Auditory rhythmic cueing in movement rehabilitation: findings and possible mechanisms

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Review

Moving to music is intuitive and spontaneous, and music is widely used to support movement, most commonly during exercise. Auditory cues are increasingly also used in the rehabilitation of disordered movement, by aligning actions to sounds such as a metronome or music. Here, the effect of rhythmic auditory cueing on movement is discussed and representative findings of cued movement rehabilitation are considered for several movement disorders, specifically post-stroke motor impairment, Parkinson's disease and Huntington's disease. There are multiple explanations for the efficacy of cued movement practice. Potentially relevant, non-mutually exclusive mechanisms include the acceleration of learning; qualitatively different motor learning owing to an auditory context; effects of increased temporal skills through rhythmic practices and motivational aspects of musical rhythm. Further considerations of rehabilitation paradigm efficacy focus on specific movement disorders, intervention methods and complexity of the auditory cues. Although clinical interventions using rhythmic auditory cueing do not show consistently positive results, it is argued that internal mechanisms of temporal prediction and tracking are crucial, and further research may inform rehabilitation practice to increase intervention efficacy.

1. Introduction

Rhythm and movement are intuitively connected, as demonstrated through the widespread inclination to spontaneously move to music. Coordinated movement and rhythm perception both necessarily include precise timing mechanisms, arguably leading to commonalities in neural processing [1,2]. This notion is supported by cognitive neuroimaging findings; motor areas are found to be active when people—musicians or non-musicians—listen to musical rhythms [1,3,4]. Thus, rhythm perception, possibly also facilitated by rich connectivity between cerebral auditory and motor systems, has been described as a 'backdoor' into the motor system and a means to improve efficiency in movement (re-)learning [5].

By auditory cueing, I refer to the process whereby movement is synchronized to sound. Auditory cues can guide movement through their temporal structure to which movement can be aligned, and although these cues are usually rhythmic, this is not strictly necessary. Here, rhythmic auditory cueing in movement rehabilitation is discussed, and underlying mechanisms are considered that may increase rehabilitation effectiveness for different patient populations. After identifying key neuroscientific findings related to rhythm perception, the effects of auditory cueing on healthy movement are discussed. Next, paradigms and representative findings are described for three motor disorders for which cued rehabilitation has been reported, namely residual motor impairment after stroke, Parkinson's disease (PD) and Huntington's disease (HD), and possible mechanisms of efficacy are put forward. In the closing discussion, the why, the what and the how of rhythmically cued movement rehabilitation are considered by looking at mechanisms that speak to disorder-specific problems in the motor system, the content of the cue itself and practical aspects of the paradigm that could affect intervention efficacy.

(a) Rhythm perception

When considering how rhythm may impact movement, the relevant terms must first be specified. Generally, a 'note' or 'event' is a single sound, whereas a 'rhythm' or 'rhythmic pattern' is a combination of durations created by a group of notes. Such a pattern may explicitly or implicitly fit onto a temporal grid of equally spaced intervals, leading to an isochronous 'beat' or 'pulse', to which a listener can align their movement. The simplest example is an isochronous stimulus train, or metronome, presenting sound events at equally spaced time intervals, thus coinciding perfectly with the beat. However, in a rhythm with temporally unequally spaced notes, listeners will generally still infer an underlying isochronous beat (also called beat induction [6]), allowing isochronous periodic movements to auditory rhythms.

Perceptual grouping of beats leads to a higher level structure referred to as 'metre', most commonly grouping two, three or four beats. This grouping is emergent from the rhythm, by directing attention to specific accented events [7]. Accents can be created by the duration or intensity of an event, similarly as in speech [8]. It is this aspect of musical rhythm that shows the most overlap with speech-oriented definitions of rhythm, although a recurring pulse or periodicity, crucial to cueing movement, is usually absent in speech. In a metric group (or a 'bar'), different beat positions may have varying musical (and cognitive) importance, with strong and weak beats [9], the first beat being the strongest.

