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Extending mental practice to sleep: Enhancing motor skills through lucid dreaming

Emma Peters [a,b,*], Sanne Golembiewski [b], Daniel Erlacher [a], Martin Dresler [b]

[a] Institute of Sport Science, University of Bern, Bern, Switzerland
[b] Donders Institute for Brain, Cognition and Behavior, Radboud University Medical Center, Nijmegen, the Netherlands

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ABSTRACT

Improving motor performance without physical movements might seem counterintuitive, however, decades of research on mental practice have demonstrated its feasibility. The phenomenon of lucid dreaming – i.e. becoming aware of the current dream state during ongoing sleep – bears some resemblance to mental practice: behaviors such as motor tasks can be intentionally simulated with mental imagery. During lucid dreaming, however, the brain generates a highly immersive, VR-like environment and realistic proprioceptive impressions to match the mental practitioner's needs. In recent years the hypothesis was thus proposed that lucid dreaming can be used to extend motor practice to the sleeping state, thereby improving motor performance during subsequent wakefulness. Here, we examine this hypothesis by exploring the theoretical foundations and efficacy of this inventive approach in sports science and beyond. Experimental studies show promising performance improvements after lucid dreaming motor practice. Similarities have been observed in brain activity, eye movements, muscle activity, and autonomic responses compared to physical practice support the potential of lucid dreaming practice. Surveys show that athlete populations already implement lucid dreaming practice as part of their training. Potential placebo effects and an increase in motivation after lucid dreaming practice in the post-test should be investigated in future studies. Also, some well-known practical challenges of lucid dream research, such as its rarity, lack of proper training, and lack of control over the dream, need to be addressed. Eliminating these limitations will strengthen the potential of this inventive approach and enable lucid dreaming practice to be incorporated into various disciplines in the future.

Introduction

At first glance, improving a certain motor skill seems to require some form of physical practice. Repeatedly performing the same action will help perfect the action and achieve the desired result. In some cases, however, improving motor skills is needed while being unable to move. This is a known challenge in multiple domains: in sports, weather- and environment-dependent activities or injuries can be a limiting factor, whereas in the medical field, stroke patients require physical rehabilitation while the risk of injury is relatively large. These are examples of situations requiring motor improvement while challenged by the restraints of the physical world. Thus, solely using the brain to affect the physical performance of a motor task is a valuable and interesting approach to explore.

Mental practice

Already in the 1970s, a new method of improving motor performance became popular: mental practice. Corbin first defined mental practice in 1972 as "the repetition of a task, without observable movement, with the specific intent of learning". It can be interpreted as a recreation of an experience developed from memorized information [1].

Mental practice is a term that covers a large variety of activities ranging from closing the eyes and thinking about a motor skill without any visual or proprioceptive components to immersive, sensory-rich imaginations [2]. Mental practice utilizes motor imagery [3–6]. Motor imagery assesses the intention to perform a specific movement and uses, a normally unconscious process, consciously during movement preparation. Overt and mental movements share active brain regions [7,8]. Repetitive activation of motor networks involved in the execution of a specific action might strengthen these neural pathways in the same way

* Corresponding author at: Institute of Sport Science, University of Bern, Bremgartenstrasse 145, CH-3012 Bern, Switzerland.
E-mail address: emma.peters@unibe.ch (E. Peters).

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motor execution training would [9]. Especially the posterior supplementary motor area (SMA) and the premotor cortex seem to be highly involved areas of movement imagery and have been consistently shown to be active during motor imagery [10,11]. Mental imagery does not happen solely in the visual modality. It is very well possible for imagers to combine a range of different modalities or selectively use, for instance, olfactory, auditory, tactile, or pain imagery. However, motor imagery relies mostly on visual and kinesthetic imagery. Motor imagery is used as a part of mental practice when the goal is to improve specific motor performance.

Early mental practice research has demonstrated that it has a powerful effect on performance outcomes and affects both experienced and inexperienced subjects [12,13]. The effect was observed with various motor skills, like reaction time, landing an airplane, hockey, and skiing [2]. Several more recent studies have confirmed this and showed that, indeed, mental practice could be used for motor skill improvement. In elite sports, many athletes and their coaches confirmed that they integrate mental practice into the training program as a standard part [14]. In a study on athletes who fast during Ramadan, mental practice counteracted the negative effects of fastening by improving motor performances in these athletes [15]. Also outside of sports, mental practice has been proven valuable: post-stroke patients underwent motor rehabilitation with additional mental practice, which turned out to be an effective treatment to improve motor function [16].

