid dreams, and for 11.7% of the dreams reported information was not sufficient to make a decision (Johnson, 2007).

From mental rehearsal it was shown that mental practice in wakefulness produces a positive and significant effect on subsequent performance (e.g., Driskell et al., 1994). The average effect size is moderate, estimated to be 0.48, but it varies depending on the type of the task, the duration of the practice, the retention interval, the participants' level of experience, and other factors. Lucid dreaming practice can be considered as a special form of mental practice and it is suggested that it might be even more effective than other forms of mental training, because in lucid dreams the world is experienced as real and not perceived as existing only in imagination (Tholey, 1990). LaBerge and Zimbardo (2000) conducted a study in which participants were asked to track a circle with their eyes in three different conditions: awake with eyes open (perception), awake with eyes closed (imagination), and in a lucid dream. The results showed that perception of the circle in lucid dreams was nearly identical to actual perception in wakefulness and distinct from imagination as imagination is distinct from actual perception. LaBerge and Zimbardo (2000) consider dreaming as the special case of perception independent of external sensory input. Lucid dreaming therefore mimics a perfect simulation of the real world whereas the dreamer experiences the dream body and the dream environment as real as perception in wakefulness (Erlacher & Chapin, 2010).

Considering this fact that perception in lucid dreams is closer to actual perception than imagination, it is plausible that the effectiveness of lucid dream practice might be higher than the effectiveness of mental rehearsal in wakefulness and closer to the actual physical practice (Erlacher, 2007); however, further research is needed to verify this hypothesis.

Tholey (1990) provides several suggestions for athletes who want to use lucid dreams for rehearsing their sports. His recommendations refer not only to repetitive training of sport skills but also other aspects of sport performance. In lucid dreams, athletes can attain mental flexibility, acquire new sensory-motor skills, explore more risky actions, practice without fear of injury or negative judgments by trainers and spectators, experience themselves as both athletes and spectators at the same time, manipulate both phenomenal space and phenomenal time, and develop greater creativity in sports (Tholey, 1990).

For practical implications, it is necessary that athletes need to have techniques to learn lucid dreaming. A great variety of induction techniques are presented in the literature; however, only very few of them have been formally tested. Price and Cohen (1988) classify lucid dreaming induction techniques into three categories: "lucid awareness training," "intention and suggestion" techniques, and "cue-REMinding" techniques. "Lucid awareness training" includes those techniques in which a person attempts to develop a particular attitude or state of consciousness during wakefulness. The idea behind this is that once this attitude becomes firmly established while awake, it will also be triggered during the dream (Tholey, 1989). "Intention and suggestion" techniques focus on an act of will, auto-suggestions, or posthypnotic suggestions, where a person concentrates on the intention to become lucid or intends, for example, to perform a particular action in the dream which is associated with lucidity prior to sleep (Price & Cohen, 1988). "Cue-REMinding" techniques aim to trigger lucidity by presenting an external stimulus during REM sleep (LaBerge & Levitan, 1995). Despite the fact that a broad range of techniques have been suggested, none of them have been verified to induce lucid dreams reliably and consistently. In order to utilize lucid dreams in sports practice or other areas, such reliable techniques must be established. Currently this is one of the major tasks facing lucid dream research.

To summarize, the results of the present study indicate that most of German elite athletes in the selected sample were familiar with lucid dreaming and about a quarter of the athletes can be considered as frequent lucid dreamers. The prevalence of lucid dreaming in elite athletes is similar as in general population; however, the percentage of lucid dreams in comparison with all dreams in elite athletes seems to be higher than in general population. Lucid dreaming frequency in athletes was unrelated to their gender, age, years or frequency of practice, or type of sports (individual vs. team sport). Some athletes are using lucid dreams for their sports practice and the vast majority of them have an impression that lucid dreaming practice enhances their performance in wakefulness. Future studies should test the effectiveness of lucid dreaming practice in sports and establish reliable techniques for lucid dream induction which would make lucid dreaming practice to be accessible to a greater number of athletes.

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Review

Induction of lucid dreams: A systematic review of evidence

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ABSTRACT

In lucid dreams the dreamer is aware of dreaming and often able to influence the ongoing dream content. Lucid dreaming is a learnable skill and a variety of techniques is suggested for lucid dreaming induction. This systematic review evaluated the evidence for the effectiveness of induction techniques. A comprehensive literature search was carried out in biomedical databases and specific resources. Thirty-five studies were included in the analysis (11 sleep laboratory and 24 field studies), of which 26 employed cognitive techniques, 11 external stimulation and one drug application. The methodological quality of the included studies was relatively low. None of the induction techniques were verified to induce lucid dreams reliably and consistently, although some of them look promising. On the basis of the reviewed studies, a taxonomy of lucid dream induction methods is presented. Several methodological issues are discussed and further directions for future studies are proposed.

Contents

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1. Introduction

1.1. Lucid dreams

A lucid dream is a dream during which the dreamer is aware of the fact that he or she is dreaming and therefore often can consciously influence the dream content (LaBerge, 1985). Although awareness of dreaming while dreaming is usually considered an adequate criterion for lucid dreaming, some discussions have been held whether this is sufficient (Gillespie, 1984; Tart, 1984, 1985). Tart (1984), for example, separates dreaming-awareness dreams and lucid dreams, for which he poses an additional criterion that overall clarity of waking consciousness should also be retained. Tholey (1985) describes seven aspects of lucidity (clarity) in dreams: (1) clarity about the state of consciousness (that one is dreaming); (2) clarity about the freedom of choice; (3) clarity of consciousness; (4) clarity about the waking life; (5) clarity of perception; (6) clarity about the meaning of the dream; (7) clarity recollecting the dream. According to him, (1)–(4) are indispensible prerequisites of lucid dreaming. While in this paper we will follow the conventional minimal criterion for the definition (awareness of dreaming while dreaming), it is important to acknowledge that dream lucidity is not an "all-or-nothing" phenomenon but rather a continuum with different degrees: some dreams can be more lucid than others (Barrett, 1992; Moss, 1986).

Despite the fact that the phenomenon of lucid dreaming was known since the times of Aristotle (see Aristotle, 2007), only 30 years ago it was successfully verified in a sleep laboratory by measuring eye movements during REM sleep corresponding with dreamed gaze shifts (Hearne, 1978; LaBerge, 1980a; LaBerge, Nagel, Dement, & Zarcone, 1981). Since then, numerous studies have been conducted and research (overview: Erlacher & Schredl, 2008a) indicates that lucid dreaming is mainly a REM sleep phenomenon, although it can also occur during NREM sleep (see Dane, 1984).

During REM dreams the skeletal muscles of the sleeping body are actively suppressed by neural structures in the brain stem, keeping dreamers from actually acting out actions in their dreams (Hobson, Pace-Schott, & Stickgold, 2000). One obvious exception is eye movements. In accordance with the scanning hypothesis, eye movements during REM sleep correspond with shifts of gaze in dream imagery (cf. Roffwarg, Dement, Muzio, & Fisher, 1962). Since lucid dreamers have access to their waking memories (cf. Erlacher, 2009), it is possible for them to move their eyes during the dream according to a prearranged pattern of eye movements (usually: left–right–left–right, LRLR) and produce a distinct electrooculagram (EOG) recording during REM sleep; i.e., they can communicate from within the dream (cf. LaBerge et al., 1981). Then the lucid dreamer can be awakened and asked for a dream report to match the recorded eye signals with the dreamed gaze shifts. In such way, REM lucid dreams were successfully verified by subjective dream reports and objective EOG data in a number of different sleep laboratories across the world (e.g., Dane, 1984; Dresler et al., in press; Erlacher & Schredl, 2008b; Fenwick et al., 1984; Hearne, 1983; Hickey, 1988; Kueny, 1985; LaBerge et al., 1981; Ogilvie, Hunt, Kushniruk, & Newman, 1983; Voss, Holzmann, Tuin, & Hobson, 2009; Watanabe, 2003).

Most frequently, lucid dreams are initiated from REM sleep (so called "Dream-Initiated Lucid Dream" – DILD), however sometimes they can also be initiated from the waking state ("Wake-Initiated Lucid Dream" – WILD) (LaBerge, Levitan, & Dement, 1986). Physiologically, lucid dreams are associated with elevated levels of automatic nervous system activity (LaBerge et al., 1986), but also with higher H-reflex suppression (Brylowski, Levitan, & LaBerge, 1989). According to recent findings, lucid REM sleep when compared to non-lucid REM sleep is associated with increased EEG 40 Hz power, especially in frontal and frontolateral regions (Voss et al., 2009). Another recent fMRI study found increased activation during REM lucid dreaming in several brain regions, including the bilateral precuneus, cuneus, parietal lobules, and prefrontal and occipito-temporal cortices (Dresler et al., in press). This specific pattern of activation might explain the presence of higher order cognitive skills involved in lucid dreaming. The prefrontal cortex is associated with metacognitive regulation and self-assessment, executive function and top-down control of behaviour, attention regulation (Arnsten & Li, 2005; Fernandez-Duque, Baird, & Posner, 2000; Miller & Cohen, 2001; Schmitz, Kawahara-Baccus, & Johnson, 2004), while the precuneus is associated with self-processing operations, such as first-person perspective taking and experience of agency (Cavanna & Trimble, 2006). In lucid dreams the dreamer has to observe and evaluate his or her present experience to recognise the dream state and become lucid, then to take a first-person perspective and agency and guide behaviour and attention according to one's intentions in order to influence the dream content (see also Kahan & LaBerge, 1994).

Although frequent lucid dreaming is considered to be a rare skill, the estimates of lucid dreaming incidence within the general population suggest that about a half of the population have experienced a lucid dream at least once and about one out of five people are experiencing lucid dreams regularly, i.e. at least once a month (Schredl & Erlacher, 2011; Snyder & Gackenbach, 1988; but cf. Stepansky et al., 1998). Recent studies found that the prevalence of lucid dreaming in children is similar as in adults, however younger children seem to have lucid dreams more frequently (Schredl, Henley-Einion, & Blagrove, 2012; Voss, Frenzel, Koppehele-Gossel, & Hobson, in press). Differences across different cultures also exist (e.g., Erlacher, Schredl, Watanabe, Yamana, and Gantzert (2008) found significantly lower incidence of lucid dreaming in Japanese student sample in comparison with other countries). Since the onset of lucid dream research it was demonstrated that lucid dreaming is a learnable skill (LaBerge, 1980b; see also Saint-Denys, 1867/1982) and a number of practical applications were suggested (e.g. LaBerge & Rheingold, 1990). Lucid dreaming, for example, was successfully applied in nightmare treatment: several case studies (Abramovitch, 1995; Brylowski, 1990; Spoormaker, van den Bout, & Meijer, 2003; Zadra & Pihl, 1997) and a controlled trial (Spoormaker & van den Bout, 2006) demonstrated that the development of lucid dreaming abilities can decrease nightmare frequency and nightmare intensity. Lucid dreaming can also be used to enhance and perfect motor performance and motor skills (Erlacher & Schredl, 2010; Tholey, 1981) or employed for creative problem solving (Stumbrys & Daniels, 2010). Furthermore, lucid dreaming is an invaluable tool for scientists to explore the mind–body relationship during REM sleep (see e.g. Erlacher & Schredl, 2008a) and its uniqueness warrants lucid dreaming a special place within the whole area of consciousness research (Hobson, 2009). However, in order to utilize the advantages offered by lucid dreaming and make them available both to the scientific community and a wider population, reliable induction techniques must be established to increase the frequency of lucid dreams. This is the main challenge currently facing lucid dream research.

1.2. Induction techniques and their classifications

By the term "lucid dream induction" we refer to any means aiming to increase the frequency of lucid dreams. A plethora of various techniques (e.g. Gackenbach, 1985–1986; LaBerge & Rheingold, 1990; Price & Cohen, 1988; Tholey, 1983) has been suggested for lucid dream induction and several attempts were made to classify them.

One of the first classification systems was suggested by Gackenbach (1985–1986), who classified induction techniques into two broad categories: (1) presleep induction and (2) sleep induction. The first category, presleep induction, includes intentional techniques and "unintentional considerations". According to Gackenbach, intentional techniques focus on the present moment (e.g. reflecting whether one is dreaming right now, engaging into other focused activities, such as meditation or alpha feedback training) or are focused on the future (e.g. autosuggestion, post-hypnotic suggestion or intention to remember that one is dreaming). Furthermore, some techniques might combine both aspects, e.g. Tholey's (1983) combined technique, which includes elements of reflection (present focussing) and intention with auto-suggestion (future focussing). "Unintentional considerations" include situations during the day (e.g. interpersonal interactions, emotions) and individual propensities (e.g. field independence, creativity; for overview of individual differences associated with lucid dreaming see Snyder & Gackenbach, 1988) that are not directly related to the attainment of dream lucidity but increase the likelihood of having a lucid dream. The second category, sleep induction, can be divided into external cues and internal cues. External clues are various environmental stimuli (e.g. auditory, tactile) that can be applied during REM sleep to be incorporated into a dream and recognised as a cue by the dreamer that he or she is dreaming. Internal cues can be unusual events or inconsistencies within a dream, a sense of "dreamlikeness" or just a spontaneous insight occurring in a dream which leads to the awareness that one is dreaming.

Another classification of lucid dreaming induction techniques was suggested by Price and Cohen (1988), who grouped them into three broad classes: (1) lucid-awareness training, (2) intention and suggestion techniques and (3) cue "REM-minding" techniques. Lucid-awareness training aims to cultivate a proper waking attitude to promote lucidity, such as critically reflecting on a frequent basis whether one is dreaming or not, heightening perceptual awareness, alpha feedback or waking fantasy training. Intention and suggestion techniques aspire to trigger a lucid dream through an act of will or suggestion. Examples of such techniques include intentions to carry out a specific action while dreaming (e.g. flying), to remember that one is dreaming and post-hypnotic suggestions. The third class of induction methods described by Price and Cohen (1988), cue "REM-minding" techniques, resembles Gackenbach's (1985–1986) external cues category and includes tactile, auditory and other external stimuli presented during REM sleep to trigger lucidity. Price and Cohen (1988) also acknowledge that there are some other methods that do not fit into their three major classes described, such as Tholey's combined technique or hypnagogic techniques that aim to enter lucid dreams directly from the waking state at sleep onset.

Although both these classification systems were useful and provided an adequate coverage of lucid dream induction techniques presented in literature, they seem to be fragmentary, not including all techniques. Over the recent years a number of empirical studies have been carried out that expanded our knowledge about induction techniques and new prospective methods emerged (e.g., Noreika, Windt, Lenggenhager, & Karim, 2010). Another issue is that a considerable number of techniques included in these systems were based on personal or anecdotal accounts and lacked any empirical validation. The overlap between different categories is also a problem of these systems: Some induction methods, e.g. Tholey's combined technique, encompass both lucid awareness training and intention, or an intentional technique might result in an internal cue during a dream that will lead to the attainment of lucidity.

Therefore, in this paper we aim to present an empirically based classification of lucid dream induction techniques together with an extensive systematic review of published empirical evidence on lucid dream induction. Considering difficulties defining the exact boundaries between different groups of induction techniques, we defined the following broad categories:

(1) cognitive techniques – encompass all cognitive activities (lucid awareness training, intention, suggestion, hypnagogic techniques, etc.) that are carried out to increase the likelihood of achieving lucidity in a dream state;
(2) external stimulation – includes all types of stimuli (acoustic, light, electric, vibration, vestibular, brain stimulation, etc.) presented during REM sleep that can trigger dream lucidity;
(3) miscellaneous techniques – cover all other diverse induction methods that are not covered by the two categories above (e.g. intake of specific substances).

We hope that such an empirically-based classification will benefit not only lucid dreaming-interested scientists, providing them most promising directions for future research and most effective means to facilitate lucid dreaming both in a sleep laboratory or home environment, but also a broader audience, including therapists, artists, athletes, nightmare sufferers and others who may want to purse lucid dreams for their professional or personal reasons.

2. Method

2.1. Identification of studies

A comprehensive literature search was carried out to identify relevant studies, including both electronic bibliographic databases and (lucid) dreaming specific resources. The following electronic databases were searched: MEDLINE, PsycINFO, PsycArticles, Academic Search Premier, IngentaConnect, ScienceDirect, Scopus, Web of Science, ProQuest Dissertations & Theses Database and PSYNDEX. Specific resources included scientific journals dedicated to (lucid) dream research (such as Lucidity Letter, NightLight, International Journal of Dream Research, Dreaming), references in relevant articles and other sources (such as personal collections). When searching the literature databases, the following search query was used: *dream* AND lucid* AND* (*induc* OR learn* OR technique* OR method* OR exercise**). For a German PSYNDEX database, in addition we also used a corresponding query with German keywords: *traum* AND* (*luzid* OR klar**) *AND* (*indu* OR lern* OR technik* OR method* OR train**).

2.2. Inclusion and exclusion criteria

We aimed to identify any empirical studies that were concerned with lucid dream induction or applied any methods to increase the frequency of lucid dreams in their participants. We also included those studies that were not primarily concerned with lucid dream induction but used some methods to promote lucid dreaming in their participants, e.g. studies that employed lucid dreaming as a treatment for nightmares. Both controlled studies in a sleep laboratory with sleep recording and quasi-experimental field studies without sleep recording were included. No language restrictions were applied. Single case reports were excluded.