The extent to which a musical rhythm is *beat-based* or *metrical* refers to the ease with which the beat can be inferred, and how apparent the metric grouping is from the rhythmic pattern, respectively. Rhythms that are less beat-based or metrical are generally considered to be more complex. Once inferred, the beat and metre are surprisingly stable when encountering new sound events that conflict with the simplest interpretation of periodicity, for instance by accenting weak beats or neglecting strong beat positions, also termed syncopation [10]. These deviations from the beat are often considered to create a more engaging or interesting rhythm, and constitute the primary difference between a metronome and musical rhythms.

Another element of complexity is added through performance expression, where musicians generally deviate from exact mechanical timing, adding microtiming deviations to the rhythmic pattern within the metre. Expressive timing is integral to music performance, and it is something expert musicians can control exquisitely [11]. These two types of temporal deviations—either from the beat 'grid' or from single event timing—happen at different time scales, and both types of deviation arguably contribute to musical quality, through the composer and the performer, respectively. Analogous to musical structure more generally [12], this affective response may happen for rhythm through temporal predictions induced by the beat and the metre from which certain deviations may lead to an affective response [13,14] and induce a sense of 'groove' and the urge to move to music [15]. For the purpose of cued movement, the implication is that whereas metronomes are clear, unambiguous pacing signals, music has more rhythmic complexity, a moderate amount of which may create more engaging rhythms. Importantly, when moving to rhythm, the hierarchical periodic level can be chosen to suit a particular movement: by taking the beat level, or the metric level, where one movement is made per bar, or an even longer periodicity of multiple bars.

(b) Cerebral correlates

Using functional magnetic resonance imaging, several cerebral motor network regions have been identified as being involved in auditory rhythm perception, carrying significance for how auditory cueing may impact movement. Specifically, the supplementary motor areas (SMA), dorsal premotor areas (PMd), basal ganglia and areas within the cerebellum are reported as involved in perceiving the beat in a rhythm [3]. Further reports indicate that SMA, PMd and cerebellar activations increase with rhythmic complexity [4] and that more beat-based rhythms increase connectivity between premotor and auditory areas [16].

Electrical brain signals, although less suited to localizing brain activation, offer fine-grained temporal information on brain responses to rhythmic auditory stimuli. The expectations induced by periodic patterns are evident from gamma-range frequency responses related to unexpected omissions or perturbations [17], and spontaneous groupings of metronome beats are measurable in the event-related potentials (ERPs) in the brain [18]. Subtle differences between responses to different metres in the basal ganglia, auditory and association cortices [19], as well as different events within a metric group [20] have been reported, suggesting that ERPs are modulated by different aspects of auditory rhythms. Moreover, when a metric grouping is created *subjectively*, by imagining strong and weak beats superimposed on identical metronome events, this accenting structure is reported in the beta-range frequency response [21] and the ERP [20], showing substantial overlap with perceived accents. A more extensive overview of the brain signatures of rhythm perception is provided by Grahn [22].

In sum, rhythm perception involves regularity detection and tempo tracking at multiple hierarchical levels of auditory patterns varying in rhythmic complexity, from which a periodic pulse is inferred. In addition to auditory regions, this stimulus is processed by motor network areas of the brain, and the cognitive processing (or imagining) of rhythm induces a brain response that is similar to actual rhythm perception.

2. Cueing healthy movement

Music has been reported to facilitate performance for various sports [23], increasing endurance and reducing perceived exertion. Thus, before turning to uses of auditory cueing in movement rehabilitation, I will first consider healthy rhythmic movement, the effects of auditory cueing and the role of temporal prediction.

(a) Rhythmically cued movement

When we perform repetitive movements without cueing, these often spontaneously become periodic, at a speed (or tempo) that fits the movement, possibly varying that tempo somewhat over time. We can distinguish rhythmic and discrete movement, where the former refers to repeating, continuous movement and the latter to a single, goal-directed action [24], although within these formal definitions, certain variants of rhythmic movement are indistinguishable from a rhythmic sequence of discrete movements. Thus, rhythmic movement may still involve event timing, where a focal point of the movement is explicitly timed, or, for more continuous movements, so-called 'emergent timing', where the temporal structure is implicitly embedded in the movement [25]. The brain

activations for rhythmic and discrete wrist flexions have been found to differ [26], with additional brain areas being active during discrete movement but not rhythmic. This suggests that more cerebral resources are needed for discrete movements and that rhythmic movements are not simply concatenated discrete actions. Synchronizing to auditory cues, also termed sensorimotor synchronization (SMS), can alter the trajectory of a movement [27], but more so for discrete than for rhythmic movements [28], implying that the potential impact of a cue may depend on the type of movement. Additionally, interpersonal differences in SMS abilities are reported [29,30], and SMS difficulty also depends on the type of entrainment, where phase entrainment denotes synchronizing movement to specific beats, and period entrainment refers to SMS without alignment to the start of the pattern.