The efficacy of mental practice on motor performance is affected by several factors. One of these is the imagery ability. Increased modulation of corticospinal excitability, an effect of mental practice, is more pronounced for people with a greater imagery ability [17]. Imagery perspective also plays a role in its efficacy, as mental practice is realized from two different perspectives. 'Internal imagery' occurs when the person is directly involved in the action and imagines being inside their own body and experiences those sensations that might be expected in the actual situation. When the person is an external observer of their own action, we speak of 'external imagery' [18]. The specific task also interacts with the factors mentioned before and influences improvement. For example, goal-directed tasks benefit more from internal imagery, while external imagery is more effective for open skill (changing environmental conditions, body transport) performances [18]. Finally, additional factors that influence mental practice efficacy are imagery duration, attention focus [19], and imagery speed [20]. A combination of mental and physical practice seems superior to mental or physical practice alone [12,21].

So why does mental practice work? An important theory that supports the foundations behind the efficacy of mental practice is the neural simulation theory developed by Jeannerod in 2001 [5]. It states that imagined actions are actual overt actions even though they are not physically executed. The state in which an action is mentally practiced, the so-called 'S-state', and the state in which the action is performed, seem to share the same neural circuits. Mental simulation, or mental practice, is thus categorized as an S-state. Because the mental practice of an action shares neural similarities to overt actions during wakefulness, one can practice physical movements in terms of fine-tuning the performance [22]. Mental practice is an effective strategy to improve motor performance. Imagery ability, attention, and perspective are factors influencing its efficacy. An extended, and more immersive version of mental simulation would be the phenomenon of lucid dreaming. With lucid dreaming, mental imagery is topped by a fully immersive VR-like environment that is available to aid in practice. A dreamed body performs the actions while the environment is shaped to provide additional feedback to the dreamer. This new approach has the potential to reveal a highly effective method of motor performance enhancement that transcends mental practice in its capabilities.

Lucid dreaming

The phenomenon of lucid dreaming is defined as becoming aware of the dream state while remaining asleep [23]. In lucid dreaming, the dreamer is able to recognize the absurdity of the dream content, and realize the experience must be a dream. Once this realization is made, the dreamer has the opportunity to steer the dream according to their own intent. Reflecting on the current state of mind is also known as metacognition [24]. Unlike the state of wakefulness, dreaming is usually not accessible to metacognitive processes [25]. This is supported by the fact that during Rapid Eye Movement (REM) sleep, the dorsolateral prefrontal and frontopolar areas, responsible for wake-like metacognitive monitoring, are deactivated. Restricted by this absence, the dreamer lacks the ability to think critically, question their own true state of mind, and act with any volitional control [26]. In the rare case of lucid dreaming however, metacognitive questioning of the state of mind becomes available [27]. Several studies have shown significant differences in the activity in these areas during the state of lucid dreaming. Regions of the anterior prefrontal, parietal and temporal cortex, areas related to metacognitive processes during wakefulness, seem to be involved in lucid dreaming [28]. An increase was found in the gamma band of frequencies (40 Hz) during lucid dreaming, which is known to be associated with processes related to consciousness [29,30]. In addition, a significant increase in global cognitive networking was found according to evidence across all ranges for all frequency bands [30]. Additionally, greater blood oxygen level dependent (BOLD) activity was found in the right dorsolateral prefrontal cortex and bilateral frontopolar areas in lucid dreams as compared to non-lucid REM sleep [31], again suggesting an increase in metacognitive abilities in lucid dreaming. Lucidity can emerge in various degrees of consciousness and control. These degrees can range from simply recognizing that one is dreaming to intentionally performing self-chosen actions and having complete control over the dream content, story, and characters [29]. In other words, using reflective and metacognitive consciousness, dreams become malleable and lucid dreamers are able to experience a fully immersive virtual reality while asleep [27].