2.3. Data extraction, analysis and assessment

Literature search was conducted in November–December 2010 by one researcher and then carried out by a second researcher in April–May 2011. Data was extracted by using a specially devised form and then was reviewed by a second researcher. The methodological quality of all studies was assessed independently by two researchers using a quality checklist developed by Downs and Black (1998), which can be used for evaluation of both randomised and non-randomised studies. The checklist contains 27 items distributed into five subscales: reporting ($n = 10$), external validity ($n = 3$), internal validity – bias ($n = 7$), internal validity – confounding ($n = 6$) and power ($n = 1$). One item on the reporting subscale (No. 5), can have a maximum score of 2, the other items are scored either 0 or 1 (although the item on power [No. 27], can get the score up to 5, in this review the maximum score for this item was considered 1). Hence the maximum score possible score for methodological quality was 28. The Downs and Black (1998) checklist is considered to be among the six best quality assessment tools to be used for systematic reviews (Deeks et al., 2003). Any differences between the researchers were resolved by discussion. Quality scores of 21 and higher were considered good, 11–20 – moderate and 10 and lower – poor (Hartling, Brison, Crumley, Klassen, & Pickett, 2004).

3. Results

3.1. Literature search and excluded studies

Initial literature search and its replication brought equivalent results: Only one additional citation was retrieved and 11 sources were no longer available on ProQuest database. In total, literature search in electronic databases yielded 131 initial

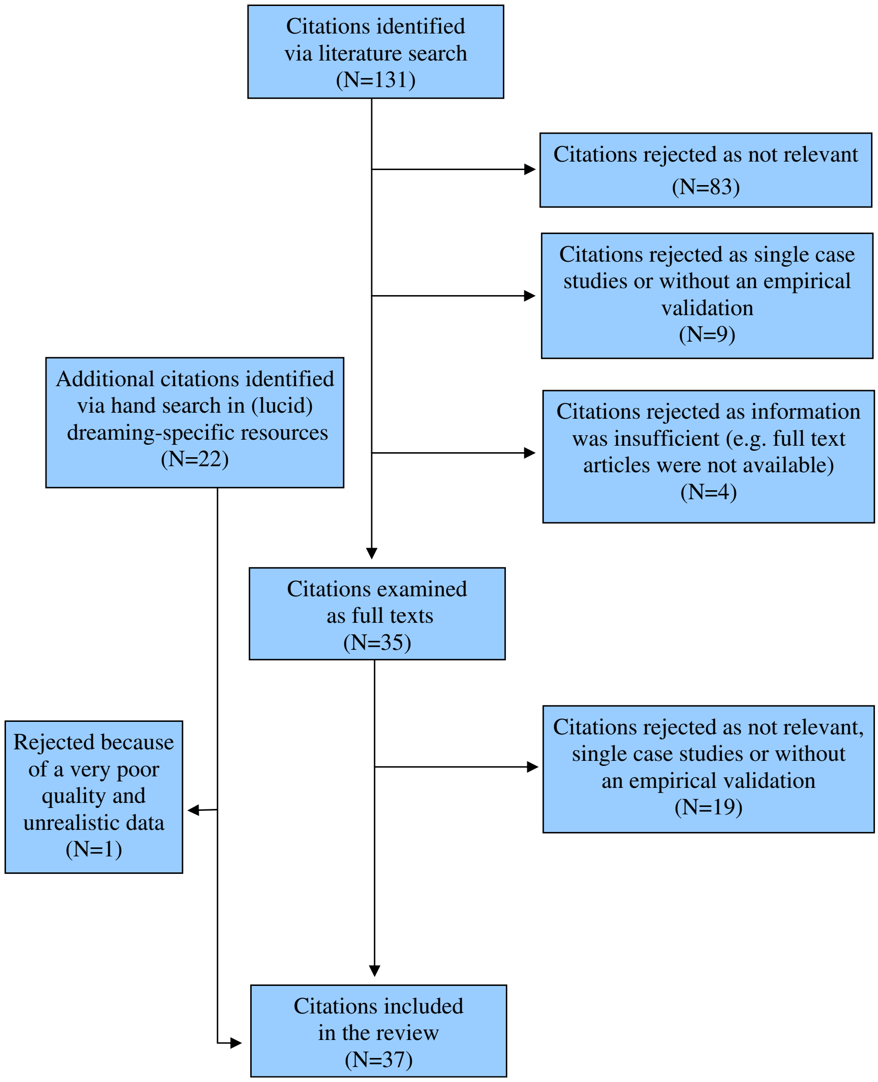

Fig. 1. Study identification flow chart.

references. A first examination of titles and abstracts led to the following: 83 citations were rejected as not relevant, i.e. they were not dealing with lucid dream induction. Further nine citations were rejected according to our inclusion/exclusion criteria, i.e. were either not empirical studies (lacked empirical validation) or just single case studies. Four other citations (three thesis and one conference abstract) were eliminated as information in the abstract was insufficient and full texts were not available. Thus a total of 35 references were examined as full texts. After examination, 19 papers out of them were excluded as not dealing with lucid dream induction, being without an empirical validation or single case studies.

Furthermore, 22 additional papers were identified via hand search in lucid dreaming-specific resources, cited references in relevant articles and personal collections. One study identified via hand search (Ripert in Price, LaBerge, Bouchet, Ripert, & Dane, 1986) contained unrealistic data (according to the data reported, some participants had about 40 lucid dreams per night) and was judged of extremely poor quality (initial assessment by a first judge yielded 0 score on the Downs and Black (1998) checklist), hence it was discarded from further analysis.

The flowchart of the study identification process is demonstrated in Fig. 1.

3.2. Included studies

Therefore 37 manuscripts (16 identified via literature search in electronic databases and 21 via hand search) were included in the review. Some studies were reported in two different manuscripts (e.g., Zadra, 1991; Zadra, Donderi, & Pihl, 1992), while in two other cases (Galvin, 1993; Hickey, 1988) studies involved both sleep laboratory and field experiments witch for the purpose of this review were considered as two separate studies. Thus, a total number of 35 studies were analysed in this review. Details of the included studies are presented in Table 1.

Table 1
Included studies.

No	Reference	Type	Methods	Sample	Techniques used	Main results	Quality
1	Levitan (1989)	Field (within)	4 weeks; different technique each week (1st week – baseline with no technique)	$N = 62$ (lucid dreamers)	MILD, reality testing, autosuggestion	BL: 20% participants had LDs; 0.21 participant/week MILD: 26.3%; 0.37 p/w RT: 29.1%; 0.53 p/w AS: 19.5%; 0.21p/w	8 (poor)
2	Levitan (1990a)	Field (within)	2 nap conditions: wake up 2 h earlier and take a 2 h nap (a) after 2 h or (b) after 4 h; compared with the night before naps	$N = 10$ (lucid dreamers)	MILD, WBTB	Night before naps: ~10% of dreams were lucid (9 in total) Naps in total: ~40% (25) Nap after 2 h: ~50% Nap after 4 h: ~33%	5 (poor)
3	Levitan (1990b)	Field (within)	2 conditions: 15 min MILD (a) in the evening or (b) in the morning	$N = 20$ (lucid dreamers)	MILD	Evening: 0.44 LDs/night (6 participants) Morning: 0.26 LDs/night (3)	5 (poor)
4	Levitan (1991a)	Field (within)	3 nights, 3 conditions: (a) wake up 90 min earlier, 90 min awake, MILD and 90 min nap; (b) wake up 90 min earlier, MILD and 90 min nap; (c) wake up at normal time, MILD and 90 min nap	$N = 12$ (lucid dreamers)	MILD, WBTB	(a): 9 had LDs (75%); 8 during the nap (67%), 1 at night (8%) (b): 4 had LDs (33%); all 4 during the nap (c): 3 had LDs (25%); 1 during the nap (8%), 2 at night (17%)	8 (poor)
5	Levitan (1991b)	Field (within)	2 conditions: after waking up from a dream either (a) to count or (b) to focus on the body image	$N = 30$ (lucid dreamers)	WILD (dream re-entry)	43 LDs out of 191 attempts (23%); 66% of participants LDs following re-entry; 33% of all re-entered dreams were lucid	5 (poor)
6	Edelstein and LaBerge (1992)	Field (within)	2 conditions were intended: (a) wake up 90 min earlier, 90 min awake, MILD and 90 min nap; (b) go to bed 90 min later, wake up at normal time, MILD and 90 min nap. However, they were not compared due to methodological problems. Compared instead naps with the nights	$N = 18$ (lucid dreamers)	MILD, WBTB	11 participants had LDs, 9 of them had more LDs during the naps than the nights 8% of the nights and 37% of the naps had LDs. 6% of dreams reported from the nights were lucid and 20% from the naps	4 (poor)
7	Levitan et al. (1992)	Field (within)	2 conditions: (AM nap) wake up 90 min earlier, 90 min awake, MILD and 90 min nap; (PM nap) go to bed 14–17 h after a regular bedtime, MILD and 90 min nap	$N = 22$ (lucid dreamers)	MILD, WBTB	32% (27 in total) of nap dreams were lucid (42% of AM and 12% of PM nap dreams), while only 4.1% (6 out of 145) of night dreams were lucid 12 people (55%) had LDs in naps, 9 had more LDs in AM than PM	6 (poor)
8	Levitan and LaBerge (1994)	Field (within)	28 days dream diary	$N = 46$ (lucid dreamers; 32M/14F)	MILD, reality testing, hypnotic induction, light stimulus	1228 nights, 2968 logged dreams 262 (8.8%) of all dreams were lucid (from 38 participants) Light stimulus device: 3.7% LDs; MILD: 5.3%; device + MILD: 8.6%	6 (poor)
9	LaBerge et al. (1994)	Field (within)	3 conditions: (a) 50 min later to bed, wake up 10 min earlier, 10 min reading about LD, MILD and 90 min nap; (b) 30 min later to bed, wake up 30 min earlier, 30 min reading about LD, MILD and 90 min nap; (c) regular time to bed, wake up 60 min earlier, 60 min reading about LD, MILD and 90 min nap	$N = 22$ (lucid dreamers; 12M/10F)	MILD, WBTB	Baseline (last 6 months): 1 LD in 7 nights Nap (a): 1 LD in 11 nights (5 LDs in total) Nap (b): 1 LD in 2 nights (20 LDs) Nap (c): 1 LD in 1.6 nights (25 LDs) 50 out of 189 naps dreams (27%) were lucid, while only 3 out 235 night dreams (1.3%)	6 (poor)

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Table 1 (*continued*)

No	Reference	Type	Methods	Sample	Techniques used	Main results	Quality
10	LaBerge and Levitan (1995)	Field (within)	4–24 nights ($M = 11$), 2 conditions: device producing light cues (Q-ON) and producing no light cues (Q-OFF). Reports evaluated by blinded judges	$N = 14$ (lucid dreamers; 10M/4F)	Light stimulus	162 reports (81 in each condition) 32 LDs in total: 22 (69%) Q-ON and 10 (31%) Q-OFF. Mean rate (participant/night): Q-ON 0.30 ± 0.24; Q-OFF 0.09 ± 0.15 ($p < .025$) 6 LDs (5 participants) were trigered by a cue (6 in Q-ON, 0.071 ± 0.10 vs. 0 in Q-OFF; $p < .025$) 8 LDs (6 ps) were initiated by the Reality Testing Button (6 in Q-ON, 0.091 ± 0.16 vs. 2 in Q-OFF, 0.016 ± 0.04; $p < .10$) 18 LDs (9 ps) had dreams triggered by any occurrence of the device (Q-ON, 0.174 ± 0.21 vs. Q-OFF, 0.04 ± 0.09; $p < .05$)	14 (moderate)
11	Purcell et al. (1986)	Field (between)	3 weeks; 5 groups: (1) Baseline – dream reports only; (2) Contrast –dream reports, weekly group contact, report skills questionaire [RSQ] and motivated to make more detailed reports; (3) Rossi – dream reports, weekly group contact, self-reflectiveness [SR] and motivated to advance SR; (4) Mnemonic – dream reports, weekly group contact, RSQ, reality testing and motivated to LD; (5) Hypnosis – dream reports, weekly individual contact and post-hypnotic suggestion (with individual variations)	$N = 48$ (undergrad students; 22M/26F)	Reflection, reality testing, post-hypnotic suggestion	Baseline: 0 LDs Contrast: 1 LD Rossi: 7 LDs Mnemonic: 15 LDs Hypnosis: 0 LDs	13 (moderate)
12	Zadra et al. (1992) and Zadra (1991)	Field (between)	6 weeks, 3 groups: No Experience, No Technique (NENT); No Experience, Technique (NET); Experience, Technique (ET)	$N = 47$ (university students; 17M/30F)	Tholey's combined technique	NENT: 2 LDs from 2 participants ($M = 0.13$[SD = 0.35]); 6 PreLDs (0.40 [0.63]) NET: 23 LDs from 9 ps (1.44 [1.93]); 13 PreLDs (0.81 [0.75]) ET: 110 LDs from all 16 ps (6.88 [6.62]); 23 PreLDs (1.44 [1.32]) Both access to the technique ($p < .05$) and previous LD experience ($p < .02$) influenced LD probability Lucidity: 28% spontaneously; 44% observation of incongruities; 23% nigtmares/anxiety dreams; 5% positive emotions	16 (moderate)
13	Schlag-Gies (1992)	Field (between)	8 weeks; 5 groups: Autosuggestion (A); Intention (I); Reflection (R); Control group without information about LD (K); Control with information about LD (X). More strict criteria were used for defining a dream as lucid (e.g. involved some action taken as a consequence of awareness of dreaming) in comparison with other studies	$N = 90$ (34M/56F)	Autosuggestion, intention, reflection	A: original criteria – 16 LDs (2.3%)/conventional criteria – 32 LDs (4.6%) I: 11 LDs (1.7%)/31 LDs (4.8%) R: 32 LDs (5.5%)/79 LDs (13.6%) K: 0 LDs (0%)/2 LDs (0.5%) X: 3 LDs (0.7%)/18 LDs (4.4%) There were more LDs in the technique groups (A, I, R) than control groups ($p < .001$). R had more LDs than I ($p < .01$) and A ($p < .05$)	18 (moderate)

14	Spoormaker and van Den Bout (2006)	Field (between)	12 weeks; 3 groups: (A) 2 h individual LD session; (B) 2 h group LD session; (C) waiting list. LD used as a means for nightmare treatment	$N = 23$ (nightmare sufferers; 6M/17W)	Intention	A: 4 participants became lucid and altered nightmares B: 2 participants C: 0	11 (moderate)
15	Paulsson and Parker (2006)	Field (within)	2 weeks (baseline – the week before)	$N = 20$ (11M/9F)	Tholey's combined technique	Baseline: LD frequency (nights/week): $M = 0.13$ (SD = 0.22) 1st week: 11 participants had LDs (5 who never had before); LD frequency: 0.90 (1.02) 2nd week: 9 lucid participants; LD freque ncy: 1.25 (1.86) Technique significantly increased LD frequency ($p < .05$)	15 (moderate)
16	LaBerge et al. (1981)	Sleep lab (within)	1–2 nights each; 5–10 min after beginning of each REM period, phrase "This is a dream" was played repeatedly with increasing volume	$N = 4$	Acoustic stimulus	15 trials in total, lucidity in 5 (33%) cases. Incorporation with lucidity: 3 (20%) Incorporation without lucidity: 2 (13%) Lucidity without incorporation: 2 (13%) Awakening without incorporation: 8 (53%)	5 (poor)
17	LaBerge et al. (1988) and LaBerge (1987)	Sleep lab (within)	1–5 nights each (58 in total); flashing light during REM sleep	$N = 44$	Light stimulus	25 participants (55%) had LDs 50 LDs in total: 5 (10%) in REMPs before the stimulus; 11 (22%) in REMPs after the stimulus, but not triggered by the stimulus; 33 (66%) triggered by the stimulus; 1 LD from NREM2	4 (poor)
18	LaBerge (1988)	Field (within)	8 weekly group meetings; participants had access to DreamLight devices	$N = 49$	Light stimulus, MILD, reality testing	Baseline: 3.7% of LDs DreamLight without MILD: 5.5% LDs MILD without DreamLight: 13% LDs MILD with DreamLight: 20% LDs DreamLight usage correlation with LDs: $r = .098 \pm .095$, $p < .022$ MILD: $r = .124 \pm .087$, $p < .003$ Reality testing: $r = .036 \pm .102$, $p < .24$	5 (poor)
19	Hearne (1983)	Sleep lab (within)	1 night each; 4 electric impulses to the wrist during REM sleep; one "catch trial" (awakening after no stimulation)	$N = 12$ (mostly students; 12F)	Electric stimulus	6 participants got lucid; 2 participants became lucid but woke up at signalling; and 1 participant falsely perceived stimulation and became lucid	9 (poor)
20	Dane (1984) and Dane and Van De Castle (1984)	Sleep lab (between)	1 night each; 4 conditions (instructions have shifted during the course of study – participants were encouraged to signal even if they were not sure whether awake or dreaming [revised: whether awake or sleeping]): Post-hypnotic Suggestion (PHS) + Original Waking Instructions (OWI); PHS + Revised Waking Instructions (RWI); OWI only; RWI only. PHS employed personal symbols	$N = 30$ (hypnotically susceptible women; 30F)	Post-hypnotic suggestion, reflection	3 types of LDs indentified: Unambiguous REM LDs (UREMLDs); Ambiguous REM LDs (AREMLDs); NREM LDs (NREMLDs) PHS + OWI: 3 UREMLDs (from 3 participants); 4 AREMLDs (3); 9 NREMLDs (4); 7 (of 8) participants in total PHS + RWI: 2 UREMLDs (2); 3 AREMLDs (2); 12 NREMLDs (7); 7 (of 7) ps OWI: 3 NREMLDs (1); 1 (of 8) ps RWI: 3 UREMLDs (3); 3 AREMLDs (3); 6 NREMLDs (5); 6 (of 7) ps All other conditions were significantly better than OWI	15 (moderate)
21	Reis (1989)	Field (within)	1–4 nights each; varying conditions (in some cases individual training sessions varied in kind, number and length)	$N = 8$ (4M/4F)	Vibration, acoustic stimulus, reflection	Vibration + reflection (5 participants; 13 nights): 2 LDs from 2 participants Vibration only (1 p; 2 n): 0 LDs Sound only (1 p; 1 n): 0 LDs Vibration + sound + reflection (1 p; 3 n): 2 LDs	6 (poor)