Direct comparisons of brain signatures of entrained movement with those of uncued movement have yielded disparate results; cerebellar activation was found for musically entrained over self-paced dance steps on an inclined surface [31], but metronome-cued step-like movements (without a stepping surface) yielded no extra activations when compared with uncued movement, and putamen activation was found for the uncued condition, interpreted as related to self-pacing [32]. Further investigations of motor network activations found that for cued wrist flexions, different cueing conditions led to different activation patterns when compared with uncued movement, but no activations were found for self-paced movement [33], suggesting that the cue type and the movement type mediate the effect of the cue. A meta-analysis of finger tapping studies [34] showed that in comparison with visually cued or uncued tapping, auditorily cued paradigms more often resulted in basal ganglia activations. Rhythmic complexity was also reported to impact brain activations related to finger tapping, with increased activations in bilateral PMd, functionally coupled to activation increases in auditory areas with increasing clarity of the metric structure of the stimulus [35]. Ventral premotor cortex (PMv) was also shown to be crucially involved, as disruptions in synchronization abilities are found after transcranial magnetic stimulation (TMS) [36].

There are indications that cueing can help learning; motor learning studies with difficult movements may use assistive pacing signals (cf. [37]). Longer term learning benefits specifically owing to auditory cueing have not yet been demonstrated in healthy subjects, however, using motor-evoked potentials (MEPs), increased plasticity, measured in terms of cortico-motor excitability, was reported for wrist flexions cued by a metronome at a preferred pace as compared with uncued movement [38].

(b) Predictive mechanisms and mental representations

The precise timing of SMS has been extensively researched, and meticulously reviewed [39,40]. Although detailed discussion of this work is beyond the current scope, findings that are crucial to clinical applications are that synchronization processes consist of both conscious and unconscious processes, where phase correction is largely automatic and considered to be implemented more peripherally, and period correction relies more on cognitive control [40,41]. Furthermore, people tend to tap predictively, leading to taps that are slightly early (referred to as a negative asynchrony), which is a strong

indication that cued motor behaviour is driven by a mental representation of the rhythm, that can be adjusted sub-attentively through auditory perception. This representation has also been used as a so-called 'auditory model' in motor learning, where the temporal structure of a movement is first presented as a sound, and this rhythm can then be used in silence, as a mental temporal pattern or rhythmic imagery of the movement timing. This model can be as simple as an isochronous metronome in tapping continuation, where a pacing sound stops but the temporal representation continues in silence, or as complex as learning to tap out a polyrhythm, where a complex sound pattern is used as an example of the goal timing to be attained [42]. This auditory model, or inner rhythm, has been described as specific to auditory cueing, as opposed to visual cueing [43] for which discrete signals (i.e. flashes) were shown to impact the brain differently from auditory metronome beeps [44]. The relevance of these auditory models is that apparently, learning can be assisted by a mental representation of the timing of a movement. Once a temporal pattern is mentally 'set up', a pacing sound does not cue or trigger each tap in a recurring stimulus–response pattern, but rather fine-tunes any tempo deviations that may occur in the mental representation, while the movement itself is carried out periodically. This difference between the sounds acting as a *trigger* or as a *tempo guide* is captured in recent research on rhythm perception, which has reported that basal ganglia activation was most prominent once the beat had already been induced [45], implying that this activation is related to predicting and tracking periodicity, rather than inducing the beat through auditory regularity detection. Moreover, afferent feedback of the movement appears to be crucial to the anticipatory processes in SMS, based on findings from a small sample of deafferented patients who could synchronize to a metronome, but did not show the typical negative asynchrony in their taps [46], whereas healthy participants with local anaesthesia from peripheral nerve block instead showed greater asynchronies [47]. However, when investigating the neural correlates of temporal predictions, a much larger network of motor areas (including SMA, PMd, cerebellum as well as primary motor cortex) was shown to be involved in generating predictions about auditory cues while tapping [48].