Lucid dreams predominantly appear during Rapid Eye Movement (REM) sleep. However, some cases describe lucid dreams appearing during Non-REM (NREM) sleep stages [32]. REM sleep dreams are more vivid, emotionally bizarre, and more often narrative of structure than NREM dreams which seem more abstract [28]. The phenomenon of lucid dreaming shows a considerable variation in inter-individual frequency. Some people never experience a lucid dream (40–50%), monthly (20%), and a small percentage that experience this phenomenon weekly [28]. Lucid dreaming can emerge spontaneously, but is also a learnable skill and can be trained with the help of several induction strategies, such as the wake-back-to-bed (WBTB) and mnemonic induction of lucid dreams (MILD) [23]. There are two standard measurement methods to examine the psychophysiology of lucid dreaming. First, the eye signaling method [33] uses a predetermined eye signaling pattern visible with polysomnography and enables verification and time stamping. The signal is a complete left–right-left–right shift with both eyes and will be visible on the electrooculogram (EOG) as soon as a person becomes lucid. The second measurement method is the use of questionnaires. First, the Metacognitive, Affective, Cognitive Experience (MACE) questionnaire [34] assesses metacognitive skills while asleep. Second, the Dream Lucidity Questionnaire (DLQ) [35] assesses different lucidity aspects of dreams. Third, the Lucidity and Consciousness in Dreams Scale (LuCiD) [36] enables the assessment of the consciousness levels within dreams. Lastly, the Lucid Dreaming Skills Questionnaire (LUSK) [37] measures inter-individual lucid dreaming skills and thus predicting the potential of a dreamer to successfully perform tasks in a sleep laboratory environment. Lucid dreaming has a wide variety of potential applications, including the treatment of phobias, PTSD, the practice of social skills, creativity, and even sports. Enhancing wakeful motor performance during sleep seems unlikely, yet some studies provide promising results to support this claim. In some cases, improving motor skills is needed while unable to move. This might be due to injury or a medical condition, such as stroke, or because environment-dependent activities such as swimming or skiing require a specific time and place for practice.

The hypothesis

Planning and coordination of movements happens not peripherally, but via neural processing in the brain. Mental practice research shows that using solely such motor imagery, without actually performing overt movements, motor performance can be enhanced. With physical activity not being a fixed requirement, the hypothesis can be proposed that lucid dreaming provides a more effective, more immersive experience for improving wakeful motor performance. Lucid dreaming motor practice allows a person to experience a fully immersive VR-like environment while practicing motor skills. Dreamers can shape themselves, the action, the environment, the equipment, and other dream characters to make the simulation as close to reality as possible. Physiological similarities between the physical and dreamed body support the potential of lucid dreaming motor practice. These similarities are found in a broad range extending from eye-movements to cardiovascular functions, and will be discussed during the following evaluation of this hypothesis.

Evaluation of the hypothesis

Theoretical foundations

Eye movements – Erlacher and Schredl [38] reviewed the shared physiological substrates and found comparisons in many domains. A well-known demonstration of the connection between the physical and dreamed body can be found in eye movements. Specific dream content often matches eye movements recorded with electrooculography (EOG) [39,40]. This is also referred to as the scanning hypothesis which explains that the directional properties of rapid eye movements are coherent with dream imagery, like in a virtual reality environment [41]. In lucid dreams, pre-arranged gaze shifts were carried out and were strongly correlated to the eye movements of the sleeping body [42]. As mentioned before, the gold standard for verifying lucid dreaming uses eye signaling. With this technique, the participant performs a sequence of eye movements once they realize they are dreaming. This sequence, a left–right-left–right movement with both eyes, is visible using EOG [43,44] and is an example of how eye movements in lucid dreams are strongly correlated to the measured EOG signal. In addition, dreamed eye movements are more closely related to wakeful perception than imagination. Participants had to trace a circle with their stretched arm and follow the tip of the finger with their gaze. They did this during wakefulness, waking imagination, and lucid dreams. The number of saccades in both the wakeful and lucid dream performances was distinguishable from the imagined performances [45].