(continued on next page)

Table 1 (*continued*)

No	Reference	Type	Methods	Sample	Techniques used	Main results	Quality
22	Leslie and Ogilvie (1996)	Sleep lab (within)	2 nights each sleeping in a hammock; 2 counterbalanced conditions: stationary hammock (control); rocking hammock (at 1 Hz frequency for 5 min). Reports from 2nd–4th REM periods. Measures included self-reflectiveness scale and mentation continuum scale	$N = 7$ (university students)	Vestibular stimulation	45 valid reports, subset of 28 REM periods (4 per participant) used Peak self-reflectiveness (PSR): rocking in early morning ($M = 4.90$) and late morning (4.62) vs. stationary early (2.95) and late (4.43) ($p < .05$) Mentation continuum (MC): rocking early (3.00) and late (1.91) vs. stationary early (1.05) and late (2.33) ($p \leqslant .05$) PSR and MC correlation $r = .80$ ($p \leqslant .001$) Lucid: 25% (6 out of 24) of rocking dreams vs. 14% (3 out of 21) of control dreams	14 (moderate)
23	Kueny (1985)	Sleep lab (within/ between)	3 weeks MILD training program; 4 non-consecutive nights in a lab each: 1st and 2nd nights: MILD only; 3rd and 4th nights: MILD + acoustic stimulus during REM. Acoustic stimulus: (a) voice "Remember, this is a dream", 5 dB increase every 20 s (Step-Voice); (b) voice "Remember, this is a dream", 4 dB increase every 4 min (Constant-Voice); (c) musical tone, 5 dB increase every 20 s (Step-Tone); (d) musical tone, 4 dB increase every 4 min (Constant-Tone)	$N = 16$	Acoustic stimulus, MILD	MILD only: 6 confirmed LDs from 5 participants (19 reported LDs from 5 ps) MILD + acoustic stimulus: 5 from 5 (22 from 9) Step-Voice: 3 from 3 (12 from 4) Constant-Voice: 1 (1) Step-Tone: 0 (5 from 4) Constant-Tone: 1 (4 from 2) Trend ($p < .1$) for Step condition to be more effective than Constant.	12 (moderate)
24	Ogilvie et al. (1983)	Sleep lab (within)	1–4 nights in a lab; acoustic stimulus (buzzer) after 15 min of REM in the presence of either high or low REM activity. Participants were asked to signal with their eyes after a stimulus. Awakenings after eye signalling or 30–60 s after stimulus	$N = 8$ (lucid dreamers)	Acoustic stimulus	Total: 57% lucid, 21% prelucid, 22% non-lucid dreams Spontaneous eye signaling ($N = 14$): 64% lucid, 27% prelucid, 22% non-lucid Cued high ($n = 16$): 43% lucid, 21% prelucid, 36% non-lucid Cued low ($n = 15$): 69% lucid, 12% prelucid, 36% non-lucid	2 (poor)
25	Spoormaker, van den Bout, and Meijer (2003)	Field (within)	2 months; LD used as a means for nightmare treatment	$N = 8$ (nightmare sufferers; 2M/6F)	Intention	4 participants became lucid, 3 of them were able to alter the nightmare	7 (poor)
26	Galvin (1993)	Sleep lab (within)	5 nights (baseline + 4 experimental nights) in a lab over 9 weeks. Post-hypnotic suggestion (PHS) was repeated before each of experimental nights	$N = 8$ (nightmare sufferers; 2M/6F)	Post-hypnotic suggestion	Only 1 participants had verified LD in a sleep lab on 3 occasions (REM/NREM2; NREM2; unclear)	11 (moderate)
27		Field (within)	9 weeks period; dream diary; PHS delivered on weeks 4, 5, 7, and 8 at the lab and the participants were also given a tape-recording for home use			6 out of 8 participants reported LDs in home settings (9 LDs in total out of 446 dream reports [2%]); self-reflectiveness increased over the time ($p = .035$)	14 (moderate)
28	Malamud (1979)	Qualitative	Dialectical approach; about 12 weeks period (varying)	$N = 6$ (2M/4F)	Reflection	4 participants had LDs during or shortly after the training	8 (poor)

29	Purcell (1988)	Field (between)	3 weeks; 3 conditions: (1) Baseline – dream reports only; (2) Attention Control – dream reports, report skills questionnaire (RSQ), weekly meeting; (3) Schema: the same as (2) + dream control questionnaire and a cue (bracelet). Dream reports scored by judges	N = 94 (undergrad students; 49M/46F; 54 high and 41 low dream recallers)	Reflection	Baseline: 4 (12.5%) lucid participants, 7 LDs out of 433 dreams (1.6%) Attention Control: 3 (10%) lucids, 3 LDs out of 345 (0.9%) Schema [Reflection]: 16 (50%) LDs, 57 LDs out of 434 (13.1%) Number of lucid participants vs. non-lucids – significant differences across groups (p < .001). Dream control training had significant effect (p = .026)	17 (moderate)
30	Hickey (1988)	Sleep lab (within)	4 non-consecutive nights in a lab	N = 4 (children aged 10–12)	MILD, reflection, re-dreaming and other	2 out of 4 children (50%) had verified LDs in a sleep lab; 6 LDs in 16 nights (38%)	7 (poor)
31		Field (within)	6 weeks training program (included also art activities)	N = 13 (children aged 10–12)		12 out of 13 children (92%) had LDs (24 in total) during the training programme	7 (poor)
32	Ogilvie et al. (1982)	Sleep lab (within/between)	2 nights in a lab; 2 groups: (1) with alpha feedback training (AFT); (2) without AFT. Awakened 4 times during REM sleep (twice with high alpha and twice with low alpha). 7 point lucidity and 15 point lucidity/dream control scales used	N = 10 (lucid dreamers; 5M/5F)	Alpha feedback	AFT had no effect on lucidity/REM alpha levels; arousals from high alpha had higher lucidity ratings than arousals from low alpha	11 (moderate)
33	Zadra and Pihl (1997)	Field (within)	Case series; 2 participants (cases 1–2) had progressive muscle relaxation, guided imagery, and LD induction; other 3 participants (cases 3–5) LD induction alone (with some guided imagery)	N = 5 (nightmare sufferers)	Intention	Case 1: LD after 4 weeks Cases 2–3: No LDs Case 4: LD after 1.5 weeks Case 5: LD after 2.5 (?) weeks	5 (poor)
34	Hearne (1978)	Sleep lab (within)	1 night in a lab (+adaptation night before); 2 awakenings during late REM periods: (1) experimental condition -after splashing some water on their face or hand with a syringe; (2) control condition – only standing with a syringe (without splashing water). Dream reports rated by judges	N = 10 (university students; 2M/8F)	Water stimulus	None of the participants had LDs. Water-spray theme was present in 6 out of 10 experimental reports, but not in 10 control reports	12 (moderate)
35	LaBerge (2004)	Field (within)	3 nights, 3 conditions: (1) Placebo; (2) Donepezil 5 mg; (3) Donepezil 10 mg	N = 10 (7M/3F)	Donepezil ingestion	9 of 10 reported LDs on Donepezil nights, while 1 out of 10 only on control nights LD rates per night: 0.031 for placebo; 0.429 for 5 mg Donepezil; 0.754 for 10 mg Donepezil. 10 mg Donepezil vs. placebo (p < .001) Donepezil was also associated with an increased sleep paralysis rate and 40% increase in estimated time awake	7 (poor)

Note: If more than one study reference is provided, the first in the list was the used as the primary one (e.g. for which methodological quality was assessed).

3.3. Methodological quality

The 35 studies included in the review (11 sleep laboratory and 24 field studies) were assessed for their methodological quality independently by two researchers. The interrater reliability between the initial ratings of the two judges was very high (kappa = .91; 95% CI 0.88–0.94). The agreed final ratings are presented in Table 2.

Taking together, the methodological quality of the studies was quite poor: The average score on the Downs and Black's (1998) checklist was only 9.1 out of 28. Both sleep laboratory and field studies had the same level of methodological quality (9.3 and 9.0, respectively). The "reporting" subscore for the included studies averaged 4.3 out of 11, external validity 0.7 out of 3, internal validity-bias 2.5 out of 7, and internal validity-confounding (selection bias) 1.6 out of 6. None of the studies had a good methodological quality (>20). Fourteen studies (40%) had a moderate quality (11–20) and 21 (60%) poor (<11). Considering the overall poor quality of the studies, small sample sizes used, great variability of the exact conditions in which induction techniques were applied and lack of reporting effect sizes respective data for computing effect sizes, it was not possible to carry out a meta-analysis. Hence our analyses will focus on a descriptive level.

3.4. Cognitive techniques

Twenty-seven (77%) studies employed cognitive techniques for lucid dream induction. Cognitive techniques were applied in 22 (96%) field experiments and five (45%) sleep laboratory studies. The following techniques were used: MILD (Mnemonic Induction of Lucid Dreams), Reflection or Reality Testing, Intention, Tholey's Combined technique, Autosuggestion, Dream

Table 2
Methodological quality of the included studies (agreed ratings).

No	Reference	Item number on the Downs and Black's (1998) checklist																											Total score
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	
1	Levitan (1989)	1	0	1	1	0	0	0	0	0	0	0	0	1	0	0	0	1	0	1	0	1	1	0	0	0	0	0	**8**
2	Levitan (1990a)	1	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	1	0	0	0	0	0	**5**
3	Levitan (1990b)	1	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	1	0	0	0	0	0	**5**
4	Levitan (1991a)	1	0	0	1	0	1	0	0	0	0	0	0	1	0	0	1	1	0	0	0	1	1	0	0	0	0	0	**8**
5	Levitan (1991b)	1	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	1	0	0	0	0	0	**5**
6	Edelstein and LaBerge (1992)	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	1	0	0	0	0	0	**4**
7	Levitan, LaBerge, and Dole (1992)	1	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	1	1	0	0	0	0	0	**6**
8	Levitan and LaBerge (1994)	1	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	1	1	0	0	0	0	0	**6**
9	LaBerge, Phillips, and Levitan (1994)	1	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	1	1	0	0	0	0	0	**6**
10	LaBerge and Levitan (1995)	1	1	1	1	0	1	1	0	0	0	0	0	1	1	1	1	0	1	1	1	1	0	0	0	0	0	0	**14**
11	Purcell et al. (1986)	0	0	1	1	0	1	1	0	1	1	0	0	1	0	0	0	1	1	0	1	1	1	1	0	0	0	0	**13**
12	Zadra, Donderi, and Pihl (1992)	1	1	1	1	1	1	1	0	1	0	0	0	1	0	1	0	1	1	0	1	1	1	0	0	0	1	0	**16**
13	Schlag-Gies (1992)	1	1	1	1	1	1	1	0	1	1	0	0	1	0	0	0	1	1	1	1	1	1	1	0	0	0	1	**18**
14	Spoormaker and van den Bout (2006)	0	0	1	0	1	0	0	0	1	1	0	0	1	0	0	1	1	1	0	0	0	0	1	0	1	1	0	**11**
15	Paulsson and Parker (2006)	1	1	1	1	1	1	1	0	1	0	0	0	1	0	0	1	1	1	0	0	1	1	0	0	0	0	1	**15**
16	LaBerge et al. (1981)	1	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	**5**
17	LaBerge et al. (1988)	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	**4**
18	LaBerge (1988)	0	0	0	0	0	0	1	0	0	1	0	0	1	0	0	0	0	0	0	0	1	1	0	0	0	0	0	**5**
19	Hearne (1983)	1	0	1	1	0	1	0	0	0	0	0	0	0	1	0	1	1	0	1	1	0	0	0	0	0	0	0	**9**
20	Dane (1984)	1	1	1	1	1	1	0	0	1	0	0	0	0	0	1	0	1	1	1	1	0	0	1	0	1	1	0	**15**
21	Reis (1989)	0	0	0	1	0	1	0	1	1	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	**6**
22	Leslie and Ogilvie (1996)	1	1	0	1	1	1	0	0	1	1	0	0	0	1	1	0	1	1	1	1	0	0	0	0	0	1	0	**14**
23	Kueny (1985)	1	0	1	1	1	1	0	0	0	0	0	0	0	0	1	0	1	1	1	1	0	1	0	0	0	0	1	**12**
24	Ogilvie et al. (1983)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	**2**
25	Spoormaker, van den Bout, and Meijer (2003)	1	0	1	1	0	0	0	0	1	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	1	0	**7**
26	Galvin (1993) (sleep lab)	1	1	1	1	1	1	0	0	0	1	0	0	0	0	0	0	1	0	1	1	0	1	0	0	0	0	0	**11**
27	Galvin (1993) (field)	1	1	1	1	1	1	1	0	0	1	0	0	1	0	0	1	1	1	1	0	0	1	0	0	0	0	0	**14**
28	Malamud (1979)	1	1	1	1	1	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	**8**
29	Purcell (1988)	1	1	1	1	0	1	1	0	1	1	0	0	1	0	1	0	1	1	1	1	1	0	1	0	0	1	0	**17**
30	Hickey (1988) (sleep lab)	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0	1	1	0	1	1	0	0	0	0	0	0	0	**7**
31	Hickey (1988) (field)	1	1	0	0	0	0	0	0	1	0	0	0	1	0	0	1	1	0	0	0	0	0	0	0	0	1	0	**7**
32	Ogilvie et al. (1982)	0	0	1	1	0	0	0	0	1	0	0	0	0	1	1	0	1	1	1	1	0	1	0	0	0	1	0	**11**
33	Zadra and Pihl (1997)	0	0	1	1	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	**5**
34	Hearne (1978)	1	1	1	1	0	1	0	0	1	0	0	0	0	1	0	0	1	0	1	1	0	0	1	0	0	1	0	**12**
35	LaBerge (2004)	1	0	1	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	1	0	**7**

Re-Entry, Post-hypnotic Suggestion, and Alpha Feedback. The overall methodological quality for studies involving cognitive techniques was 9.3.

3.4.1. MILD

MILD technique, which requires to rehearse a dream before falling asleep and visualise becoming lucid while focusing on the intention to remember that one is dreaming (LaBerge, 1980b), was the one most often tested empirically. It was applied in 10 studies: nine field experiments and one sleep laboratory study. However, the only sleep laboratory study (Kueny, 1985) that involved MILD, used it only as a control condition, while the nine field studies, conducted entirely by LaBerge, Levitan and their colleagues (Edelstein & LaBerge, 1992; LaBerge, 1988; LaBerge, Phillips, & Levitan, 1994; Levitan, 1989, 1990a, 1990b, 1991a; Levitan & LaBerge, 1994; Levitan, LaBerge, & Dole, 1992), showed poor reportability scores (average "reporting" subscore was only 2.1 out of 11). The overall quality score for those nine studies was also very low (only 5.9).

It seems that MILD practice can increase the frequency of lucid dreaming (LaBerge, 1988; Levitan, 1989, 1991a; Levitan & LaBerge, 1994). The relation between MILD practice and lucid dreaming frequency appears to be quite weak ($r = 0.124$), but significant (LaBerge, 1988). When using MILD in early morning hours, lucid dreams seem to be much more likely during following naps than the night before (Edelstein & LaBerge, 1992; LaBerge et al., 1994; Levitan, 1990a, 1991a; Levitan et al., 1992). It appears to be favourable to wake up 30–120 min earlier, stay awake for those 30–120 min, go back to bed, practice MILD and take a nap (LaBerge et al., 1994; Levitan, 1990a, 1991a; Levitan et al., 1992). The shorter periods of wakefulness, such as taking a nap after 10 min (LaBerge et al., 1994) or immediately after awakening (Levitan, 1991a), as well as longer ones, such as taking a nap after 4 h (Levitan, 1990a) or after 14–17 h in the afternoon (Levitan et al., 1992), seem to be less favourable for MILD practice. MILD seems to be slightly more effective than light stimuli presented during REM sleep; however, the combination of both appears to be even more favourable for lucid dream induction (LaBerge, 1988; Levitan & LaBerge, 1994).

3.4.2. Reflection/reality testing

Reflection or reality testing technique involves asking oneself regularly during the day whether one is dreaming or not, and examining the environment for possible incongruences (Tholey, 1983). Reflection/reality testing was employed in one sleep laboratory experiment (Dane, 1984), but was not used as an experimental condition, and in eight field studies (LaBerge, 1988; Levitan, 1989; Levitan & LaBerge, 1994; Malamud, 1979; Purcell, 1988; Purcell, Mullington, Moffitt, Hoffmann, & Pigeau, 1986; Reis, 1989; Schlag-Gies, 1992). However, one field study did not report the relevant findings (Levitan & LaBerge, 1994) and in another study (Reis, 1989) it was used only in combination with external stimulation, so only the data from the remaining six field studies (average methodological quality 11.5) was considered.

Reflection/reality testing seems to increase frequency of lucid dreams (Levitan, 1989; Purcell, 1988; Purcell et al., 1986; Schlag-Gies, 1992), although one study did not find any relation between reality testing practice and lucid dream frequency (LaBerge, 1988). There are some indications that reflection/reality testing might be more effective than other cognitive techniques, such as autosuggestion (Levitan, 1989; Schlag-Gies, 1992), post-hypnotic suggestion (Purcell et al., 1986) or intention (Schlag-Gies, 1992). Comparison with MILD is ambiguous: in one study (LaBerge, 1988) reality testing seemed to be somewhat less effective than MILD, while other study (Levitan, 1989) yielded opposite results.