Arguably, a richer stimulus (with more rhythmic complexity, such as natural music) may lead to a richer set of predictions, leading to finer grained guidance for the temporal model of a movement. In a study investigating the effect of different types of music on walking [49], both slower and faster walking is found to relate to aspects of the sound, and attributed to expressive patterns of the music, with attention shifting, arousal changes or subliminal entrainment mechanisms suggested to be driving this effect. Thus, increased rhythmic complexity, providing timing cues additional to the beat, and perhaps modulating the 'groove' and movement-inducing aspects, also affects movement. In healthy older adults, music improves gait parameters as compared with a metronome cue [50]. However, an affective response or enjoyment of music, rather than the generation of more precise motor predictions, could also arguably drive this effect of rhythmic complexity.

Taken together, auditory cueing has been shown to alter healthy movement, depending on the movement type and cue type, leading to a range of results in the neuroimaging literature. In general, rhythmic movement appears to be facilitated by auditory cues, increasing endurance. Strong anticipatory mechanisms, possibly mediated by afferent

motor feedback, appear to drive entrainment through auditory models rather than waiting for individual cues. These mental auditory models, which automatically adjust to incoming auditory signals and can also occur in silence, may support movement learning, although clear evidence of this is currently lacking.

3. Clinical uses of auditory cueing

Auditory cueing is used in the rehabilitation of a range of motor impairments. Here, a brief overview is given of two cued rehabilitation paradigms, and three disorders that directly impact the motor system for which auditory cues have been used: stroke, PD and HD. As the scope of the current work does not allow the relevant literature for all disorders to be covered, the work considered is best described as representative rather than comprehensive, and refers, where available, to more detailed reviews and meta-analyses.

The use of metronomes in movement rehabilitation often happens without a formal protocol, simply by adding the pacing sound to whichever movement needs practice. Within the programme of Neurologic Music Therapy [5], pacing signals are termed rhythmic auditory stimulation (RAS), and specific protocols are described for their use, most commonly for gait. RAS uses metronome or music cues that are adjustable to the patient's preferred tempo, which are faded in the last part of training sessions to facilitate uncued walking through an auditory model (or rhythmic imagery). A less musically designed task is called bilateral arm training with rhythmic auditory cueing, or BATRAC [51], with an analogous (but less-used) task for leg training (or BLETRAC, [52]), where bilaterality of the task is emphasized and rhythmic effects of the metronome cue are not elaborately discussed. These tasks were designed for varying levels of motor impairment after stroke, where bilateral practice is thought to impact cerebral reorganization, and different bilateral movements are made using equipment guiding the movement.

When considering research findings on cued movement rehabilitation, it must be noted that randomized controlled trials (RCTs), while considered the gold standard in clinical research, are often unfeasible owing to the necessary large samples and strict randomization procedures. RCTs on cued movement rehabilitation are scarce and their conclusions are generally conservative, possibly favouring false-negatives, as the large samples that are needed may obscure valid treatment effects for sample subgroups. While internal validity is inherently high in RCTs, the external validity has been called into question [53], indicating that RCTs should consider specific characteristics of disorders and study populations to maximize clinical applicability.

(a) Stroke

After a stroke, a significant proportion of patients are left with residual motor impairment, usually lateralized, depending on the side of the stroke [54]. Gait coordination after stroke was shown to improve with auditorily paced treadmill walking, especially when every footfall is cued [55]. Anecdotally, imagined music has been reported as a cue for gait after stroke [56], implicating the aforementioned auditory model. Furthermore, changes have been reported in movement trajectories when cueing movement with the affected arm [57].

Controlled studies looking at auditory cueing effects on stroke rehabilitation are relatively scarce; a recent Cochrane review on music therapy for acquired brain injury [58] only found a small number of studies to meet their inclusion criteria. Of these, the only intervention for which sufficient data were available to support firm conclusions was that of RAS on gait (cf. [59]), for which a consistent effect was also reported in a recent, more inclusive review [60]. No conclusive support was reported for musical (so including more rhythmic complexity) cueing for upper-limb rehabilitation, not including BATRAC. However, both another Cochrane review and direct experimental comparison [61,62] also did not show BATRAC to yield improved results over other rehabilitation methods. As the impact of impairment severity and time post-stroke still best predict intervention success, further specification of a target group may allow better tailoring of cueing interventions. The BATRAC cues have not yet been evaluated critically, but new paradigms are emerging that use more naturalistic music stimuli [63], which may elucidate this issue.