Muscle activity – A sleeping body usually inhibits showing any gross movements, especially during REM sleep. This movement blockade serves as the first important argument for the hypothesis that REM dreams seem to have a high correlation to corresponding physical activity [38]. Despite this blockade, electromyography (EMG) can pick up small electrical impulses generating muscle twitches [46,47]. These tiny muscle twitches correlate to corresponding dreamed limb movements [39,40,48]. Emotional dreams have shown increased muscle activity in the facial muscles producing emotional facial expressions. However, a replication did not find this correlation [49,50]. Finally, facial muscles involved in talking were more active during talkative dreams [51,52]. Overall, the findings indicate that the EMG recordings correspond to the dream content reported by the dreamer after awakening. Aside from non-lucid dreams, EMG activity has been coupled with movements in lucid dreams. With the help of eye-signal verified lucid dreaming, the exact timing of the dreamed movements is pinned down, and corresponding EMG activity can be assessed. There seems to be a close correlation between limb movements in lucid dreams and EMG activities in the corresponding limb [53–55]. After a sequence of left and right fist clenches carried out in a lucid dream, EMG forearm twitches were recorded that matched the dreamed sequence [55]. EMG activity of the forearm can thus be affected by dreamed hand movements [42].

Brain areas – As described before, brain activity of a real executed movement can correspond with the same movement performed in the S-state. Hand movements performed during lucid dreaming activated corresponding motor areas in the brain (C3, Cz, and C4) compared to the activation during the actual execution of the movement [56]. In an fMRI study executed by Dresler et al., 2011, an increase in blood oxygen level-dependent (BOLD) signal was observed in the sensorimotor cortex contralateral to the indicated movement side during lucid dreaming motor practice [57]. Interestingly, the responses were smaller in the sensorimotor cortex compared to actual executed movement but of similar size in the SMA. The SMA is mainly involved in timing, monitoring, and the preparation of complex movements and proves that planning and coordination of movements happen similarly during wakefulness and lucid dreaming. Altogether, these findings indicate that lucid dreaming motor practice and executed movements seem to activate the same brain areas.

Autonomic responses – In addition to the similarities in brain activity, dream research has provided evidence for similarities in autonomic responses between physical and lucid dreaming motor practice. Corresponding physiological responses were found in lucid dreams that were sexual in nature. This was the case with several autonomic responses like respiration rate, vaginal EMG, skin conduction, and vaginal pulse amplitude [58]. Another study measured significantly higher heart rates while performing squats during lucid dreams compared to pre- and post-exercise periods [59]. Together, they support the suggestion that lucid dreaming motor practice shares neural cardiovascular responses with physical practice during wakefulness.

Time – Beyond this, the factor of time also seems to have similarities in both states. Earlier research demonstrated that the subjectively experienced time spent on a task in (lucid) dreams was similar to the time of performing the task during wakefulness. This was only the case for dreams with higher cognitive activity, e.g., counting. In dreams that involve motor activity, performing squats in lucid dreams took 44.5% more time compared to the wakeful condition [60]. In addition, they examined the effect of “task length” and “task complexity” on the duration of the lucid dream action. The length of the task imagined (e.g., walking 10, 20, or 30 steps) did not affect the duration of motor tasks in lucid dreams, thus preserving any relative durations [61]. Task complexity did affect time durations. The more complex the task, the smaller the time increase. The time increase for the most straightforward task (walking) was 52.5%, for the moderate complexity task (squats), 39.9%, and the most complex task (gymnastic routine), 23.3%. Perhaps due to the lack of gravity and resistance, the dreamed motor task is not executed as it would during wakefulness. Additionally, there is a lack of muscular feedback due to REM sleep atonia. The dreamed motor task thus requires more effort to compensate for this scarcity [61].