3.4.3. Intention

Intention technique requires that a person – before falling asleep – imagine himself or herself as intensively as possible being in a dream situation and recognise that one is dreaming (Tholey, 1983). Therefore intention technique is fairly similar to MILD, however it does not involve "mnemonic" component, i.e. while the emphasis in MILD is to *remember* that one is dreaming, in intention technique it is to *recognise* that one is dreaming. The technique was employed in four field studies; however, three of them were not specifically concerned with lucid dream induction, but used it as a means for nightmare treatment (Spoormaker & van Den Bout, 2006; Spoormaker et al., 2003; Zadra & Pihl, 1997). The fourth one compared intention technique with other induction methods (Schlag-Gies, 1992). The average methodological quality for these studies was 10.3.

About a half of nightmare sufferers who were taught lucid dreaming with the intention technique had lucid dreams within one to 3 months (Spoormaker & van Den Bout, 2006; Spoormaker et al., 2003; Zadra & Pihl, 1997). The other study showed that intention technique can be successfully used for lucid dream induction; however, it seems to be somewhat less effective than reflection technique and similarly effective as autosuggestion (Schlag-Gies, 1992).

3.4.4. Autosuggestion

In autosuggestion technique a person suggests to himself or herself to have a lucid dream during the night while being in a relaxed stated before falling asleep (Tholey, 1983). Only two studies empirically explored autosuggestion technique (Levitan, 1989; Schlag-Gies, 1992), with an average quality score of 13.0. The findings regarding effectiveness of this technique are inhomogeneous: While in one study autosuggestion technique seemed to increase the number of lucid dreams (Schlag-Gies, 1992), in the other study no such effect was found (Levitan, 1989). Autosuggestion appears to be less effective than reflection/reality testing, but similarly effective as intention technique (Schlag-Gies, 1992). There are some indications that autosuggestion might be slightly more useful for frequent lucid dreamers, who have one or more lucid dreams per month (Levitan, 1989).

3.4.5. Tholey's combined technique

Tholey's (1983) combined technique incorporates elements of reflection, intention and autosuggestion. It involves developing a reflective frame of mind (reflection), imagining being in a dream and recognising this (intention), as well as suggesting oneself to become lucid when falling asleep (autosuggestion). Tholey's combined technique was used in two field studies (Paulsson & Parker, 2006; Zadra et al., 1992). Their methodological quality was moderate (mean score 15.5). The evidence suggests that Tholey's combined technique can significantly increase the frequency of lucid dreaming, especially for those participants who had previous experience with lucid dreams (Paulsson & Parker, 2006; Zadra et al., 1992). But even those participants who had not had any prior lucid dreaming experience had significantly more lucid dreams when using the technique in comparison to the controls who were not exposed to Tholey's combined technique (Zadra et al., 1992).

3.4.6. Post-hypnotic suggestion

In post-hypnotic suggestion a hypnotherapist suggest to a person is who is in a hypnotic trance to have a lucid dream the next night. This method was used in two sleep laboratory experiments (Dane, 1984; Galvin, 1993) and two field studies (Galvin, 1993; Purcell et al., 1986). The overall quality of these studies was fair (mean 13.3). While in one study 14 out of 15 hypnotically susceptible women reported lucid dreams during the only night spent in a sleep laboratory (Dane, 1984), the other sleep laboratory study failed to replicate these findings (Galvin, 1993). The findings from the field experiments are also inhomogeneous: According to one study, post-hypnotic suggestion helped to increase self-reflectiveness in dreams and the majority of the participants were able to have at least one lucid dream during a 9 week period (Galvin, 1993), the other study did not find any effects during a 3 weeks period (Purcell et al., 1986). It is notable that in the successful sleep laboratory study (Dane, 1984) post-hypnotic suggestion resulted in a greater number of NREM lucid dreams than REM lucid dreams.

3.4.7. Alpha feedback

One sleep laboratory study (methodological quality: 11) employed EEG alpha activity biofeedback training before sleep for lucid dream induction (Ogilvie, Hunt, Tyson, Lucescu, & Jeakins, 1982). This method was based on an assumption that lucid dreams are associated with relatively high degrees of EEG alpha frequency synchronisation. Alpha feedback training had no effect neither on lucidity nor on REM alpha levels in this study.

3.4.8. Dream re-entry

One field study (Levitan, 1991b) explored the method of dream re-entry, which aims to enter the dream state directly from a short awakening after a dream. The dreamer is instructed to keep still and focus his or her mind on a particular activity like counting while falling asleep. Using this approach, one might enter the dream state without losing conscious awareness (this idea has ancient origins in the Tibetan dream yoga tradition, see e.g. Wangyal, 1998). Two methods for focussing were used: "Counting" (which requires the participant to focus on counting while falling asleep) and "Body" (focus on the own body while falling asleep). Dream re-entry appeared to be fairly successful (43 out of 191 attempts [23%] resulted in lucid dreams) with "Counting" method seemingly slightly more favourable than "Body" method. Notably, participants using "Counting" method were seemingly more likely to fail to return to sleep, whereas using "Body" method they were more likely to enter sleep without dream recall. However, the methodological quality of this study was low (5).

3.4.9. Other (eclectic) approaches

One study (Hickey, 1988), which involved both field and sleep laboratory experiments (methodological quality 7, both) used a combination of various methods, such as MILD, reality testing, re-dreaming among others, to promote lucidity in children aged 10–12 years. Although 12 of 13 children reported at least one lucid dream in their home setting during a 6 week training period (24 lucid dreams in total) and two of four children had a verified lucid dream in a sleep laboratory (6 lucid dreams were recorded in 16 nights), due to an eclectic approach used, it is impossible to measure the exact impact of each of the techniques used.

3.5. External stimulation

Eleven (31%) studies used external stimulation during REM sleep to trigger lucidity. External stimuli were employed in seven (64%) sleep laboratory studies and four (17%) field experiments. External stimulation involved light stimulus, acoustic stimulus, vibro-tactile stimulus, electro-tactile stimulus, vestibular bodily stimulation and water stimulus. The methodological quality of studies that employed external stimulation was 8.1.

3.5.1. Light stimulation (including DreamLight, DreamLink, NovaDreamer)

Light stimuli were administered in four studies: one sleep laboratory experiment (LaBerge, Levitan, Rich, & Dement, 1988) and three field studies which used specially constructed and commercially available devices (DreamLight, DreamLink, NovaDreamer) for producing light stimuli during REM sleep (LaBerge, 1988; LaBerge & Levitan, 1995; Levitan & LaBerge, 1994). One field experiment (LaBerge & Levitan, 1995) had a fair methodological quality (14), while the remaining three studies were of a rather poor quality (average: 5.0). While light cues can be successfully incorporated in dreams and trigger lucidity (LaBerge & Levitan, 1995; LaBerge et al., 1988), there are some indications that light stimuli might be slightly less effective than cognitive MILD technique but the combination of two seems to be even more promising (LaBerge, 1988; Levitan & LaBerge, 1994).

3.5.2. Acoustic stimulation

Acoustic stimuli (such as voice "this is a dream", a musical tone or buzzer noise) were applied in three sleep laboratory studies (Kueny, 1985; LaBerge, Owens, Nagel, & Dement, 1981; Ogilvie et al., 1983) and one field study (Reis, 1989) with an average methodological quality of 6.3. There are some indications that acoustic stimulus might help to achieve dream lucidity (LaBerge et al., 1981), but it is not conclusive (Kueny, 1985; Reis, 1989). One study did not find any difference between playing a voice message and a musical tone; however, it seems that gradually increasing in volume, acoustic stimuli are more effective than a constant one (Kueny, 1985). It is also possible that providing an acoustic stimulus during REM sleep with little alpha activity in the EEG might be more effective than during high alpha REM (Ogilvie et al., 1983). Other findings, however, suggest that lucidity itself might be associated with high alpha EEG activity (e.g. Ogilvie et al., 1982).

3.5.3. Vibro-tactile stimulation

One field study, with a methodological quality of 6, used vibro-tactile stimulation for lucid dream induction (Reis, 1989). While vibro-tactile stimulation, when used in combination with reflection (or also in addition combined with acoustic stimuli), resulted in some lucid dreams, due to a great variety of conditions used (e.g. training sessions received, their durations, etc.), the generalisation of findings is complicated.

3.5.4. Electro-tactile stimulation

Electro-tactile stimuli, applied on the wrist, were used in one sleep laboratory experiment (Hearne, 1983) with a quite good success rate: Out of 12 participants who spent a single night in a sleep laboratory, six achieved lucidity due to electric stimulation, two other subjects also achieved lucidity, but woke up at signalling and another one became lucid after falsely perceiving stimulation. The methodological quality of the study was 9.

3.5.5. Vestibular stimulation

One study (Leslie & Ogilvie, 1996) employed vestibular stimulation – participants were rocked during REM sleep at a constant frequency while sleeping in a hammock. Although findings are not conclusive, there are some indications that vestibular stimulation can increase dream reflectiveness in early vs. late morning REM periods. The methodological quality of the study was 14.

3.5.6. Water stimulus

In one sleep laboratory study (Hearne, 1978), with a methodological quality score of 12, a water stimulus was applied, i.e. some water was splashed on the face or hand of the participants. Water stimulus had no effect on dream lucidity.

3.6. Application of drugs

One study (LaBerge, 2004) administered an acetylcholine esterase inhibitor class drug – Donepezil (AriceptÂ®) – to enhance lucid dreaming. Two doses of donepezil (5 mg and 10 mg) were used as well as a control placebo condition. Nine out of 10 participants reported one or more lucid dreams in two nights, when they received donepezil, while only one participant reported a lucid dream on the control placebo night. Donepezil seemed to significantly enhance lucidity rate, frequency of sleep paralysis and increased estimated time awake during the night. The higher dose was associated with stronger effects, but seemed to provide some adverse effects (i.e. mild insomnia and gastrointestinal symptoms such as nausea and vomiting). The methodological quality of the reported study was 7.

4. Discussion

Thirty-five studies that explored over a dozen various techniques for lucid dream induction were examined in this review. Three classes of methods were employed by researchers to facilitate lucid dream induction: Cognitive techniques, external stimulation and drug application. Cognitive techniques are based on the continuity hypothesis of dreaming, which states that dreams reflect waking-life experiences (Schredl & Hofmann, 2003), and aim to increase the likelihood of lucid dreams by training cognitive skills, such as prospective memory (MILD technique), self-reflection or intention. External stimulation techniques intend to trigger lucid dreams during REM sleep either by presenting a cue (visual, auditory, tactile, etc.) that might be incorporated in the dream and recognised by the dreamer or by a specific activation (e.g. vestibular). Finally, drug application methods aim to alter cholinergic levels of the brain to enhance lucidity in dreams. Cognitive techniques were applied mainly in field studies, while external stimuli were primarily used in sleep laboratory experiments. None of induction techniques were verified to induce lucid dreams reliably, consistently and with a high success rate. Most lucid dream induction methods produced only slight effects, although some of the techniques look promising.

One of such promising methods among cognitive techniques seems to be Tholey's combined technique, which was successfully tested in two studies with a relatively high methodological quality. MILD technique, applied in the early morning after 30–120 min of wakefulness, perhaps also in a combination with light stimuli presented during REM sleep, is another example, although it was explored within a single research group only. Similarly, the intention technique as well as reflection/reality testing might also be a successful means for lucid dream induction. Although only explored in a single study with a low methodological quality, dream re-entry techniques showed a good success rate and therefore need further investigation and replication. The effectiveness of autosuggestion and post-hypnotic suggestion techniques is not clear. It might depend strongly on a person's hypnotic suggestibility, i.e., the high success rate in one study (Dane, 1984) with highly susceptible participants might be explained by the participants' high hypnotic suggestibility (selection criteria). Although it is an interesting idea to associate dream lucidity with alpha activity in the EEG during REM sleep, this causality of this relation seems to be unclear (cf. Ogilvie et al., 1982, 1983) and a possibility of using such biofeedback is a rather complicated method for lucid dream induction.

Concerning external stimulation techniques, the situation is somehow less clear. Although some stimuli, such as light flashing on the eyes of a dreamer or an electrical impulse applied on the wrist during REM sleep might be effective for lucid dream induction, these findings should be interpreted with caution: the results were achieved in within one research group, which afterwards developed special commercially available induction devices based on these modalities (LaBerge's DreamLight, DreamLink, NovaDreamer light cue devices, Hearne's electrical "dream machine"). So there might be a bias in these findings, for example, not publishing unsuccessful trials. For instance, Venus (1982) reported little success with Hearne's "dream machine". Among other modalities, gradually in volume increasing acoustic stimuli might also help to achieve lucidity in dreams. Although the findings are not conclusive, vestibular and vibro-tactile stimulations showed some success and might also contribute to lucid dream induction, but further investigations with these modalities are needed. It is much less clear whether water stimuli can possibly trigger lucid dreams. While in most cases lucidity is attained when a dreamer recognises a prearranged external stimulus as a cue in the dream that he or she is dreaming, in some cases an external cue can trigger lucidity even without being actively recognised by the dreamer (e.g. LaBerge et al., 1981, 1988). However, for successful recognition of a cue during the dream some cognitive preparation might also be needed – the dreamer should have an appropriate mindset to recognize the cue.

A separate category of induction techniques, which was not covered in earlier reviews (e.g. Gackenbach, 1985–1986; Price & Cohen, 1988), emerged in this review – drug application as a means to induce lucid dreaming. While only donepezil was tested empirically (LaBerge, 2004), it has been speculated that also other substances, such as DMAE (2-dimethylaminoethanol), rivastigmin, galantamine, huperzine, can enhance lucidity in dreams via altering cholinergic system, i.e. increasing the levels of acetylcholine in the brain (LaBerge, 2004; Sergio, 1988; see also Yuschak, 2006). Although the only study showed some success with donepezil, more rigorous studies have to be carried out in order to have a better picture of the effects of such substances, paying special attention to adverse effects like insomnia and gastrointestinal symptoms.

On the basis of the reviewed studies, we present a taxonomy of lucid dream induction methods (Table 3), based on empirical evidence identified in this review. Induction techniques are first classified into the three broad categories cognitive techniques, external stimulation and miscellaneous methods.

Cognitive techniques are divided further into DILD and WILD, in accordance with a suggestion by LaBerge and Rheingold (1990), as these two categories represent two different approaches in initiation of lucid dreams. With the former, lucid dream is initiated from within a dream, i.e. a person becomes lucid during a dream, while with the latter, one aims to retain conscious awareness when falling asleep and directly (re)enter the dream state. WILD techniques (also called techniques for retaining lucidity) can be used either immediately after awakening from a dream (dream re-entry, Levitan, 1991b) or after some period of wakefulness (Tholey, 1983). In miscellaneous techniques, we include drug application and WBTB (Wake-up-Back-To-Bed) method (Erlacher, 2010), where a person goes back to bed and takes a nap after a certain period of awakening (e.g. 30–120 min) during early morning hours (Edelstein & LaBerge, 1992; LaBerge et al., 1994; Levitan, 1990a, 1991a; Levitan et al., 1992). Although WBTB was tested empirically in combination with MILD only, it seems to be a method for facilitating lucidity on its own and perhaps might be successfully applied in combination with other induction techniques.

To provide a clearer picture of possible efficacy of induction methods, we have employed a traffic light metaphor to code the effectiveness evidence levels. Green colour was designated to those induction methods that were demonstrated to be successful in at least two empirical studies without divergent evidence. Yellow colour was used for those methods that showed some success when tested empirically, but the findings were not replicated or are ambiguous. Finally, red colour was assigned to those methods which verification was unsuccessful. These designated effectiveness evidence levels, however, do not take into account methodological rigorousness of the studies included. For example, although Tholey's combined technique was verified in two studies only, both of these had a fair methodological quality and were carried out by independent research groups, while MILD was explored in nine field experiments, but within a single research group and very poor methodological rigorousness.

While conducting the review, we also identified a number of proposed lucid dream induction methods that were not tested empirically and warrant further investigation. Among cognitive techniques, such methods include WILD techniques based on concentration on hypnagogic imagery or active visualisation (LaBerge & Rheingold, 1990; Tholey, 1983). For external stimulation, transcranial magnetic simulation (TMS) and transcranial direct current stimulation (tDCS) are proposed to be applied during REM sleep (Karim, 2010; Noreika et al., 2010) which can increase cortical excitability of brain structures that are supposedly linked to lucid dreaming, such as the dorsolateral prefrontal cortex (DLPFC) (Hobson et al., 2000) and therefore trigger lucidity in dreams. Alternatively, galvanic vestibular stimulation (GVS) can be used for direct stimulation of vestibular system (Noreika et al., 2010), which is also linked to lucid dreaming (cf. Leslie & Ogilvie, 1996). In addition to donepezil, other substances, such as galantamine, rivastigmin, huperzine and DMAE, have been suggested as drugs that can enhance lucidity in dreams (LaBerge, 2004; Sergio, 1988).

Before discussing in details methodological issues pertaining the studies reviewed, some limitations should be acknowledged about the methodology of the present review. Although we put an extensive effort in locating all possible existing evi-

Table 3
Empirically based Taxonomy of lucid dream induction techniques.