On the basis of controlled studies of stroke patients, positive findings of cueing for gait rehabilitation are relatively consistent. For upper-limb rehabilitation, the population appears too heterogeneous to broadly evaluate the impact of rhythm, currently precluding strong conclusions. However, when relaxing the inclusion criteria of relevant studies, various promising findings of RAS are reported for movement rehabilitation after stroke [64].

(b) Parkinson's disease

The main movement problems associated with PD are tremor, rigidity, bradykinesia and postural instability, leading to problems with gait and balance. The use of auditory cueing for movement (generally gait) is most developed for this population, as the positive effects of rhythmic cueing are relatively well established. A comprehensive review of these findings was recently provided [65], and a meta-analysis of RCTs on the efficacy of music-based movement therapy for PD shows that walking interventions yield better carry-over results to gait measures than dancing interventions, although the sample sizes of the studies are generally small, warranting the need for further work [66].

About half of PD patients develop a symptom called freezing, or motor blocks, which is a common cause of falls, occurring less often in patients with tremor as their main symptom [67]. A study looking at the effect of auditory cues on motor learning in PD patients [68] found that PD patients with freezing symptoms (unlike controls and PD patients without freezing) showed no indication of training-induced plasticity (measured as cortico-motor excitability with MEPs) after self-paced hand movement training, whereas after cued movement training, MEP changes did occur, similar to the other two groups. This suggests that patients who experience freezing benefit crucially from auditory cues in this paradigm, whereas non-freezers also learn without cues. Thus, the usefulness of cues may be moderated by specific symptoms, at least for upper-limb movement. The finding that PD patients generally do not report any great reduction of symptoms while listening to music [69] may also relate to a need for specificity of the cue and the patient subgroup.

In sum, while the usefulness of auditory cues for gait in PD is relatively well established, further work into the subtypes and symptoms of PD may improve outcomes, and

the complexity of the cue (which for instance is probably bigger in dancing paradigms than in gait interventions) needs to be evaluated separately.

(c) Huntington's disease

Although few studies have assessed the impact of auditory cueing on affected gait or hand function in HD, this neurodegenerative disorder, characterized by instability and uncontrollable jerky movements, also impacts the basal ganglia, arguably of interest in the context of rhythm. Large-scale meta-analyses are not possible here, but previous findings indicate that whereas gait velocity can reportedly be adapted to RAS, this is the case for period and not phase entrainment, and only for metronomes and not music [70]. More recently, HD patients were also found unable to synchronize their gait to a metronome [71], and a recent review deemed there was insufficient evidence for the usefulness of auditory cues in HD [60]. Other studies have reported synchronization abilities in early-stage HD patients, but lack of benefit from auditory cues during a distractor task [72], interpreted as an attention deficit. Considering upper-limb function, HD patients were able to turn a crank in phase bilaterally, but not $180°$ out of phase [73]. Interestingly, auditory cueing did not help, dissociating HD from PD patients, whose task performance did benefit from metronome cueing [74].

Although training of locomotor timing skills, identified as part of the disorder, has been suggested to improve movement in HD [71], the use of auditory cueing does not appear to modulate movement directly. The executive function deficit that is typical for HD [75] may be related to SMS capabilities and specifically phase entrainment, suggesting more subconscious cognitive involvement in synchronizing to specific accents and predicting temporal structure, differentiating the basal ganglia dysfunction of HD from PD in terms of synchronization abilities.

4. Mechanisms

The rationale for using cues in motor rehabilitation appears to vary for different interventions, and rarely considers relevant aspects of rhythm perception or synchronization. Here, four non-mutually exclusive mechanisms will be surveyed through which auditory cueing could affect motor (re-)learning, with varying implications for increasing efficacy. The primary factors that influence the degree of plasticity or recovery seen for stroke, PD or HD with auditory cueing may differ, implying that auditory cues might not be similarly applicable across groups.

