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CONCISE REVIEW

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Rhythmic serious games as an inclusive tool for music-based interventions

Simone Dalla Bella[1,2,3,4]

[1]International Laboratory for Brain, Music, and Sound Research (BRAMS), Montreal, Quebec, Canada

[2]Department of Psychology, University of Montreal, Montreal, Quebec, Canada

[3]Centre for Research on Brain, Language and Music (CRBLM), Montreal, Quebec, Canada

[4]University of Economics and Human Sciences in Warsaw, Warsaw, Poland

Correspondence
Simone Dalla Bella, International Laboratory for Brain, Music, and Sound Research (BRAMS), Department of Psychology, University of Montreal, CP 6128 Succursale Centre-Ville, Montréal, QC H3C 3J7, Canada.
Email: simone.dalla.bella@umontreal.ca

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Abstract

Technologies, such as mobile devices or sets of connected sensors, provide new and engaging opportunities to devise music-based interventions. Among the different technological options, serious games offer a valuable alternative. Serious games can engage multisensory processes, creating a rich, rewarding, and motivating rehabilitation setting. Moreover, they can be targeted to specific musical features, such as pitch production or synchronization to a beat. Because serious games are typically low cost and enjoy wide access, they are inclusive tools perfectly suited for remote at-home interventions using music in various patient populations and environments. The focus of this article is in particular on the use of rhythmic serious games for training auditory–motor synchronization. After reviewing the existing rhythmic games, initial evidence from a recent proof-of-concept study in Parkinson's disease is provided. It is shown that rhythmic video games using finger tapping can be used with success as an at-home protocol, and bring about beneficial effects on motor performance in patients. The use and benefits of rhythmic serious games can extend beyond the rehabilitation of patients with movement disorders, such as to neurodevelopmental disorders, including dyslexia and autism spectrum disorder.

KEYWORDS
movement, music, rehabilitation, rhythm, serious games

INTRODUCTION

The last decade has witnessed an increase in the use of music as a useful tool to complement standard methods in rehabilitation for a variety of patient populations.[1] The idea that music can provide a valid tool to support rehabilitation programs is borne out of the observation that music training and performance are strong vehicles for brain change.[2–4] Music activities are typically multisensory. By engaging our sensory, motor, and cognitive systems, music acts on the corresponding brain structures. Some of these systems are likely to play a pivotal role in the remediation of partly impoverished functions, or in recruiting neuronal circuitries, which can compensate for lost functions (e.g., in Parkinson's disease[5,6]). Grounded in this general idea, targeted music-based interventions have been devised for rehabilitation in various neurological diseases, including stroke, dementia, and Parkinson's disease.[1,7] The fact that music is a highly rewarding activity[8] adds to its beneficial effects, fostering compliance and sustaining training over time. Increasing evidence from controlled clinical studies serves to uncover the neuronal networks underlying the beneficial effects of music, such as reward, plasticity of sensorimotor systems, arousal, and affect regulation.[1,7] In sum, music appears to be a highly powerful activity capable of activating multiple brain networks and thereby showing high potential for supporting or recovering brain functioning and enhancing well-being throughout the life span.

Of particular interest is the implementation of music-based interventions using technological applications.[9] Empowering music interventions with technology responds to important societal challenges, promoting more inclusive, widely available, and cost-effective

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intervention strategies in medicine. Technological applications are varied and include approaches as diverse as sonification and enhanced feedback,[10,11] robotics and human–computer interaction,[9,12] and serious games.[13–15] The exponential growth of digital technologies and sensors is fueling this development in parallel with music multimedia technologies. These technological advances provide new and creative opportunities for producing sound and interacting with music while making people cocreators (music mediation technology).[16] Among the panoply of possible technological solutions, devices, such as tablets and smartphones, widely available to the majority, are particularly conducive to telerehabilitation in people with disabilities.[17] Dedicated applications on mobile devices can be downloaded at a low cost, are usable in the home environment, and allow for monitoring (in real-time or offline) the progress of an intervention. The advantage of these technologies that allow for remote interventions is even more evident in a time of pandemics when in-person interventions are impossible, or in the case of isolation or reduced mobility (for reviews, see Refs. 9 and 18).