Method	Effectiveness evidence level	References
1.Cognitive techniques		
1.1. Dream-initiated (DILD)		
1.1.1. MILD	Green	Edelstein and LaBerge (1992), Kueny (1985), LaBerge (1988), LaBerge et al. (1994), Levitan (1989, 1990a, 1990b, 1991a, Levitan and LaBerge (1994), and Levitan et al. (1992)
1.1.2. Reflection/reality testing	Green	Dane (1984), LaBerge (1988), Levitan (1989), Levitan and LaBerge (1994), Malamud (1979), Purcell (1988), Purcell et al. (1986), and Schlag-Gies (1992)
1.1.3. Intention	Green	Schlag-Gies (1992), Spoormaker et al. (2003), Spoormaker and van den Bout (2006), and Zadra and Pihl (1997)
1.1.4. Autosuggestion	Yellow	Levitan (1989) and Schlag-Gies (1992)
1.1.5. Tholey's combined technique	Green	Paulsson and Parker (2006) and Zadra et al. (1992)
1.1.6. Post-hypnotic suggestion	Yellow	Dane (1984), Galvin (1993), and Purcell et al. (1986)
1.1.7. Alpha feedback	Red	Ogilvie et al. (1982)
1.2 Wake-initiated (WILD)		
1.2.1. Counting	Yellow	Levitan (1991b)
1.2.2. Body image	Yellow	Levitan (1991b)
2. External stimulation		
2.1. Light stimulus	Green	LaBerge (1988), LaBerge et al. (1988), LaBerge and Levitan (1995), Levitan and LaBerge (1994)
2.2. Acoustic stimulus	Yellow	Kueny (1985), LaBerge et al. (1981), Ogilvie et al. (1983), and Reis (1989)
2.3. Vibro-tactile stimulus	Yellow	Reis (1989)
2.4. Electro-tactile stimulus	Yellow	Hearne (1983)
2.5. Vestibular stimulation	Yellow	Leslie and Ogilvie (1996)
2.6. Water stimulus	Red	Hearne (1983)
3. Miscellaneous		
3.1. Drug application		
3.1.1. Donepezil	Yellow	LaBerge (2004)
3.2. WBTB[a]	Green	Edelstein and LaBerge (1992), LaBerge et al. (1994), Levitan (1990a, 1991a), and Levitan et al. (1992)

Note: Effectiveness evidence levels: Green – method was demonstrated to be successful in several empirical studies; Yellow – method showed some success but findings were not replicated or are ambiguous; Red – method was not successful. Reference lists include empirical studies in which these methods were empirically verified.

[a] WBTB technique was tested empirically only in combination with MILD.

dence on lucid dream induction, it may still be that some evidence remained unidentified. Also we had to restrict ourselves to evaluate only such evidence which has been published at least in some form (e.g. journal article, thesis/dissertation, conference abstract, etc.). This might have affected the assessment of some evidence which was only partially available in a published form (e.g. conference presentations where only abstracts were available without the actual content of the presentation) and therefore was evaluated only according to what was published, but not necessary to what was actually presented, as the presenter might have clarified some points during the presentation itself. Finally, the methodological quality checklist used in this study (Downs & Black, 1998) is more tailored to evaluate clinical (medical) studies and its assessment criteria might have been too rigorous for the evaluation of studies within a more explorative field of lucid dream research. There were items, for example, 8 (assessment of adverse effects), 11 and 12 (representative sampling) or 24 (concealment of randomisation both from participants and staff), that were always or nearly always scored as 0.

The review revealed a number of methodological issues related both to the methodological quality of the studies reviewed and lucid dream research in general. While the application of a rigorous checklist might not have revealed all subtle methodological quality differences within the studies reviewed, the assessment results are nevertheless indicative. None of the reviewed studies can be considered as having a good methodological quality and the majority of the studies were rather methodologically poor. Based on our assessment, some suggestions for researchers on how to improve the methodological quality of their studies can be provided.

Firstly and foremostly, researchers should pay special attention to how they are reporting their studies. Many papers do not clearly describe the main outcomes to be measured and detailed outcome data, including estimates of the random variability (standard deviations, confidence intervals, etc.) and especially effect sizes. We were not able to carry out a meta-analysis regarding the effectiveness of different induction techniques and had to limit the review to a descriptive level. Reporting of effect sizes would allow proper meta-analysis and more accurate comparisons among different techniques to be done. Principal confounders and any adverse effects also have to be noted when reporting studies.

All reviewed studies lacked external validity – most participants were self-selected lucid dreamers or university students which makes it impossible to generalise the findings. Although it might be difficult to conduct a study with a representative sample, some attempt could be made to improve external validity (e.g. do the same study with different samples).

Internal validity was also an issue for many studies. Most studies were not blinded both for participants and those measuring the outcomes. In field studies, compliance with the study procedure was not always reliable – only few studies had some additional means (e.g. detailed questionnaires to be filled) to monitor if the participants have followed the exact procedure. Validity and reliability of outcome measures was another problem for some studies (see discussion about a criterion for successful induction below). Some studies relied only on participants' subjective judgement whether they had a lucid dream or not, which sometimes might be fallacious (see Snyder & Gackenbach, 1988) and some extra measures (e.g. external raters of dream reports) might be useful.

Finally, the vast majority of the reviewed studies lacked sufficient power to detect significant effects. Researchers are advised to consider possible effect sizes beforehand and calculate their sample sizes accordingly.

One of the major issues concerning lucid dream induction research in general is what to define a valid criterion for successful induction. The strict criterion for sleep laboratory studies would be unambiguous predefined eye signals on the EOG during REM or NREM sleep (see below) and a dream report received immediately after awakening following signalling, which confirms lucidity and volitional eye signals. The situation is less clear when (1) only eye signals are present on the EOG without a fully confirmatory dream report, or (2) only dream report is present that indicates lucidity, but no predefined eye signals are visible on the EOG or they are ambiguous. The latter situation is encountered in field experiments also, where no polysomnographic sleep recording is being carried out. Some field studies (e.g., LaBerge & Levitan, 1995; Purcell et al., 1986; Zadra et al., 1992) employed external blinded judges to score dream reports for lucidity, but even with this approach the validation of lucid dreams is complicated: It would still rely on the dreamer's recollection of the dream, which might be impaired by sleep inertia – a transitional state between sleep and wakefulness in which cognitive performance is decreased (Tassi & Muzet, 2000), especially if the dream was not recorded immediately after awakening. This also brings a further issue of introspection – subjective dream reports are very difficult to verify and while the presence of predefined eye-movement on the EOG can be considered as an objective verification, their absence leaves the question of verification open (cf. Nisbett & Wilson, 1977). Although the presence of predefined eye signals in the EOG but absence of a confirmatory dream report, might also be a result of sleep inertia, it is also possible that regular eye movements during REM sleep just accidently corresponded with the predefined signal. To minimize such a risk, longer sequences of predefined eye movements (e.g. LRLRLR) should be used instead of shorter ones (e.g. LRLR). Furthermore, to consider a dream as lucid unambiguously, the person should also be *convinced* that he or she is dreaming, because in some cases (e.g. Dane, 1984) researchers encouraged their participants to make a signal even if they were not sure whether they are dreaming or not. More sophisticated communication with the dreamer might also be devised, so that participants can give one signal when they think they are dreaming (e.g. LRLRLR) and another signal (e.g. LRLRLRLR) when they consider themselves awake.

Further, although lucidity sometimes is considered a sort of ''all-or-nothing'' phenomenon, i.e. either the dreamer knows that he or she is dreaming and *is lucid* or does not realise this and therefore *is not lucid*, it seems that there are different degrees of lucidity within dreams and in some dreams a person might be more lucid than in others, which suggests a continuum of dream lucidity (Barrett, 1992; Moss, 1986). Different degrees of lucidity usually are not taken into account in the induction studies. Purcell and co-workers developed a dream self-reflectiveness scale (Purcell, 1988; Purcell et al., 1986); however, it involves only two categories for dream lucidity and control. On the other hand, some researchers are using even more specific requirements for dreams to be considered as lucid dreams. While the conventional (minimal) criterion for a lucid dream is awareness of dreaming during the dream, Schlag-Gies (1992), for example, considers a dream as lucid only if some consequences arise from the awareness of being in the dream (e.g. intention to change the setting). Therefore, detailed lucidity scales must be devised in order to discriminate those different degrees of lucidity and their associations with different induction techniques. This would allow comparing induction methods both on qualitative and qualitative basis.

Furthermore, possible differences between sleep laboratory studies and field experiments for lucid dream induction must also be considered. Dreams obtained in sleep laboratory studies usually show a high rate of laboratory references (Schredl, 2008), which might be an additional trigger for dream lucidity. The participants who are coming to a sleep laboratory specifically for the experiment (sometimes they are even paid for that) and know that they will be observed by the experimenters through the whole night might be more motivated than of those participants who are carrying experimental procedures in their home setting. On the other hand, the pressure to produce a lucid dream might be very high and can even interfere with sleeping well enough to produce REM sleep and lucid dreams.

The time at which lucid dream induction techniques are applied might also be a crucial factor for the success of the technique. For example, as it was already noted, MILD technique if applied in the early morning hours (e.g. with WBTB method) seems to produce more lucid dreams. Therefore researchers should also put a time factor into consideration, i.e., explore *when* a particular technique should be applied for the best results.

The sleep stage in which a lucid dream occurs should also be taken into consideration. Although lucid dreams by a large extent happen in REM sleep and are mainly considered REM phenomena (LaBerge, 1990), they can also occur in NREM sleep. For example, Dane's (1984) study had an unusually high number of signal verified NREM lucid dreams, recorded both in NREM1 and NREM2 stages of sleep. While to our knowledge, none of lucid dreams has been recorded in NREM3 stage of sleep, self-awareness in deep sleep might also be possible (cf. Mason et al., 1997). Hobson (2009) proposes that lucid dreaming represent a dissociative state with elements of both waking and dreaming, while the alternative hypothesis is that REM sleep (and perhaps to some extent NREM sleep as well) is capable of supporting reflective consciousness (LaBerge, 2010). Further research should explore differences between REM and NREM lucid dreams in greater details. It might be that different techniques have a different success rate in eliciting REM and NREM lucid dreams.

It is also very likely that some techniques will work better for some people than others. For example, Levitan (1989) found that autosuggestion was most successful for frequent lucid dreamers while it had a very little success for infrequent or non-lucid dreamers. It might be that individual differences also play a role in success for a particular technique. For example, it is possible that for highly hypnotically susceptible people post-hypnotic suggestion will work well, while those with good prospective memory skills might benefit from MILD or those with good attention might be most successful with recognising an external cue. Therefore individual differences and the level of experience should also be considered when testing different techniques.

Finally, the overall trend regarding the number of studies carried out in lucid dream research is alarming. Out of 37 manuscripts included in this review, two were published in 1970s, 16 in 1980s, 15 in 1990s and only four in 2000s. After a "golden age" of lucid dream research in 1980s and 90s, the scientific interest in lucid dreams seems to be declining dramatically. However, with the help of new brain imaging technologies that are becoming available for lucid dream research (Dresler et al., 2011), lucid dreaming might become an invaluable tool for understanding the dreaming brain and wider questions of consciousness. But both to progress lucid dream research and make lucid dreaming available to wider populations, reliable induction techniques must be established. No single technique showed to be effective enough to facilitate lucid dreams with a high success rate and perhaps a more eclectic approach might be useful in lucid dream induction: To combine different techniques and advantages offered by them. Sleep laboratory research perhaps can benefit from a combination of cognitive techniques and external stimulation delivered during REM sleep. Inclusion of WBTB and/or ingestion of specific substances might increase odds for lucidity further, but a special word of caution should be made regarding the use of chemical substances: Their effectiveness must be explored in clinical trials and adverse effects should be carefully monitored, especially those occurring after chronic use of such substances. Combination of cognitive techniques and WBTB might be the most appropriate solution for "home lucid dreaming" and the dreamers can also benefit from specially developed devices that can identify REM sleep and deliver external cues. Increasing public interest in lucid dreaming and active online dreamers' communities where people are sharing their experiences and tips for successful lucid dreaming might be another soil that would yield another generation of lucid dream induction techniques.

5. Future directions

We hope that the present review will serve as a new starting point in the lucid dream science, inviting researchers to further explore the most promising directions for induction research and to employ the most effect techniques for general lucid dream research and practical applications. The following ideas, we believe, are worth to tackle and pursue further.

The techniques that showed to be the most effective, such as Tholey's combined technique or MILD, should be tested further and the circumstances under which they are most successful should be explored (e.g. in combination with WBTB). Also the methods that demonstrated some initial success but were not further investigated (e.g. WILD techniques, vibro/electrotactile, vestibular stimulations) must be more thoroughly tested. Application of the Acetylcholinesterase inhibitor class drugs, such as donepezil, galantamine, rivastigmin, definitely warrant further investigation, as well as new prospective yet untested methods like tDCS, TMS or GVS (Noreika et al., 2010). While the different methods and their effects on dream lucidity have to be tested separately, it may well be that more eclectic approaches combining the advantages of different techniques will show to be the most effective (e.g. to do a cognitive technique after awakening in early morning hours (WBTB) while taking an Acetylcholinesterase inhibitor drug and applying an external stimulation in a subsequent REM period). We also advise researchers to take into account the methodological considerations described above both to increase the quality of their studies and reports and shed more light on other factors (e.g. individual differences, sleep stages, timings) that may play an important role in promoting conscious awareness in dreams.

Effective lucid dream induction, allowing to have lucid dreams on demand, will open exciting opportunities both for dream and consciousness research and for practical applications. With new brain imaging methods further differences can be elicited comparing lucid and non-lucid REM sleep (e.g. Dresler et al., in press), mapping brain regions involved in self-reflective awareness and secondary consciousness in dreams (cf. Hobson & Voss, 2010). This may also help to clarify whether lucid dreaming should be considered as a distinctive hybrid state – a mixture – of REM sleep and wakefulness or only as a special instance of REM sleep (cf. Hobson, 2009; LaBerge, 2010). A possible induction of NREM lucid dreaming will make those questions even more interesting. Further, availability of lucid dreaming for brain imaging, will open opportunities to explore the neural correlates of specific dream mentation as well as "dream reading" – inferring dream content from its underlying neural activity (Dresler et al., 2011).

Finally, effective induction techniques will make practical applications of lucid dreams possible for wider audiences. Nightmare sufferers could employ lucid dreaming techniques to decrease their nightmare frequency and intensity (Abramovitch, 1995; Brylowski, 1990; Spoormaker & van Den Bout, 2006; Spoormaker et al., 2003; Zadra & Pihl, 1997). Athletes could use this to improve their performance, perfect existing motor skills and acquire new ones, explore more risky actions, practice without fear of injury or negative judgements, manipulate phenomenal space and time (Erlacher & Schredl, 2010; Tholey, 1981, 1990). Similarly, lucid dreaming could be used to rehearse any skill (e.g. presenting in front of an audience) to reduce performance anxiety and increase self-confidence (LaBerge & Rheingold, 1990). Lucid dreams can also be employed for creative problem solving – for example, by asking a dream character for a creative advice (Stumbrys & Daniels, 2010). Opportunities for self-integration, growth, development of mental flexibility, spirituality are also present in lucid dreams (LaBerge & Rheingold, 1990). While the benefits of lucid dreams currently are utilised only by a few (for example, Erlacher, Stumbrys, and Schredl (2011–2012) in a sample of 840 German athletes found that only 5% of them used the lucid dream state to practice sport skills), efficient techniques could unlock these hidden potentials for much broader audiences.

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Testing the involvement of the prefrontal cortex in lucid dreaming: A tDCS study

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ABSTRACT

Recent studies suggest that lucid dreaming (awareness of dreaming while dreaming) might be associated with increased brain activity over frontal regions during rapid eye movement (REM) sleep. By applying transcranial direct current stimulation (tDCS), we aimed to manipulate the activation of the dorsolateral prefrontal cortex (DLPFC) during REM sleep to increase dream lucidity. Nineteen participants spent three consecutive nights in a sleep laboratory. On the second and third nights they randomly received either 1 mA tDCS for 10 min or sham stimulation during each REM period starting with the second one. According to the participants' self-ratings, tDCS over the DLPFC during REM sleep increased lucidity in dreams. The effects, however, were not strong and found only in frequent lucid dreamers. While this indicates some preliminary support for the involvement of the DLPFC in lucid dreaming, further research, controlling for indirect effects of stimulation and including other brain regions, is needed.

1. Introduction

Dreaming is often described as a state of cognitive deficiency characterized by a loss of self-reflection, bizarre, illogical situations, or a lack of control over volition and attention (Hobson, Pace-Schott, & Stickgold, 2000). On a neurophysiological level, it has been suggested that these phenomena result from hyper- or hypo-activity of specific neural networks during rapid eye movement (REM) sleep, which is the sleep stage where the most vivid dreams occur (Schwartz & Maquet, 2002). Recent neuroimaging studies have underlined that during REM sleep the brain becomes selectively deactivated as compared to waking, including the dorsolateral prefrontal cortex (DLPFC) and the precuneus, whereas other brain regions become more activated, such as the limbic and paralimbic systems (Braun et al., 1997; Maquet et al., 1996). A special kind of nocturnal dreaming is lucid where the dreamer realizes he or she is in the dream state and is often able to control dream happenings (LaBerge, 1985).

In a recent article, Hobson (2009) pointed out the relevance of lucid dreaming to the study of consciousness. Lucid dreaming has been defined as a rare but robust awareness that we are dreaming and that we are not really awake. It is considered to be mainly a REM sleep phenomenon (LaBerge, 1990), although lucidity can also occur during NREM sleep (Stumbrys & Erlacher, 2012). Hobson et al. (2000) have proposed that, during the lucid state, the previously deactivated DLPFC becomes reactivated, allowing directed thought, metacognition and awareness of being while dreaming. Preliminary empirical evidence for this hypothesis has been obtained from a recent study (Voss, Holzmann, Tuin, & Hobson, 2009) which found

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that when participants become lucid, there is a shift in their EEG power, especially in the 40 Hz range and in frontal brain regions. Moreover, in lucid dreaming, EEG coherence is also largest in frontolateral and frontal areas (for all frequency bands, 1–45 Hz). Another recent study, which has used fMRI to study cerebral regional activation in lucid dreams, replicated these findings and showed that, in lucid dreams, not only prefrontal but also occipito-temporal cortices, bilateral precuneus, cuneus and parietal lobes exhibit higher activation compared to what occurs during non-lucid dreams (Dresler et al., 2012). Based on this background, the hypothesis was formulated that activation of the frontolateral area of the brain during REM sleep should increase dream lucidity.