Simulation Theories – The foundations of the relationship between dream content and changes in the physical body can be theoretically explored considering several simulation theories. One of these is the threat simulation theory. This theory predicts that part of the evolutionary psychological explanation of dreaming is the simulation of threats. This is based on the observation that threatening events are overrepresented in dreams. Threat recognition, response, and avoidance can be rehearsed in a safe dream environment and carries benefits for situations in waking life [62]. Similarly, the social simulation theory is a rather recently developed theory that predicts that dreams simulate social perception, cognition, bonding, and social interaction and makes a similar claim to the treat simulation theory, yet using social situations [63]. In a broad sense of evolutionary selection, threat and social simulations are the two main drivers in adapting to the current waking environment. Together, these theories assume that simulation and rehearsal of a certain skill improves general performance in wakeful life [64]. Both of these theories are able to explain an interesting feature of dream phenomenology: obliviousness to the current state of mind, a feature that is however not present during lucid dreaming [65]. Threatening events or dream characters occur in a non-lucid dream as autonomous events and entities instead of being controlled by the dreamer. They are thus more challenging. In a lucid dream, a threatening (social) situation might be treated as less serious in comparison to those in non-lucid dreams. In order for a successful simulation to take place, the dreamer is required to be oblivious to the current state, including the fact that the other dream characters are not real, but hallucinated. On the contrary, the phenomenon of lucid nightmares provides evidence that, even though the dreamer is aware of the fake dream situation, a high level of anxiety is experienced [66]. Additionally, practicing coping with anxiety in any therapy form also works, while it is clear the situation is simulated in a safe environment. Lucid dreaming does not seem to perfectly follow the framework of these simulation theories and in itself challenges them. The simulation theories help to build a framework that explains the possible evolutionary foundations by which dream content affects waking life. Additionally, the neural simulation theory mentioned before regarding the efficacy of mental motor practice, is also capable of supporting lucid dreaming motor practice as lucid dreaming is another example of an 'S-state' [5].

Additionally, in 2022, a review on general wakeful skill improvement using lucid dreaming was published [67]. Bonamino mainly focused on describing the empirical data in high detail and some of these studies will be discussed in the further evaluation. The theoretical foundations combined with empirical data build a solid foundation for the hypothesis that lucid dreaming motor practice can improve wakeful motor performance.

Empirical evidence on lucid dreaming motor practice

Lucid dreaming has been proposed to act as a space where hyper-realistic mental rehearsal of recently learned motor skills can be practiced. Here, four studies testing different motor tasks against physical practice and/or mental practice are presented. Additionally, some qualitative data, such as interviews and anecdotal reports, will also be discussed.

Many years ago, the study of Tholey [68] was the first that addressed some qualitative aspects of lucid dreaming motor practice. Lucid dreamers stated they were able to manipulate the physical laws during lucid dreaming motor practice. They manipulated the perceived space and time within their dreams and adequately shifted their focus of attention from being in their own body to being an outsider that saw the overall situation. Thus, lucid dream environments can be carefully curated to match the dreamer's objectives. In 2012, anecdotal reports of amateur and elite athletes were collected stating they use lucid dreaming to practice sports [69]. These reports triggered a rise in interest in this phenomenon within the world of sports science, and systematic research started to be conducted. Around 57% of the participating elite athletes experienced a lucid dream at least once in their lives. Furthermore, around 24% were frequent lucid dreamers (once a month or more), and 9% of the athletes had used their lucid dream to practice a motor skill, with 77% feeling that their sports performance during wakefulness improved as a result of this. Altogether, these results show that a relatively large part of the German elite athlete population is already familiar with the phenomenon of lucid dreaming, showing the potential of this new approach for performance improvement.

Coin toss – One of the first quantitative studies that contributed to the belief that lucid dreaming motor practice enhances motor performance is the study of Erlacher and Schredl [70]. Forty participants formed three groups: a lucid dreaming motor practice group, physical practice group, and a control group. All participants had to toss 10-cent coins into a cup and hit as many as possible out of twenty tosses. They did a pre-test in the evening and a post-test the following day. The results of this study indicate that lucid dreamers are competent to practice a motor task within a lucid dream and show improvement in their wakeful performance afterward. The physical practice group showed the most improvement but did not significantly differ from the lucid dreaming motor practice group, rendering lucid dreaming motor practice equally beneficial. Lucid dreaming motor practice is thought to trigger the same motor learning processes as mental practice, both involved in motor activity without producing overt movements. Lucid dreaming motor practice might have increased an individual's confidence and motivation for the next morning's test, which resulted in enhanced performance.