(a) Accelerated motor learning

The simplest way for cueing to potentially impact motor learning is by speeding up the process. By regularizing movements, repetitive movements are performed *more similarly* every time, possibly resulting in more specific (and thus faster) learning and increased plasticity. Through the ubiquity of pattern repetition, music is perfectly suited to facilitate many instances of identical movements, speaking to the core principles of experience-dependent plasticity [76]. Another way to potentially accelerate movement learning would be if the perception-driven activation of motor areas known to be involved in motor learning would lead to faster plasticity.

The implication of faster motor learning is that with enough, and precise enough, practice, non-cued movement practice would lead to identical outcomes as cued movement practice. In this case, the motor network activations related to rhythm perception would have a simple facilitating role. This would imply that for a cue to be effective, its temporal structure needs to be maximally stable, and any rhythmic patterns additional to the beat should not detract from the clarity of the pacing signal, but only serve to further refine the temporal structure of the movement.

(b) Qualitatively different motor learning

Auditory cueing could also lead to a different type of motor learning process by providing a richer setting for motor learning and stimulating connectivity between auditory and motor areas [5]. This idea is supported by the literature describing potential differences in brain connectivity related to music training [77], although it is clear that music performance entails more than cued movement. In addition to activation in auditory areas, this different learning process could also be driven by perception-driven activation of specific motor learning areas, but rather than simply speeding up learning, this motor activation would result in a different learning process than uncued movement.

Here, the implication is that irrespective of the amount of practice, cued and uncued movement training lead to different outcomes of plasticity and reorganization, which would be especially relevant for stroke rehabilitation, where reorganization is at the heart of recovery [54].

(c) Acquiring temporal skills

A third way in which music and rhythm could impact movement is through a more general effect of developing temporal skills. This idea is supported by findings reporting PD patients to show increased perceptual skills after cue-assisted gait training [78]. Regularity detection and prediction impact an extensive range of human functions, both in motor control and cognition, and recently, a general role of predictive processing was suggested for cerebral processing [79]. Interestingly, several motor areas implicated in rhythm perception are known to also have cognitive functions, possibly related to regularity detection and prediction. Cortico-striatal connectivity measures (specifically SMA–putamen interactions) are found to correlate with both motor performance and executive functions [80]; striatal areas, known to be implicated in reward and learning processes, were shown to modulate cortical coupling based on prediction error [81], and specifically encode timing information related to prediction error in reward learning [82]. The cerebellum has also been reported to serve several cognitive functions, including executive function, learning, attention and behavioural-affective modulation [83].

Given the effect of rhythm and entrainment on fluctuating attention, the effect of the cue may well be attentional, supported by the possible role of executive functioning in cued movement, implying a necessity to further assess the cognitive aspects of rhythm perception.

(d) Motivation

Finally, a common rationale for using music in clinical settings concerns emotional engagement and motivation. By providing a positive experience, rehabilitation may feel less

effortful. If this reward is sufficient to lead to increased practice, other mechanisms may not even be necessary for better rehabilitation results. If motivation is at the basis of the efficacy of music interventions, the question of personal preference for music, and possibility of using patient-selected music becomes of the highest importance. Of course this is more generally the case, as every possibility of improving the rehabilitation experience should be exploited, but even the emotional engagement could already constitute a mechanism; peak music listening experiences have been related to dopamine release in the striatum [84] and clinical effects of preferred music have been shown in other settings (i.e. in pain reduction [85]).

5. Discussion

After discussing rhythm perception and SMS, three movement disorders for which auditory cueing are used and four potential mechanisms of intervention efficacy were highlighted. Finally, I consider the why, the what and the how of auditorily cued movement rehabilitation interventions, and several current unknowns that may be addressed in future research and may lead to improved interventions.

(a) Impact of the efficacy mechanism: *why*

The mechanisms that may drive intervention efficacy—how we think cueing works—should be prioritized in paradigm design. As varied movement disorders are addressed using cueing interventions, the way different afflictions may impact these mechanisms is crucial. For instance, for disorders affecting brain areas involved in rhythm perception, caution is needed when generalizing findings from healthy subjects to patient populations. PD is an example where rhythm appears to facilitate movement, but other motor impairments may result in impaired SMS, at least compared with healthy individuals. This could relate to the type of neural damage, possibly not only impacting predictive processing (for example, focal and atrophic cerebellum lesions may affect SMS differently [86]), but also to interpersonal differences [29,30].