Although these findings and hypotheses concerning the neurobiology of dreams are intriguing, this research field poses several methodological challenges. One problem is the approach of activating the brain by external stimulation. In 1985, transcranial magnetic stimulation (TMS) was introduced as a neuroscience research tool able to focally and painlessly stimulate the cortex by means of a time-varying magnetic field (Barker, Jalinous, & Freeston, 1985). Although the application of TMS in sleep research is possible (Massimini et al., 2005, 2007), it is complicated due to the auditory artifacts and tactile sensations on the scalp (Noreika, Windt, Lenggenhager, & Karim, 2010). Unlike TMS, transcranial direct current stimulation (tDCS) does not induce auditory artifacts, and the voltage needed to hold the current constant decreases after a short time and usually becomes subthreshold for evoking peripheral sensations. TDCS involves continuous administration of weak currents (1 mA) through a pair of surface electrodes, cathode and anode, attached to the scalp (Nitsche & Paulus, 2000).

Several studies have demonstrated that cerebral excitability was diminished by cathodal stimulation, which is thought to hyperpolarize neurons, whereas anodal stimulation results in increased cortical excitability (Nitsche et al., 2008). These tDCS induced effects have been observed in several cortical regions such as the motor (Nitsche & Paulus, 2000), visual (Antal, Kincses, Nitsche, Bartfai, & Paulus, 2004), somatosensory (Rogalewski, Breitenstein, Nitsche, Paulus, & Knecht, 2004) and prefrontal cortices (Karim et al., 2010). In 2004, it was demonstrated for the first time that tDCS can be reliably applied during sleep without awakening the participants (Marshall, Mölle, Hallschmid, & Born, 2004). Moreover, it was found that repeated application of anodal tDCS over frontocortical areas during slow wave sleep (SWS) improved declarative memory consolidation. Furthermore, another group of researchers recently explored the effects of simultaneous tDCS stimulation on the frontal and posterior parietal cortices during different stages of sleep (Jakobson, Conduit, & Fitzgerald, 2012; Jakobson, Fitzgerald, & Conduit, 2012a, 2012b). While cathodal-frontal and anodal-parietal stimulation increased reported visual dream imagery during Stage 2 sleep (Jakobson et al., 2012b), no such effects were observed during slow wave sleep (Jakobson et al., 2012a) and the reversed stimulation (i.e. cathodal-parietal, anodal-frontal) did not have an effect on visual imagery during REM sleep (Jakobson et al., 2012).

In order to go beyond the correlational data regarding the neural correlates of dream lucidity as suggested by previous EEG and fMRI studies (Dresler et al., 2012; Voss et al., 2009), we aimed in this study to experimentally manipulate the activation of the prefrontal brain cortex and test the neurobiological basis of dream lucidity. Anodal tDCS was applied during REM sleep to activate the DLPFC and – by modulating cortical excitability – should have had an effect on subjective experience of dreaming by increasing dream lucidity.

2. Materials and methods

2.1. Participants

Twenty-three participants (7 male, 16 female) aged from 21 to 33 years ($M = 25.0 \pm 3.1$) were recruited for the study via e-mail advertisements sent out to psychology students and known lucid dreamers. The inclusion criteria were: (1) at least average dream recall (one or more recalled dreams a week); (2) good sleeping; and (3) no serious health problems, chronic illnesses and/or medication intake. An additional criterion, which was employed towards the middle of the study, was a higher frequency of lucid dreaming: During recruitment participants were asked to estimate their lucid dreaming frequency on a 7-point scale (see 2.5 below) and those with a higher frequency of lucid dreams (e.g. once a month or higher) were invited to participate in the study. The exclusion criteria were: (1) presence of sleep disorders (sleep apnea and periodic limb movements during sleep), and (2) high sensitivity to tDCS (some participants awakened every time the simulation was applied during REM sleep). This was tested during the first (adaptation) night. Three participants were withdrawn from the study due to high tDCS sensitivity after the first night. Furthermore, one participant withdrew after the second night due to not being able to sleep in the sleep laboratory. Therefore, only 19 participants completed the study (6 male/13 female; age range: 21–33, $M = 25.1 \pm 3.2$). All participants signed an informed consent form and were paid for their participation. Ethical approval for the study was obtained by the Ethics Committee of the Medical Faculty Mannheim/Heidelberg University.

2.2. Procedure

The participants spent three consecutive nights in the sleep laboratory with continuous polysomnographic recording (from about 23:00 to about 7:00). Before the first night, the participants were asked to complete a questionnaire about their dream and lucid dream frequency (see Section 2.5 below). The first night served as an adaption night, during which the participants were also screened for sleep disorders (sleep apnea and periodic limb movements during sleep) and for sensitivity to tDCS: Several times during the night, tDCS was shortly applied during REM sleep. If after each application the participant was awakened, he or she was considered as being too sensitive to tDCS and was withdrawn from further participation in the study. Before going to sleep, the stimulation was demonstrated to the participants (1 mA for 3 min), so they could see if they are comfortable with the sensations.

The second and third nights served as experimental nights. In a randomized and counter-balanced order, the participants received tDCS stimulation one night while, during the other night, they received sham stimulation. The participants were blind as to which condition on which night they received. Prior to bedtime, the participants were instructed to produce a specific sequence of eye movements (left–right–left–right-left–right, LRLRLR) when they realized they were dreaming (LaBerge, Nagel, Dement, & Zarcone, 1981) and to repeat the signal at a rate of about once a minute while still retaining lucidity. Furthermore, they were instructed on awakening to describe their dream as detailed as they could and report on all their cognitive activities, sensory qualities, locations, events, actions, people and objects.

The stimulation was delivered in each REM period, starting with the second REM period of the night. One minute after the stimulation was ended, the participants were awakened via an intercom system by calling their name and were asked to report any mental content that was in their mind before the awakening. Further, they were asked to confirm whether they gave any LRLRLR signals and several additional questions about their experience during the dream (see Section 2.5 below). Moreover, they were asked if this dream was somehow different (unusual) in comparison to their other sleep laboratory dreams or dreams at home. The dream reports were recorded by a portable voice recorder, transcribed, randomly permutated and rated by a "blind" judge (see Section 2.6 below).

2.3. Polysomnography

For the first night, polysomnography included electroencephalogram (EEG: F3-A2, F4-A1, C3-A2, C4-A1, CZ-A1, O2-A1, O1-A2), electroocculogram (EOG), submental and leg (left and right anterior tibial muscles) electromyogram (EMG), electrocardiogram (ECG) and respiration measures (oral and nasal airflow, thoracoabdominal respiratory movements, and oxygen saturation). For the second and third nights, polysomnographic recording encompassed EEG (FZ-A1, C3-A2, C4-A1, O2-A1, O1-A2), EOG, submental EMG and ECG. EEG electrodes were placed according to the international Ten-Twenty system (Jasper, 1958). Sleep stages were manually scored according to the AASM criteria (Iber, Ancoli-Israel, Chesson, & Quan, 2007).

2.4. TDCS stimulation

For tDCS stimulation, two battery-driven devices DC-Stimulator CX-6650, Model TRCU-04A were used, manufactured by Rolf Schneider Electronics (Goettinger Landstr. 10, D-37130 Gleichen). The stimulation was delivered through two pairs of conductive rubber electrodes (4 cm × 3 cm) that were put inside saline soaked sponges (6 cm × 5 cm). Synapse conductive electrode cream was applied between the internal side of the sponge and the rubber electrode, and on the external side of the sponge which was attached to the skin. Each anode was applied to the DLPFC (positions F3 and F4 according to the Ten-Twenty-system, as used in other tDCS studies, e.g. Fecteau et al., 2007; Fregni et al., 2005), whereas the cathodes were applied to the supraclavicular area of the same side. The anodes were fixed on the scalp by using a tubular net bandage, while the cathodes were fixed using an adhesive tape.

During the tDCS stimulation nights, the direct current of 1 mA was delivered for 10 min with a fade-in period of 10 s and a fade-out period of the same length. If, during the stimulation the participant awakened or entered Stage 2, the stimulation was discontinued and resumed only if the same REM period continued (a 15 min criterion was used to define separate REM periods). During the sham stimulation nights, only a fade-in period of 10 s (ramping to 1 mA) of tDCS was delivered to mimic possible physical sensations, such as tingling, on the skin (Gandiga, Hummel, & Cohen, 2006).

2.5. Self-questionnaires

Prior to the first night, the participants were asked to indicate their dream and lucid dream recall frequency during the previous few months. Dream recall frequency was measured on a 7-point scale (0 – never, 1 – less than once a month, 2 – about once a month, 3 – twice or three times a month, 4 – about once a week, 5 – several times a week, 6 – almost every morning). This scale has been shown to have a high retest reliability ($r = .85$; Schredl, 2004). The frequency of lucid dreams was measured on a 8-point scale (0 – never, 1 – less than once a year, 2 – about once a year, 3 – about 2–4 times a year, 4 – about once a month, 5 – about 2–3 times a month, 6 – about once a week, 7 – several times a week; Schredl & Erlacher, 2004).

Upon each REM awakening, after a dream report, the participants were asked to evaluate the intensity of positive and negative emotions during their dreams on two 4-point scales (0 – none, 1 – mild, 2 – moderate, 3 – strong) and answer two questionnaires verbally: Metacognitive, Affective, Cognitive Experience questionnaire (MACE, Kahan & LaBerge, 2011) and Dream Lucidity Questionnaire (DLQ).

MACE contains 7 items, scored on a 5-point scale (anchor points: 0 – none, 2 – some, 4 – all) that assess different types of metacognitive activities: choice, suddenly captured attention, focused attention, public self-consciousness and reflective awareness of own thoughts/feelings, own behavior and external events.

DLQ was an especially devised questionnaire to measure different aspects of lucidity within dreams. It consists of 12 items, scored on a 5-point scale (0 – not at all, 1 – just a little, 2 – moderately, 3 – pretty much, 4 – very much) that evaluate different types of awareness (awareness of dreaming, awareness that physical body is asleep, awareness that dream characters and objects are not real, awareness of different possibilities), control (deliberately choosing an action, changing dream events, dream characters, dream scene, breaking the physical laws), and remembrance (of waking life and of intentions) (see Section 3.1 below for the questionnaire items).

To reduce the number of variables and statistical tests required, factor analysis was carried out for both the MACE and DLQ questionnaires for the whole set of collected dream report ratings.

2.6. Judge ratings

After dream reports were transcribed and permutated, they were scored by an external judge (who was unaware of to which participant and to which condition the dream report belongs) for lucidity and bizarreness. Dream lucidity was evaluated on a 3-point scale (0 – no evidence of a lucid dream, 1 – possible indications of a lucid dream, 2 – clear indication of a lucid dream). For the assessment of dream bizarreness, a 4-point scale was used (1 – possible in waking life and also occurs in normal, everyday life; 2 – many elements of waking life, but with unusual sequences and connections, yet realistic; 3 – one or two fantasy objects, bizarre connections or actions impossible in waking life; 4 – frequent/numerous fantasy objects, bizarre connections or actions impossible in waking life). The number of bizarre elements within the dreams was also calculated.

Both bizarreness measures had been used in previous research and showed good interrater reliability: bizarreness scale $r = .69 - .78$ (Schredl, Burchert, & Gabatin, 2004); a number of bizarre elements within the dream $r = .91$ (Schredl & Erlacher, 2003). To evaluate interrater reliability of the lucidity scale, a second external judge was used (who scored dream reports for lucidity only).

2.7. Statistical analysis

IBM SPSS Statistics 17 software was used for the statistical analysis. Statistical tests were applied with alpha = .05. Non-parametric Wilcoxon signed-rank test was used for comparing the two conditions. 1-tailed statistical tests were applied within the direction of our hypothesis (i.e., that tDCS will increase lucidity in dreams), while 2-tailed tests were applied in those cases where no predictions were made.

3. Results

For nineteen participants, who completed the study, the median value for reported dream recall frequency was "several times a week" and the median value for reported lucid dream frequency was "about once a month". Eleven participants could be considered frequent lucid dreamers according to the terminology of Snyder and Gackenbach (1988) (lucid dreaming frequency is once a month or higher).

A total of 109 REM awakenings were made (in average, 5.7 per participant). The comparative data on awakenings between the two conditions is provided in Table 1. Stimulation had disruptive effects on REM sleep – in many cases participants awakened when tDCS was applied. There were thus fewer awakenings in the tDCS condition and awakenings were made later considering both average time since sleep onset and (to some extent) average clock time in comparison with sham stimulation nights. For three participants, who were very sensitive to the stimulation, no awakenings were possible during the tDCS night. No differences were found in the dream recall rates and unusual dream report rates.

A lucid dream was recorded with LRLRLR eye signaling only once during REM sleep (tDCS night). The participant signaled twice (after 3 and 4 min since the beginning of stimulation) and awakened by herself after the second eye-signaling. Eye-signaling occurred during the third REM period, 4 h 21–22 min after sleep onset. Notably, earlier in the same night, the participant also signaled from NREM sleep (N2), which has been described elsewhere (Case 1; Stumbrys & Erlacher, 2012).

Table 1
Data on awakenings ($N = 19$ participants).

	Sham			tDCS			Z	p-Val (2-tailed)
	M	SD	Range	M	SD	Range		
Number of awakenings	3.21	1.03	2–5	2.53	1.81	0–7	−1.960	.050*
Dream recall rate (%)[1]	90.4	15.7	50–100	90.4	15.9	50–100	−0.254	.799
Unusual dream report rate (%)[1]	19.7	30.1	0–100	25.9	35.4	0–100	−0.772	.440
Average awakening clock time[1]	5:07	0:44	4:05–6:23	5:40	1:09	3:48–7:44	−1.862	.063+
Average awakening time since sleep onset[1]	5:55	0:46	4:58–7:18	6:29	0:58	4:46–8:15	−2.379	.017*

[1] $N = 16$ for tDCS condition.
* $p \leqslant .05$.
+ $p < .1$.

Six times one of the tDCS cables became disconnected and only one side of DLPFC was stimulated. Three times on those occasions no dream had been recalled and the remaining three dream reports were excluded from comparative dream analysis.

3.1. Factor analysis

A two-factor structure emerged for the MACE questionnaire, explaining 54.6% of variance (Table 2). The first factor (F1) could be described as "metacognition with internal focus" and the second (F2) as "metacognition with external focus". Overall rating scores (averages) for both components were calculated.

For the DLQ questionnaire, a first main factor emerged, explaining 44.1% of variance (Eigenvalue = 5.286), while Eigenvalues of other factors were below 1.5. This suggests that there is an underlying construct of "lucidity" (Table 3). For calculating the overall lucidity rating score, two items (No. 7 and 12) that loaded poorly (<.4) were excluded. Notably, those two items dealt with recall of waking facts, episodes or intentions. The overall DLQ lucidity score correlated positively with the MACE "metacognition with external focus" subscale ($r = .212$, $p = .018$, 1-tailed), but not with the MACE "metacognition with internal focus" subscale ($r = .086$, $p = .200$, 1-tailed).

3.2. Self- and judge ratings

A comparison of dream report data for two conditions is provided in Table 4. As no REM awakenings for tDCS nights were possible for three participants, the sample was reduced to 16 participants. Emotional tone was calculated as the difference between positive and negative feelings (range from −3 to 3). Interrater agreement for the lucidity rating was $r = .86$ and lucid dreams were identified correspondingly.

On tDCS nights, dream reports were significantly longer than on sham stimulation nights. Furthermore, the participants rated their dreams from tDCS nights to be more lucid than their dreams from sham nights. No differences were found in self-reported emotional tone of the dreams or metacognitive activities within the dreams. Self-reported lucidity was not associated with dream report length ($r = -.029$, $p = .776$), awakening clock time ($r = .078$, $p = .447$) or time since sleep onset ($r = .104$, $p = .308$). Self-reported metacognition was also not associated with the awakening time; however, longer dream reports had more externally-focused metacognition ($r = .228$, $p = .024$). Metacognition with internal focus was not associated with dream report length ($r = .160$, $p = .116$).

The judge scored seven dream reports as with clear indications of lucidity: 4 out of 40 (10%) from tDCS nights and 3 out of 55 (5.5%) from sham nights. According to the judge ratings, dreams from tDCS nights were more lucid and somewhat more bizarre (less realistic but without differences in numbers of bizarre elements). An initial analysis of the judge ratings showed that external lucidity and bizarreness ratings were associated with the dream length (correlations with dream report word count: lucidity $r = .206$, bizarreness $r = .344$, number of bizarre elements $r = .255$, all $p < .05$). To control this variable, we computed regression analyses and then compared the residuals. When controlled for the dream report length, there were no differences in dream lucidity and bizarreness between the two conditions (only a non-significant trend for higher bizarreness in dreams from tDCS nights; Table 4).

3.3. Post-hoc analyses

Post-hoc DLQ sub-item analysis showed that on tDCS nights, the participants were more aware that dream objects were not real (0.719 ± 1.341 vs. 0.292 ± 0.769, $Z = -1.753$, $p = .040$). There were also tendencies for them to be more aware that their dream characters were not real people (0.797 ± 1.418 vs. 0.365 ± 0.830, $Z = -1.332$, $p = .092$) and their physical body was asleep (0.625 ± 1.218 vs. 0.369 ± 0.889, $Z = -1.439$, $p = .075$), as well as making more deliberate choices (0.823 ± 0.963 vs. 0.769 ± 1.191, $Z = -1.471$, $p = .071$) during tDCS nights.

Another post-hoc analysis was made by separating participants into two subgroups: (1) frequent lucid dreamers (frequency of lucid dreaming is once a month or higher) and (2) infrequent or non-lucid dreamers. Each subgroup consisted of eight participants. The subgroup analysis revealed that only frequent lucid dreamers had increased dream lucidity on tDCS

Table 2
Factor loadings for MACE questionnaire items.