Finger tapping – Stumbrys et al., [71] compared lucid dreaming motor practice's effectiveness with physical and mental practice. The study included 68 participants separated into four groups: lucid dreaming motor practice group, physical practice group, mental practice group, and a control group. All groups had to perform an online version of a finger-tapping task in the evening (pre-test) and the following day (post-test). The results of this study confirmed the observed performance improvement after lucid dreaming motor practice in the study of Erlacher & Schredl [72]. All three practice groups showed improved performance in the post-test. Lucid dreaming motor practice had the highest improvement (+20%), followed by physical practice (+17%) and mental practice (+12%). There was no significant difference between the three practice groups, demonstrating that lucid dreaming motor practice is just as effective as the other two and can be considered a promising new motor improvement method. The effect size of the lucid dream group was the lowest out of the three, showing a higher variability in this group.

40-yard sprint – A study by Grummer [73] examined the effect of lucid dreaming motor practice on motor performance for another task, in this case, a 40-yard sprint. The participants were divided into three groups: a lucid dreaming motor practice group, a mental practice group, and a no-practice control group. All participants had to run the 40 yards once in a pre-test and repeat it after thirty days of the practice condition during a post-test. During these 30 days, the participants attempted to practice four days per week. The results showed that lucid dreaming motor practice was effective in performance improvement, but so were mental practice and even no practice. The three groups did not differ significantly. However, these results should be taken with a grain of salt, as in the discussion, it was briefly stated that a portion of the lucid dreamers had failed to lucid dream at all throughout the study but was included regardless. A more significant effect might thus be very well possible, but this effect might be concealed because not all lucid dreamers actually practiced successfully. There is no mention of the skill level of the people in the lucid dream group. It is stated that they received a week of lucid dream training beforehand. This might be a bit short for proper lucid dream training, let alone for preparation to execute a specific task in a lucid dream. These limitations make it difficult to draw any significant conclusions.

Dart throwing – In 2017, another study investigated the effectiveness of lucid dreaming motor practice under controlled conditions [74]. The 27 participants in this study were divided into three groups: a lucid dreaming motor practice group, physical practice group, and a control group. They had to perform a dart-throwing task which consisted of 21 dart throws during the pre-test and after they woke up the following day during the post-test. The results showed that lucid dreaming motor practice is effective. However, a new factor was uncovered: the dreamer should not experience too many distractions during the dream practice. The results corresponded to the field experiments and showed that the dream conditions play an essential role in the effectiveness of lucid dreaming motor practice. Lucid dreamers are not suited to be a single homogeneous group regarding lucid dreaming motor practice experiences. With little distractions and good focus, the dreamer can practice the motor task properly. However, with distractions, a decline in performance can be seen.

The first study that entirely focused on obtaining empirical data on the qualitative aspects of lucid dreaming motor practice was the study of Schädlich & Erlacher [75]. Sixteen lucid dreamers that were able to practice their sports at least once before in a lucid dream were interviewed. The results of the interviews proposed that lucid dreaming motor practice can be used for various movements and routines. The participants also mentioned that motivation seemed to positively influence lucid dreaming motor practice's efficacy. A strong kinesthetic perception was noticed and sometimes experienced as the most dominant sense during lucid dreaming motor practice. They stated that their waking performance had improved after lucid dreaming motor practice. Even one participant already experienced a significant improvement after one single lucid dreaming motor practice session, so a lack of experience or repetition might not be disadvantageous for its effectiveness. In addition, multiple participants already included lucid dreaming motor practice in their routine combined with physical and sometimes mental practice. Aside from these promising results, the participants also experienced problems during lucid dreaming motor practice. Sometimes they could not manipulate the equipment, body, or gravity in the way they wanted. Therefore, doubts emerged about the reliability of lucid dreaming motor practice as an approach for performance enhancement. Lack of control seems to be both a problem on its own as well as a source of distractions [75]. Lucid dreaming motor practice has been tested in laboratory studies on several different motor tasks, including fine motor movements such as the coin-toss task and gross motor movements, a 40-yard sprint. The anecdotal reports by German athletes state many additional sports that have been practiced using lucid dreaming motor practice. This varies from dancing to alpine skiing and football and supports the notion that lucid dreaming motor practice seems suitable for most motor tasks and is not restricted by task difficulty, size of movement or environmental factors.