Therapeutic goals are also relevant; for instance, rehabilitating fine hand motor control after stroke versus gait in PD contrasts precise motor learning processes with more large-scale behaviour such as walking. Additionally, the rehabilitation goal may involve neural reorganization after stroke, or slowing neural degeneration, depending on the disorder. As populations such as stroke or PD patients tend to be heterogeneous groups, individuals may require interventions designed for different levels of functioning, or different rehabilitation stages.

(b) Impact of the cue: *what*

The cues used in motor rehabilitation are often not evaluated. Available findings suggest that perceiving an intricately structured temporal stimulus (such as music) constitutes a cognitive task that is demanding for some populations, although cognitively intact groups may prefer more complex cues to metronomes. Strikingly, both musical and metronome cueing appear to disrupt gait in Alzheimer's disease, which is not characterized as a movement disorder [87]. *Post hoc* analyses relate this impairment to level of executive functioning,

known to be related to gait [88], implying that a certain cognitive capacity may be necessary for auditory cues to support gait. This echoes the interpretation of HD patients' attentional deficits in using the cues as compared with PD patients [73]. Although the moderation of executive functioning in SMS has not been explicitly tested, it may differentially affect phase or period synchronization. Arguably, a more explicitly rhythmic perspective may advance progress in understanding rehabilitation, especially given the particular behavioural and neural deficits of specific patient populations. Finally, music preference should always be considered, especially if enjoyment of the exercise is meant to facilitate practice.

(c) Impact of the intervention: *how*

Cued movement interventions have several dimensions that concern practical aspects independently of the cue. Depending on the patient, choices can be made to work individually or in groups, with strictly prescribed, or more free, dance-like movements, and different instructions or feedback. If social or motivational aspects carry primary importance, these choices are crucial. However, if the cerebral mechanisms of entrainment are found to primarily drive efficacy in cued movement rehabilitation, this would rather provide support for the use of home-based systems that allow practice at any time, without even a therapist present (RAS has been developed for home use, cf. [89]). Computerized, game-like applications can further provide informative training feedback and also automatically log practice progress. The impact of such telerehabilitation applications promises to increase with the average age of computer users [90].

(d) Future directions

Taken together, substantial unknowns clearly remain that need to be addressed before more solid claims can be made about the mechanisms and clinical effects of cued movement. Most prominently, we currently lack understanding of why cueing is more effective in some patient groups than others, how different cues may affect phase and period entrainment and how representations of rhythm (even if this is only a metronome) are established. Although executive functioning and cue complexity may interact to impact SMS abilities, the cognitive aspects of entrainment are generally understated in the literature. Research on SMS strongly suggests that entraining movement involves more than being externally triggered to move, and imagined rhythm, like imagined music, is reported to share brain activation with perceived rhythm or music [20,91,92]. However, investigations into the impact of the mental representations of rhythm on the ability to entrain movement are relatively scarce (but see [48]). The generalizability of several findings of rhythmic or entrained movement is often hampered by the use of expert musician or athlete participants. Although studying experts contributes important knowledge about the limits of performance coordination, this does not necessarily generalize to the wider population, the majority of whom will be those needing rehabilitation interventions.

Finally, it is difficult to separate out the affective, motivational effects that are a part of social music activities from pure motor network effects, even though both may be relevant. The impact of synchronization on shared experience cannot be understated, and increasingly findings are emerging that elucidate the role of moving together in time

(cf. [93]). Placing these findings in the context of clinical situations would be a valuable addition.

To summarize, auditory cues are increasingly used in movement rehabilitation, however, there is paucity in controlled clinical trials and little standardization in terms of cues. A number of mechanisms may be relevant, but possibly specific to particular patient groups, warranting further investigation to increase the efficacy of rhythm-based interventions. Possible avenues for improvement include tailored cue design and specific paradigms for specific types and stages of movement disorders. Further investigation of the cognitive aspects of entraining movement to sound, namely mentally tracking rhythmic cues and generating temporal predictions, may be crucial to fully exploit the potential of auditorily cued movement rehabilitation paradigms.

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