Item	F1	F2
Making choice	**.711**	−.072
Attention captured suddenly	−.121	**.787**
Focused attention	**.500**	.311
Public self-consciousness	**.780**	−.020
Awareness of own thoughts/feelings	**.704**	−.119
Awareness of own behavior	**.594**	.377
Awareness of external events	.096	**.775**

Note: Oblimin rotation with Kaiser normalization. Loadings of ≥.4 are in bold.

Table 3
Factor loadings (unrotated) for DLQ questionnaire items.

Item	
1. I was aware that I was dreaming	**.869**
2. I was aware that my physical body was asleep	**.843**
3. I was aware that all my dream characters were not real people	**.872**
4. I deliberately chose one action instead of the other	**.417**
5. I was aware that all dream objects were not real	**.920**
6. I changed dream events in the way I wanted	**.728**
7. I recalled some facts or episodes from my waking life	.314
8. I changed dream characters in the way I wanted	**.574**
9. I broke the physical laws of the waking reality (e.g., flew, went through a wall)	**.577**
10. I changed the dream scene in the way I wanted	**.629**
11. I thought about different possibilities of what can I do in a dream	**.550**
12. I clearly remembered my intentions of what I wanted to do in a lucid dream	.225

Loadings of ≥.4 are in bold.

Table 4
Comparison data on dream reports for two conditions ($N = 16$ participants).

	Sham		tDCS		Z	p-Value
	M	SD	M	SD		
Word count	116.6	70.7	159.9	111.1	−2.430	.015[*,a]
Self-ratings						
Emotional tone	0.510	0.741	0.318	1.114	−0.544	.586[a]
Lucidity (DLQ)	0.343	0.507	0.488	0.749	−1.798	.036[*,b]
Metacognition with internal focus (MACE)	1.123	0.803	1.187	0.860	−0.854	.197[b]
Metacognition with external focus (MACE)	1.202	0.937	1.330	0.914	−0.028	.489[b]
Judge ratings						
Lucidity	0.167	0.365	0.396	0.611	−2.070	.019[*,b]
Bizarreness	1.660	0.513	1.929	0.523	−2.282	.022[*,a]
Number of bizarre elements	0.219	0.415	0.242	0.393	−0.315	.752[a]
Judge ratings (controlled for dream report length[1])						
Lucidity	−0.060	0.362	0.121	0.571	−0.724	.235[b]
Bizarreness	−0.163	0.471	−0.002	0.494	−1.810	.070[+,a]
Number of bizarre elements	−0.032	0.400	−0.076	0.382	−0.621	.535[a]

[*] $p < .05$.
[+] $p < .1$.
[a] 2-Tailed test.
[b] 1-Tailed test.
[1] Residuals are provided.

nights in comparison to sham nights (0.917 ± 0.881 vs. 0.599 ± 0.626, $Z = -2.117$, $p = .017$) while no difference was found for infrequent and non-lucid dreamers (0.058 ± 0.068 vs. 0.087 ± 0.101, $Z = -0.171$, $p = .568$). The aforementioned differences on a DLQ single item level in greater awareness about unreality of dream objects and dream characters, as well as about the sleeping physical body were all statistically significant for frequent lucid dreamers ($p < .05$), but not for infrequent and non-lucid dreamers. However, infrequent and non-lucid dreamers made more deliberate choices during tDCS nights ($p < .05$).

Furthermore, we checked if lucidity might be explained by increased arousal to tDCS. An additional micro-arousal analysis has been conducted for those tDCS and sham stimulation episodes from which dream reports were collected (one or two epochs at the beginning and at the end of the stimulation have been excluded as EEG signals were uninterpretable due to tDCS effects). Micro-arousal episodes were counted according to the criteria of the American Sleep Disorders Association (Bonnet et al., 1992). The number of micro-arousals per REM period was not different between tDCS and sham conditions (1.11 ± 0.85 vs. 0.96 ± 0.72; $Z = -0.369$; $p = .712$) and there was no association between the number of arousals and the reported dream lucidity rating ($r = .058$, $p = .573$).

4. Discussion

TDCS stimulation delivered over the DLPFC during REM sleep had an effect on the subjective experiences of dreaming. As hypothesized, it resulted in increased dream lucidity according to the self-rating of participants. This study thus provides preliminary empirical support for the causal involvement of the DLPFC in lucid dreaming. The effects, however, were not very strong and post-hoc analysis showed that they were pronounced only in frequent lucid dreamers, who reported increased awareness that their physical body is asleep, that dream objects and dream characters are not real, as well as overall lucidity. No effects of increased lucidity were reported by infrequent and non-lucid dreamers. External "blind" judge scored dream reports from tDCS nights as more lucid and somewhat more bizarre than dream reports from sham nights, yet when judge ratings were controlled for dream report length, the differences in lucidity were no longer significant and differences in bizarreness remained only marginal. One possible explanation is that in shorter dream reports it might be difficult for an external judge to recognize explicit signs of dream lucidity.

It is possible that activation of a wider network of different brain areas is needed to achieve steady lucidity in dreams. For example, Dresler et al. (2012) found an increased activation during REM lucid dreams, not only in the prefrontal, but also in the occipito-temporal cortices, bilateral precuneus, cuneus and parietal lobes. These cerebral areas can also be targeted for stimulating lucid dreaming. On another hand, a combined tDCS and PET of regional cerebral blood flow (rCBF) study found that both cathodal and anodal tDCS induced increases and decreases in rCBF, not only in the cortical areas beneath the electrodes, but also in a much wider network of cortical and subcortical areas (Lang et al., 2005). Thus it is possible that not only the DLPFC but also some other brain regions have also been activated due to the stimulation.

Further, there is a possibility that lucidity occurred due to indirect effects of tDCS application. For example, the stimulation might have increased arousal which could lead to increased lucidity, as lucid dreams are associated with elevated levels of physiological activation during REM sleep (LaBerge, Levitan, & Dement, 1986), or lucidity might be induced due to electrotactile stimulation effects (cf. Hearne, 1983). To explore such possibility we carried out an additional analysis of micro-arousals for those REM periods from which dream reports were collected. While we did not found more arousals during tDCS as compared to the sham condition and there was no association between the number of arousals and reported dream lucidity, we cannot completely rule out such a possibility. To control for this, futures studies, in addition to the sham condition, are advised to use stimulation over another brain region or to compare anodal vs. cathodal stimulation.

Furthermore, it might be that the activation itself has not reached a sufficient threshold to induce lucidity. For example, a combined tDCS and blood oxygenation level dependent (BOLD) MRI study found that while cathodal tDCS resulted in a significant global decrease of activated pixels by 38%, anodal tDCS yielded only a 5% (insignificant) increase (Baudewig, Nitsche, Paulus, & Frahm, 2001). More pronounced effects found in frequent lucid dreamers might suggest that due to their frequent experience, the required DLPFC activation threshold might be somewhat lower or their DLPFC is already more activated during REM sleep as compared to what would be needed with infrequent and non-lucid dreamers (a hypothesis to be tested in future studies).

In many cases tDCS applied during REM sleep was somewhat disturbing for the participants – it disrupted REM sleep and resulted in brief awakenings. Thus the number of awakenings was lower on tDCS nights (for three participants no awakenings were possible at all) and awakenings were carried out later. This also explains longer dream reports for the tDCS nights: If the stimulation awakened a participant, it was discontinued and reapplied if the participant re-entered REM sleep; the participants could therefore spend more time in REM sleep during the tDCS nights. This, however, did not affect lucidity ratings – lucidity was neither associated with awakening times nor with dream report lengths.

Another study which applied tDCS during REM also reported cases where the stimulation disrupted REM sleep each time it was applied (Jakobson et al., 2012). In our study, the participants often started to scratch the area of stimulation upon the application of tDCS, indicating some itching sensations. To eliminate those sensations, in future studies topically applied local anesthetic cream, such as EMLA, could be used (McFadden, Borckardt, George, & Beam, 2011).

In the present study only one lucid dream was verified with volitional eye-movements, despite the fact that lucidity was observed in much more dreams (seven dreams, for example, were scored as clearly lucid by an external judge). Although lucidity is often considered as an "all-or-nothing" phenomenon, there seem to be different degrees (or continuum) of lucidity and in some dreams a person might be less lucid than in others and have delusions or memory impairments (Barrett, 1992). In many cases the participants of the present study forgot to signal after becoming lucid in a dream. Our recent survey, which included 571 lucid dreamers, revealed that waking memory recall is often impaired in lucid dreams – in average lucid dreamers are able to recall only a half of those actions that they plan in wakefulness for accomplishment in lucid dreams (Stumbrys, Erlacher, Johnson, & Schredl, in press). In the present study these numbers were markedly lower. One possible reason is that our participants were only briefly instructed about LRLRLR eye-signaling before going to sleep and a more extensive training and mental set preparation is needed to ensure a better recall. Awakening after a longer time in REM sleep might also increase the chances for successful eye-signaling (cf. LaBerge et al., 1986).

The finding that infrequent and non-lucid dreamers were making more deliberate choices in their dreams on tDCS nights can be explained by involvement of the DLPFC in decision making, especially in ambiguous situations (Krain, Wilson, Arbuckle, Castellanos, & Milham, 2006). On another hand, dreams of frequent lucid dreamers on tDCS nights were marked by an increased awareness that their physical body was asleep and that their dream characters and dream objects were not real. DLPFC is known to play an crucial role in working memory (Curtis & D'Esposito, 2003), which is necessary for recognizing and maintaining the awareness of the dream state and its illusory nature. Furthermore, it has been demonstrated that of all brain regions, the DLPFC is exclusively associated with conscious perception (Lau & Passingham, 2006), which is, of course, the cornerstone of lucidity in dreams.

In this study it was also found that lucidity in dreams had some associations with externally-focused metacognition but not with internally-focused metacognition. Lucid dreams are often initiated by observing an oddity within the dream environment (Purcell, Mullington, Moffitt, Hoffmann, & Pigeau, 1986); metacognitive activities with external focus might therefore play a more important role in lucid dreaming than metacognitive activities with internal focus.

TDCS did not affect the emotional tone of dreams and dreams from stimulation nights were not reported to be more unusual than dreams from sham nights, yet the external judge scored them to be somewhat more bizarre. While it has been suggested that prefrontal deactivation accounts for bizarreness in dreams (Muzur, Pace-Schott, & Hobson, 2002), lucid dreams, on the other hand, are associated with higher dream bizarreness (McCarley & Hoffman, 1981). The relation between dream lucidity and bizarreness could be two-fold. On one hand, bizarreness might help to facilitate lucidity (e.g. by recognizing an oddity), while, on the other hand, in lucid dreams the dreamer can do bizarre things that are impossible in waking life, such as flying (Barrett, 1991). Future studies should explore the involvement of the prefrontal cortex in dream bizarreness by applying cathodal (inhibitory) stimulation during non-lucid dreaming.

When interpreting the results, some methodological considerations have to be acknowledged. Different placements of the second tDCS electrode might yield qualitatively different effects (Nitsche et al., 2008). For example, the tDCS sleep study by Marshall et al. (2004) applied the cathode electrodes at the mastoids while in this study the cathodes were applied at the supraclavicular areas. Furthermore, carry-over effects of tDCS to subsequent REM periods might also occur (Nitsche et al., 2008); yet, in this study lucidity was not associated with later awakening times. Also the present study was conducted as a single-blind experiment and, despite all precautions taken, some possibility of the experimenter's bias remains (e.g. by unintentionally giving cues which night was which or by a voice tone when reading lucidity questions aloud).

In summary, this study provides some preliminary evidence for involvement of the DLPFC in lucid dreaming. While this causal connection is important on the neurophysiological level, due to the small effects, tDCS might not be a promising tool for lucid dream induction on a practical level (Noreika et al., 2010). For practical purposes, other lucid dream induction methods can be suggested (Stumbrys, Erlacher, Schädlich, & Schredl, 2012). Future studies could target other brain areas, such as the precuneus, to increase dream lucidity, as well as higher stimulation intensities (e.g. 2 mA) with topically applied local anesthetic creams. To control for indirect tDCS effects, in addition to sham stimulation, the stimulation over another brain region or inversed stimulation (anodal vs. cathodal) should also be used. To increase the frequency of lucid dreams with volitional eye-signaling, more extensive mental set preparation training should be employed and awakenings carried out after a longer time in REM sleep.

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Running title: Effectiveness of motor practice in lucid dreams

Effectiveness of motor practice in lucid dreams: A comparison with physical and mental practice

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Abstract

Motor practice in lucid dreams is a form of mental rehearsal where the dreamer can consciously rehearse motor skills in the dream state while being physically asleep. Previous pilot study showed that practice in lucid dreams can improve subsequent performance. This study aimed to replicated those findings with a different (serial reaction) task and compare the effectiveness of lucid dream practice not only to physical but also to mental practice in wakefulness. Online experiment was completed by 68 participants within four groups: lucid dream practice group, mental practice group, physical practice group and control (no practice) group. Pre-test was accomplished in the evening, post-test in the next morning, while the practice was done during the night. All three practice groups significantly improved their performance from pre-test to post-test, but no significant improvements were observed for control group. Subjective sleep quality was not affected by night practice. This study thus corroborates the previous findings that practice in lucid dreams is effective in improving performance. Its effects seem to be similar to actual physical practice and mental practice in wakefulness. Future studies should establish reliable techniques for lucid dream induction and verify the effects of lucid dream practice in sleep laboratory conditions.

Keywords: lucid dreams; motor learning; lucid dream practice; mental practice; finger tapping

Introduction

Mental practice is the cognitive rehearsal of a physical activity in the absence of overt physical movements (Richardson, 1967). It is a well-established technique in sports science and practice (Morris, Spittle, & Watt, 2005). Several meta-analyses demonstrated that mental practice significantly improves performance, albeit to a smaller extent as actual physical practice (Driskell, Copper, & Moran, 1994; Feltz & Landers, 1983). A novel and relatively unknown type of mental rehearsal is motor practice in lucid dreams (Erlacher, 2007).

Lucid dreams are nocturnal dreams in which the dreamer is aware that he or she is dreaming and often can influence the dream plot (LaBerge, 1985). This ability to be aware in the dream state and deliberately perform actions while physically asleep opens up opportunities to use lucid dreams for sports practice, for example, to consciously rehearse specific motor tasks without waking up (Tholey, 1990). Practice in lucid dreams is similar to mental practice in wakefulness: Movements are rehearsed with a representation of the body on a cognitive level without overt physical movements (cf. Erlacher, 2007). Similarly, as with imagined actions (cf. Decety, 1996), dreamed actions also seem to share the same neural mechanisms with executed actions (Erlacher & Schredl, 2008b): Correspondences exist in underlying brain activity (cf. Dresler et al., 2011), autonomic responses (cf. Erlacher & Schredl, 2008a) and temporal dynamics (cf. Erlacher, Schädlich, Stumbrys, & Schredl, 2014).

Empirical evidence on lucid dream practice is rather scarce. In a sample of 840 German athletes from various sports, 57% stated that they had at least one lucid dream in their life, 24% reported frequent lucid dreams (one or more lucid dreams per month), however only 9% of the lucid dreamers used this dream state to practice sport skills (Erlacher, Stumbrys, & Schredl, 2011-2012). Yet, the majority of those who practiced had the impression that the rehearsal within the lucid dream improved their subsequent performance in wakefulness. Several such anecdotal accounts on how practice in lucid dreams improved waking performance have also been reported in the literature (e.g. Erlacher, 2007; LaBerge & Rheingold, 1990; Tholey, 1990).

In a qualitative study, Tholey (1981) asked six proficient lucid dreamers to perform and practice movements and complex sport skills, such as skiing on gymnastics, with which they were already familiar from waking life. The participants reported no difficulties while performing complex sport skills in their lucid dreams and had an impression that their movements improved following the practice.

Further, Erlacher and Schredl (2010) conducted a pilot study (field experiment) with a pre-post design in which the participants were asked to practice a simple motor task – to toss 10-cent coins into a cup, positioned at the distance of two meters, as many times as possible out of 20 trials. Twenty participants attempted to practice the task in a lucid dream on a single night and seven of them succeeded. Their peformance was compared to a group which accomplished actual physical practice ($n = 10$) and a control group without practice ($n = 10$). Both practice groups showed significant increases in hitting the target from pre-test to post-test, while no increase was found for the participants who did not practice the task. Although the improvements following lucid dreaming practice were somewhat lower in comparison to physical practice, the differences were not significant.

The present study aimed to replicated these findings with a different motor task (a serial reaction task – finger-tapping; cf. Karni et al., 1998; Walker, Brakefield, Morgan, Hobson, & Stickgold, 2002) and compare the effectiveness of lucid dream practice not only to physical practice but also to mental practice in wakefulness. It was expected that all three types of practice will improve subsequent performance.

Methods

Participants

The sample included 68 individuals (32 male and 36 female) who completed an online experiment. Their ages ranged from 19 to 54 years, with the mean age of 31.3 ± 7.3 years. Participants were recruited via electronic advertisements (posted on lucid dreaming-related discussion boards, social networking sites and via personal contacts) and assigned to one of four groups: (1) lucid dream practice (LDP) group (if they were frequent lucid dreamers; n = 21); (2) mental practice (MP) group (n = 15); (3) physical practice (PP) group (n = 16); (4) control (no practice) group (n = 16). The data of four participants from LDP group were excluded (reducing the sample to n = 17) as three participants reported that they practiced the task only very briefly (tapping the sequence only 2-4 times) and one participant reported additional practice in the evening while awake. Group characteristics are depicted in Table 1. Participation was voluntary and unpaid. The study was conducted according to the principles of the Declaration of Helsinki. All participants signed an electronic informed consent form and were free to withdraw from the experiment at any time.