Sport sciences and lucid dreaming

The field of sports science can provide the right context when we talk about the improvement of motor skills. Improving a specific motor skill depends on a combination of two factors. First, a person must learn the skill. Learning means that the body gets to understand the proper execution [76]. Once the appropriate execution is known, the skill can be improved by repetition using a form of practice or rehearsal. While practicing, learning takes place as the skill is slowly fine-tuned, adjusted, and improved. Simultaneously, abilities are improved by training. Training is the physiological improvement of strength, agility, flexibility, and body coordination. Improving abilities will affect the performance of a skill, and when training stops, abilities go down. The skill performance consequently goes down as well because the body is physically unable to execute the task. An early-life example is the blueprint for the skill: 'walking' in infants. They have the blueprint but not the ability; their muscles are too weak to do so. In order to successfully improve a skill, most often, physical practice is used. Repeatedly performing the same action will help perfect the action and achieve the desired result. While learning is involved in planning and coordinating movements, which mostly happens in the brain, training occurs at a peripheral level. It needs actual physical execution to take place [77]. In the case of mental and lucid dreaming motor practice, learning a motor skill is possible, but training is not.

Consequences of the hypothesis and discussion

This review provides insight into the findings and theories behind the efficacy of lucid dreaming motor practice as a novel approach to improve motor performance during wakefulness. Several findings and theories support the proposed hypothesis of lucid dreaming motor practice and its positive effect on wakeful motor performance. The tasks used differed in task complexity and included gross and fine movement, showing the rich extent to which lucid dreaming motor practice can be useful. Beyond the tests in laboratory settings, qualitative measures in athlete populations show that the reach of lucid dreaming motor practice goes far beyond this. Firstly, a large interest in alternative forms of motor practice is present, and secondly, athletes claim the practice is beneficial to their wakeful performance. An extension of motor practice in lucid dreaming would be the simulation of anxiety-triggering scenarios that challenge the performance of a motor task. The threat, social and neural simulation theory combined with the phenomenology of lucid nightmares support the notion that simulating the potential additive anxiety with performing a motor task might be used to practice anxiety-coping strategies.

The threat- and social simulation theory provide a theoretical foundation for the safe simulation of different challenges, however, seem to require a state of obliviousness of one's true state of mind. The phenomenon of lucid nightmares challenges this constraint as they can contain high levels of emotion and anxiety even though the dreamer is not oblivious to their current state of mind and the reality of the situation [66]. The anxiety caused by having to perform for large crowds or with high stakes, such as correctly performing at a sports competition or during a difficult surgery, can be detrimental to the execution of an action. Thus, in combination with the improvement of the motor task itself, all surrounding challenges can also be faced, by simultaneously designing coping strategies, making the overall motor performance more successful. The overall correspondence in brain activity, autonomic responses, and time aspects between lucid dreaming motor practice and the execution of overt movements during wakefulness serves as proof of the similarities between the two processes and supports the hypothesis that lucid dreaming motor practice uses similar psychophysiological processes, enabling the transfer of changes from the dream environment and body, into wakeful life.

Limitations

Several limitations identified in the literature can be seen as a threat to its efficacy and require further research. A well-established limitation in this field is the fact that not everyone is capable of (stable) lucid dreaming in the first instance. Lucid dreaming is trainable in several ways. However, so far, there is no known highly reliable induction technique [28], which results in smaller study populations and a threat to the applicability of lucid dreaming in practice. Therefore, more research should focus on improving lucid dreaming induction techniques. A comprehensive evaluation of earlier empirical studies showed that almost all studies are field experiments. Field experiments have a preference in lucid dream research due to the low number of lucid dreamers that otherwise can be reached. However, a significant drawback of this research design is the lack of experimental control, which results in less reliable results. Schädlich et al., 2017 conducted the first and only laboratory pilot study on this topic [74]. Nevertheless, an essential limitation of this controlled research design is that it is challenging to transfer lucid dreaming to the laboratory successfully. Consequently, many participants fail to induce a lucid dream due to the unfamiliar sleep environment. Future research should thus focus more on laboratory research and how to successfully transfer lucid dreaming to the lab (e.g., habituation nights). Another challenge arises when participants are capable of lucid dreaming yet experience dream instability. Participants report difficulties with keeping the dream scene stable. Another challenge is that lucid dreamers experienced a lack of control. They are sometimes not able to properly execute the predetermined skill during lucid dreaming due to a lack of control over their own body, the environment or equipment, and other dream characters [75]. For instance, participants report difficulty with distracting dream characters: 'The doll kept throwing darts at me' [74].