Motor task

A computerized online version of the sequential finger tapping task was used, which requires the participant to press four keys on a computer keyboard with a non-dominant hand producing a sequence of five elements "as quickly and accurately as possible" for a period of 30 s (Walker et al., 2002). Each sequence started and finished with the little finger while index, middle and ring fingers were used once (e.g. "4-1-3-2-4"; cf. Karni et al., 1998). Four differences sequences were prepared for each hand, allowing repeating the experiment up to four times. During the initial (learning) phase, the participants were asked to memorize the sequence shown on the screen and tap it correctly 10 times. Each correct key press produced a green dot on a corresponding finger in a hand picture presented on the screen, while an incorrect key press produced a red dot. The assessment phase consisted of two test periods of 30 s with a 30 s rest period in between. Each key press produced a white dot. No other feedback was provided. The number of correct sequences completed and the number of incorrect key-presses were recorded. The average scores of two test periods were calculated.

Procedure

The study was conducted as a field experiment, i.e. the participants accomplished the procedure by themselves in their home setting. Firstly, the participants had to fill an initial online questionnaire, which included demographical data (age, gender, country), questions about lucid dream recall, vividness of motor imagery and handedness. Lucid dream frequency was assessed on an 8-point scale (0 – never; 1 - less than once a year; 2 - about once a year; 3 - about 2 to 4 times a year; 4 - about once a month; 5 - about 2 to 3 times a month; 6 - about once a week; 7 - several times a week), with a high re-test reliability (r = .89; Stumbrys, Erlacher, & Schredl, 2013). To ensure a clear understanding of lucid dreaming, a definition was provided: "In a lucid dream, one is aware that one is dreaming during the dream. Thus it is possible to wake up deliberately, or to influence the action of the dream actively, or to observe the course of the dream passively." In order to obtain units in frequency per month, the scale was recoded using the class means: 0 → 0, 1 → 0.042, 2 → 0.083, 3 → 0.25, 4 → 1.0, 5 → 2.5, 6 → 4.0, 7 → 18.0 (see Stumbrys et al., 2013). Further, the participants filled a revised version of the Vividness of Motor Imagery Questionnaire (VMIQ-2, Roberts, Callow, Hardy, Markland, & Bringer, 2008), which assesses 3-factor (internal visual imagery, external visual imagery, and kinesthetic imagery) individual imagery characteristics on a 5-point scale (ranging from 1 – perfectly clear and vivid to 5 – no image at all). VMIQ-2 has demonstrated acceptable factorial validity, construct validity and concurrent validity (Roberts et al., 2008).

The order in which VMIQ-2 imagery modalities where presented was randomised. Lastly, the participants filled the Edinburgh Handedness Inventory – Short Form (EHI-SF,Veale, 2013), which contains four items for which the preference in the use of hands is scored on a 5-point scale (from 1 - always right to 5 - always left). The modification was shown to have good reliability, factor score determinacy and correlation with the original 10-item inventory (Oldfield, 1971).

After filling the initial questionnaire, the participants were assigned to one of the groups. Firstly, LDP group was assembled from the participants with a higher lucid dream frequency (2-3 or more lucid dreams per month). Other participants were put on the waiting list and randomly assigned to one of the other groups after LDP group completed the experiment. Instructions to the participants were sent by email. All participants were asked to choose a time schedule for the experiment so that the time difference between the evening pre-test and the morning post-test would be 10 hours. MP and PP participants were assigned corresponding practice times (from the bed time) and durations as LDP group. Two lucid dreamers practiced the task in two different dreams during the night, hence two corresponding participants in MP and PP groups were also asked to awaken and practice the task twice during the night (although one PP participant did only a single awakening). Further, all participants were asked to set alarm clock to awaken at least 30 min before the post-test time, so that their performance would not be impaired by sleep inertia (Tassi & Muzet, 2000).

LDP group. The participants could use any technique to induce lucid dreams (cf. Stumbrys, Erlacher, Schädlich, & Schredl, 2012), except of drug intake. After becoming lucid in a dream, they had to start immediately practicing the task (repeating the memorized sequence) and continue the practice for as long as possible. The participants were instructed to do the practice in 30 s (self-estimated) intervals with 30 s (self-estimated) rest periods in between. During the 30 s rest periods they were allowed to apply techniques that prolong lucid dreams (e.g. spinning, hand rubbing; LaBerge, 1995).

MP group. Each participant was assigned one exact practice time and duration from LDP group. The participants were asked to awaken 30 min before the assigned practice time and keep themselves awake during this period (to avoid possible effects of sleep inertia). Then they were instructed to close their eyes and start practicing the task in their mind without moving their actual fingers during the practice. With their eyes closed, they had to attempt to imagine themselves producing the sequence by visualizing the movement of each finger. The participants were asked to try to *feel* each movement of their fingers while repeating the memorized sequence. The practice had to be accomplished in 30 s (self-estimated) intervals with 30 s (self-estimated) rest periods in between.

PP group. As in MP group, PP participants were assigned exact practice times and durations from LDP group and asked to awaken 30 min before the practice time keepinf themselves awake during this period. Then they were instructed to start practicing the task physically, also in 30 s (self-estimated) intervals with 30 s (self-estimated) rest periods in between.

Control group. The participants were not asked to do any practice (only pre-test in the evening and post-test in the morning).

Upon completing the post-test, the participants had to fill a report, indicating their bed times, and rating their sleep quality of the night on a 4-point scale (1 – very good to 4 – very bad). Three practice groups were further asked to provide their practice details. If unsuccessful, participants could repeat the experiment with a difference sequence (up to four times).

On one occasion (MP) no results were recorded for the second post-test interval, whereas in two other occasions (LDP and MP) the number of correct sequences produced during one of the pre-test intervals (in both cases the second interval) was very low (2 sequences) as compared to the average performance during the other three test intervals (16.0 and 13.7 sequences, respectively). To avoid possible distortions, the data from these intervals were excluded (thus only a single test interval result and not the average of the two test intervals were used).

Statistical analysis

IBM SPSS Statistics 20 software was used for statistical analysis. One-way ANOVA were performed to compare the characteristics of the four group on interval variables (age, scores on motor imagery scales), whereas Kruskall-Wallis test was used for ordinal variables (sleep quality and lucid dream frequency) and Chi-square for categorical variables (gender and handedness). Two-way repeated-measures ANOVA were conducted to compare the performance from pre-test to post-test between the groups. Differences between the groups were located with post-hoc least significant difference (LSD) tests. Student t-tests were used to compare the performance from the pre-test to the post-test for each individual group. Spearman's *rho* correlations were used to check the associations between changes in performance and potential confounding variables: lucid dream frequency and repeated trials. G*Power 3.1.7 software (Faul, Erdfelder, Buchner, & Lang, 2009) was used for calculating effect sizes *d*. An alpha = .05 significance level was employed.

Results

Group characteristics

According to the EHI-SF results, six participants were considered left-handed and were assigned to do the motor task with the right hand, whereas the rest 58 participants were right-handed and performed the task with the left hand. There were no significant handedness differences between the groups, as well as differences in motor imagery abilities as measured by VMIQ-2 and reported sleep quality of the night, although the groups differed in their lucid dream frequency (Table 1).

****Table 1 near here****

Practice times and durations

A few participants in MP and PP groups slightly diverged from the original instructions (considering their exact practice times and durations), but the conditions were very much similar nevertheless. LDP group carried out their practice in average at 6:07 ± 2:20 hours since their bed time (range: 1:20 to 9:00), MP at 5:49 ± 2:17 hours (range: 1:20 to 8:40), and PP at 5:51 ± 2:23 hours (range: 1:20 to 9:00). LDP group did 4.2 ± 6.3 blocks of 30 s practice (median: 2; range: 1 to 22), MP 5.3 ± 6.4 (median: 3; range: 1 to 22), and PP 3.8 ± 5.3 (median: 2; range: 1 to 22). Three practice groups did not differ in their amount of practice ($F_{3,60} = 0.08$, $p = .927$) and duration ($F_{3,60} = 0.28$, $p = .760$).

****Table 2 near here****

Effects of practice

All three practice groups had significant improvements from pre-test to post-test, whereas the control participants had only insignificant improvements (Table 2). There was a significant time (pre-test to post-test; $F_{1,60} = 50.12$, $p < .001$) but not group ($F_{3,60} = 0.48$, $p = .695$) effect. Group x time interaction was significant ($F_{3,60} = 3.43$, $p = .023$), showing that four groups improved differently from the pre-test to post-test. Post-hoc LSD pair-wise comparisons showed significant differences between LDP and control group ($p = .003$), as well as between

PP and control group (p = .031), but not between other pairs of the groups. Increases in performance from pre-test to post-test were not associated with lucid dream frequency (*rho* = .100, p = .432). Further, no significant association between changes in performance and the number of trials (*rho* = -.402, p = .110) was found in LDP group, where most of participants attempted the experiment more than once.

LDP group made in average 5.3 ± 5.2 errors on the pre-test, MP 5.5 ± 6.7, PP 5.0 ± 8.1, and control group 8.3 ± 13.0. On the post test the respective error rates were 5.6 ± 5.0, 7.1 ± 7.8, 5.7 ± 9.7, and 10.9 ± 13.3. Differences between the two tests were significant for control group (more errors on the post-test; t = 3.76, p = .002) but not for practice groups (LDP: t = 0.23, p = .820; MP: t = 1.63, p = .125; PP: t = 0.69, p = .504). Overall differences for the change in the error rate between the four groups were not significant ($F_{3,60}$ = 0.95, p = .423).

Discussion

The present study corroborates the findings of a pilot study by Erlacher and Schredl (2010) that motor practice in lucid dreams enhances subsequent performance. All three types of practice lead to significant improvements from the pre-test to the post-test, whereas only a small but not statistically significant improvement was found in the control (no practice) group. LDP and PP participants had significantly higher improvements as compared to control group who did only the test and retest. No significant differences were found between three different practices, as well as between MP and control group. LDP resulted in highest average gains (+20%), followed by PP (+17%) and MP (+12%), however the effect size was highest for PP (1.57), followed by MP (1.16) and LDP (0.91). All these effect sizes are considered large (≥ 0.8) according to Cohen (1992).

Before discussing the findings, several methodological issues have to be acknowledged. Firstly, the study was conducted as a field experiment and therefore the experimental control was lacking. For example, it is possible that some participants did not adhere to the instructions correctly. Although instructions sent to the participants were written as clearly as possible, in a few cases the participants slightly diverged (e.g. by awakening for practice at a slightly different time, by doing a somewhat different number of practice intervals, or by forgetting to do rest periods during LDP). To have a better experimental control, sleep laboratory studies can be recommended where actions in lucid dreams can be monitored by using eye movements (cf. Erlacher et al., 2014). Yet such sleep laboratory studies are always affected by small sample sizes (limited usually only to a few successful participants), because it is very difficult to recruit proficient lucid dreamers. In general population, only 5% of people have at least one lucid dream a week (Schredl & Erlacher, 2011), which is necessary for sleep laboratory studies, restricted only to a few nights. The biggest advantage of online field experiments is that they allow recruiting participants from all over the world (e.g., 21 lucid dreamers who completed the present study represented 11 different countries) and therefore samples can be much higher. Secondly, the assignment to the experimental groups was not completely randomized, as LDP group was selected by lucid dream frequency. Improvements in performance, however, were not associated with lucid dream frequency. Further, a number of participants who registered for the experiment did not complete it. The participation in the study was quite demanding for MP and PP participants, as they had to awaken at a certain time during the night and wait for half an hour before starting to practice. Lucid dreamers could have had an additional stress "to be successful" (i.e. to be able to have a lucid dream and practice the task in it). Thus this might have resulted that only certain (e.g. highly motivated) individuals completed the study, and therefore the generalization of the findings should be cautious. Thirdly, most participants in LDP group and a few participants in other practice groups did the experiment a few times (up to four). While each time a different sequence was used, there is a possibility that some transfer (positive or negative) in learning had occurred. The possibility to have a task which could be repeatable with a different variation was important to increase the chances of success for lucid dreamers – for example, out of 21 lucid dreamers who completed the study, only 6 were successful on their first trial. Yet multiple trials did not seem to influence the performance: No significant association was found between the changes in performance and the number of trials in LDP group.

As in the previous study (Erlacher & Schredl, 2010), LDP was found to improve subsequent performance in wakefulness. It had somewhat highest gains but the lowest effect size, which suggests that its effects might be more variable. The previous study (Erlacher & Schredl, 2010) with a different – aiming – task found higher improvements (+43% for LDP and +88% for PP), but the reanalysis of the data showed that effect sizes for practices were similar (LDP: 1.24; PP: 1.32) and the effects of PP showed greater variability than of LDP. Considering the results of the two studies together, LDP appears to be similar or slightly less effective than PP. The comparison with MP is somewhat less clear. LDP showed significantly greater improvements as compared to control group, whereas MP did not significantly differ from any of groups. LDP resulted in somewhat higher performance gains as compared to MP, yet somewhat lower effect size. Previous studies with similar finger tapping tasks showed that MP improves performance and the gains are similar or slightly lower as compared to PP (e.g. Debarnot, Creveaux, Collet, Doyon, & Guillot, 2009; Nyberg, Eriksson, Larsson, & Marklund, 2006). The present study corroborates those findings and suggests that the effectiveness of LDP might be similar or slightly higher than the effectiveness of MP, however more research is needed.

Both lucid dream and wakeful mental practices are cognitive rehearsals with a representation of the body without overt physical movements and both seem to some extent to share the same neural mechanisms that produce actual movements (Decety, 1996; Erlacher & Schredl, 2008b). A recent fMRI/NIRS study showed that brain activity in the sensorimotor cortex is similar during imagined and lucidly dreamed movement (Dresler et al., 2011). The perception in lucid dreams, however, seems to be much closer to actual perception and both are quite distinct from imagination (LaBerge & Zimbardo, 2000). In lucid dreams the simulation is experienced as real (not just existing in imagination) and therefore it has been suggested that LDP should be more effective than MP performed in wakeful imagination (Tholey, 1990). The present study, however, did not show a clear difference between the two types of practice.

In comparison with the earlier study (Erlacher & Schredl, 2010), this study involved a larger sample and practice times were matched. In the previous study PP group accomplished practice in the evening, whereas lucid dreamers practiced at some later point at night. Sleep memory consolidation research showed that improvements in performance seem to be associated with various sleep parameters, such as a higher amount of REM sleep (Fischer, Hallschmid, Elsner, & Born, 2002) or a greater proportion of time spent in Stage 2 sleep (Walker et al., 2002). Therefore PP group might have had an advantage in the previous study. In this study the practice times were matched. PP and MP participants had a small disadvantage to awaken at night and wait 30 min before starting their practice. LDP group, however, also had to awaken after a lucid dream (to write down the dream) and several lucid dreamers indicated that they used Wake-up-Back-To-Bed method for lucid dream induction, which requires to awaken at night and stay awake for some time (cf. Stumbrys et al., 2012). Thus the conditions were comparable and the awakenings did not seem to significantly disturb the sleep – all groups rated their subjective sleep quality similarly.

In summary, the present study corroborates the findings that motor practice in lucid dreams improves subsequent performance in wakefulness. No significant differences were found when comparing the effectiveness of LDP to PP and MP in wakefulness. While further research with more complex skills is very much needed, current research with simple motor skills, such as finger-tapping or coin-tossing, shows that LDP gives an additional opportunity to athletes to practice specific sport skills during the night time when physiologically asleep. It provides a realistic simulation of the waking environment and could be used when an athlete is injured, unable to practice physically or actions are dangerous. While only a limited number of athletes have lucid dreams on a frequent basis (Erlacher et al., 2011-2012), there is a wide range of techniques that can be used for lucid dream induction (Stumbrys et al., 2012), yet none of them has been verified to induce lucid dreams reliably and consistently. This is one the main challenges facing lucid dream research. Future studies should establish reliable techniques for lucid dream induction and examine the effects of LDP in controllable sleep laboratory conditions.

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Table 1. Group characteristics

	LDP (n = 17)	MP (n = 15)	PP (n = 16)	Control (n = 16)	Statistical test	p
Age (y)	31.2 ± 8.1	32.1 ± 8.1	31.3 ± 6.0	30.1 ± 8.1	$F_{3,60} = 0.18$	.909
Male / Female	11 / 6	6 / 9	7 / 9	6 / 10	$\chi^2_3 = 3.08$	.379
Right-/Left-handers	13 / 4	15 / 0	15 / 1	15 / 1	$\chi^2_3 = 5.93$	.115
VMIQ-2						
External visual	31.4 ± 12.3	32.9 ± 10.3	33.3 ± 9.3	29.8 ± 9.6	$F_{3,60} = 0.36$	.781
Internal visual	30.7 ± 11.4	30.1 ± 9.3	29.2 ± 11.4	27.1 ± 10.8	$F_{3,60} = 0.34$	.800
Kinesthetic	28.8 ± 11.1	31.5 ± 9.3	24.8 ± 6.9	25.9 ± 9.3	$F_{3,60} = 1.63$	.192
Lucid dreams / month	8.8 ± 7.0	0.5 ± 1.1	0.4 ± 0.7	0.3 ± 0.6	$\chi^2_3 = 36.1$	<.001
Sleep quality	1.9 ± 0.7	1.9 ± 0.8	2.3 ± 0.8	1.8 ± 0.4	$\chi^2_3 = 3.70$	.296

Table 2. Effects of practice on motor task performance

	Pre-test		Post-test		Change in %	T-test		Effect size
	M	SD	M	SD		t	p	
Lucid dream practice	17.1	4.1	20.5	4.7	+20%	3.75	.001	0.91
Mental practice	15.4	4.9	17.3	5.6	+12%	4.46	<.001	1.16
Physical practice	16.2	5.8	18.9	6.4	+17%	6.25	<.001	1.57
Control (no practice)	17.1	6.8	17.9	7.7	+5%	1.56	.070	0.39

Note: One-tailed T-tests were used