Despite mostly positive attitudes towards lucid dreaming, there is some resistance to making lucid dreaming easily accessible. Dresler, 2015 [78] deliberated that if lucidity is achieved too easily and broadly, this might result in sudden problems regarding dream simulation theories and other functions of non-lucid dreams. In the case of simulation theories, they cannot be reached without a state of obliviousness of the state of mind. Lucid dreaming is different in the way the dreamer is aware of their state, and thus these processes might be disrupted. If lucid dreaming becomes too easily accessible, it might interfere with non-lucid dream functions that require obliviousness [65]. Logically, the necessity of lucid dreaming motor practice due to the similarity in efficacy with mental practice should be discussed, as mental practice is a more straightforward and accessible approach. So far, research has found no significant difference in efficacy between the two approaches on wakeful motor performance. In order to ensure the potential of lucid dreaming motor practice as a promising inventive approach in fields like sports science, research needs to indicate if it is worthwhile to further examine this approach by comparing it with mental practice.

A *prima facie* counterargument to the very possibility of motor practice during dreams leading to performance gains during subsequent wakefulness is the phenomenon of dream amnesia: upon awakening, we rarely remember any external (e.g., sensory cues from our sleep environment) or internal events (e.g., dreaming) during sleep, suggesting a considerable inability to form new memories during sleep [79]. Such dream amnesia might be seen as a functional adaptation to protect the dreamer from confusing actual events with merely dreamed experiences [65], however, it is at odds with the possibility of motor learning occurring during sleep. Critically, most research on dream amnesia is based on explicit rather than implicit memory [79]: explicit memory involves the conscious memory for factual information including episodic memories (knowing "what"), whereas implicit memory includes the learning of motor and perceptual skills (knowing "how") and is retained and retrieved unconsciously. Accordingly, implicitly learned skills can be demonstrated without explicit recall of the learning episode: patients with severe amnesia due to medial temporal lobe damage can show considerable improvements in motor skill memory without remembering any training episode [80–82]. Hence, the processes and structures underlying amnesia for explicit dream memories are most likely different from those underlying motor learning during dreaming, rendering the phenomenon of dream amnesia compatible with effective motor practice during lucid dreaming.

Future prospects of lucid dreaming motor practice

If future research further supports the potential of lucid dreaming motor practice as a method of improving performance in wakefulness, several groups might find this new approach beneficial. Medical professionals such as surgeons, can practice complicated interventions, making them more skilled and better prepared [83] while avoiding potential health implications caused by flawed motor execution. Any profession that requires specific motor skills can use lucid dreaming motor practice. Furthermore, research has already discussed its potential in the case of improved motor learning in people recovering from a stroke [16]. Expanding lucid dreaming motor practice to rehabilitation programs for similar patient groups like paraplegic and locked-in patients seems promising. Athletes can use it in their training programs to practice specific skills [68]. In particular, injured athletes that must train less or even wholly pause training can use lucid dreaming motor practice to compensate for the lack of physical practice. Likewise, people participating in hazardous sports (e.g., ski jumping) or sports which are very weather dependent (e.g., surfing) can use lucid dreaming motor practice to reduce the risk of an injury or to train while weather conditions sabotage the possibility of training [38]. Training motor skills in a safe environment, independent of a real body and world, can be valuable for many.

Altogether, several lines of empirical and theoretical evidence suggest that there is a positive effect of lucid dreaming practice on wakeful performance and that it might be a successful extension of mental motor practice, thus supporting the hypothesis. Its potential is highly supported by the correspondence in brain activity, autonomic responses, and time aspects compared to physical practice. While lucid dreaming motor practice seems to have high potential, the field is relatively young and thus with many challenges. For lucid dreaming motor practice to become an accepted new approach in sports science and other disciplines, highly reliable induction methods are needed to investigate its efficacy systematically.

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Consent statement/Ethical approval

Not required.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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