An important component of music-based intervention is that they are multisensory and often engage auditory–motor processing and learning. Sensorimotor integration and learning are instrumental to a variety of everyday tasks, such as speaking, walking, playing, or learning to play a musical instrument. In particular, auditory–motor skills play an important role across the lifespan in healthy populations (e.g., for achieving expert performance),[19] in development,[20] and in aging or disordered populations (e.g., after stroke, in Parkinson's).[21,22] Learning or reacquiring these skills can foster behavioral change (acquisition of novel motor patterns and cognitive abilities, or their recovery) and is driven by brain plasticity,[2] for example, in patient populations.[1] Music is an excellent model for studying auditory–motor skill learning. Humans encounter regular events in the environment defined by different time scales and are highly skilled at processing their durations.[23] This is apparent in our ability to extract the regular pulse of music (i.e., its *beat*) from a complex auditory sequence, and to align our movements to this pulse by tapping our foot, dancing, or walking (beat perception and synchronization). Notably, beat perception and synchronization skills are widespread in the general population,[24,25] as shown with perceptual and sensorimotor timing tasks.[26,27] Performance in these tasks can be affected by neurodegenerative diseases[28,29] and neurodevelopmental disorders (attention-deficit/hyperactivity disorder [ADHD], stuttering, and developmental dyslexia).[30–32] In the present article, I will focus in particular on music-based interventions that target auditory–motor rhythmic training. I will propose that technologies, such as serious video games, can be particularly efficient to implement music-based interventions targeting auditory–motor rhythmic processes. The use of technology in music-based interventions is in its infancy, and there is still a paucity of research focusing on the use of music technology in health.[9] However, serious games present a few ingredients (e.g., the motivation derived from gaming, reward, high availability, not needing a therapist, etc.) that raise expectations that they could play a significant role in the development of music-based interventions for health and well-being.

SERIOUS GAMES FOR HEALTH

The use of games with a serious purpose, such as training patients for rehabilitation or collecting data for scientific research, has witnessed considerable growth in the last two decades. By "serious games," we indicate games that have primary purposes other than purely entertainment. This development has been fueled by the emergence of low-cost and widely available innovative technologies providing opportunities to implement training protocols. The simplest implementation of these technologies is to exploit off-the-shelf devices, such as the *Nintendo Wii* or *Kinect*, and video games in the context of re-education for increasing health and well-being (exergaming).[33,34] Using off-the-shelf video games has provided promising results in stroke,[33] Parkinson's disease,[35] and in the elderly.[36,37] Moreover, dedicated video games have been developed with the purpose of treating patients with neurological disorders,[38,39] for movement rehabilitation[40,41] and cognitive rehabilitation,[42] for example, in patients with Parkinson's disease,[15] traumatic brain injury,[43] stroke,[44] and dementia.[45] One of the advantages of serious games is to allow for at-home training, without the presence of a therapist. In addition, because serious games provide a reward in real-time as well as progressive levels of difficulties that can be personalized, this helps engage patients in the rehabilitation process while improving motivation and compliance. Serious games implemented in at-home rehabilitation protocols can foster the interaction between the patients and their family members. This may be particularly beneficial, given the improvements observed in rehabilitation when partners are involved.[46] As opposed to standard therapy, serious games offer the opportunity to monitor and control training (offline or online) by the recording of quantitative data (time of play, progression in the game levels, reaction times, etc.) during the training. Having access to quantitative measures of the patient's progress is an invaluable source of information, both in the context of clinical research (e.g., to link the benefits of the intervention to patients' individual trajectories) and clinical practice. In spite of the fact that the practice of serious games is usually not supervised in real-time by a therapist, the clinician can have access to these data, following the progress of the patient, and can ideally use this information for tailoring the treatment strategy to the individual patient. Finally, serious games can complement standard in-person therapy sessions, in situations when the game is treated as a way to foster in-between session practice.[9]

Rhythmic serious games

Music is often integrated in video games and can be used instrumentally for achieving different effects when employed in serious games for rehabilitation. In gaming settings, the effects of music can pertain to emotions, motivation, and reward, but it can also foster auditory–motor processing (e.g., in rhythmic games) or merely help focusing attention to a given game feature. The benefits of using music as a tool to help patients focusing attention, with the goal of helping achieving

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the therapy goals, are broad and are particularly relevant for patients with poor attentional focus (e.g., in ADHD) or in developmental populations. Hence, it is not surprising that there is a variety of musical serious games that were proposed for the purposes of music education.[47] Examples are the popular apps *VoxTrain* and *Yousician*. The *VoxTrain* app is supposed to act as an interactive vocal teacher, with the goal of improving singing skills, with exercises tailored to beginners, intermediate, and more expert singers. It uses simple displays to provide feedback about the performance and interactive exercises aimed at gaining better control over breathing and tone. *Yousician* is an app created by music teachers with the purpose of helping to learn a musical instrument such as the guitar or the piano at home. The approach combines interactive lessons and games. The games offer the opportunity to play along with the app, thus providing feedback in real-time in terms of pitch and timing. These examples of music technologies generate considerable interest, as shown by their commercial success, and are likely to be rewarding for single individuals. Their main shortcoming, however, is that they are typically not used for the purpose of rehabilitation. The approach they use is mostly holistic; the outcome measures to be improved by the games (e.g., pitch discrimination, beat perception, and auditory–motor synchronization) are often not explicitly indicated; and proof of their beneficial effects based on evidence-based studies is lacking.

To date, just a handful of games have used music per se to target specific clinical conditions.[9] They can be found, for instance, in using music for movement rehabilitation, owing to the tight link existing between musical features, rhythm in particular, and motor control.[48–50] Tools supporting music-based motor rehabilitation are, for example, the Music Glove[51] and music-based serious games exploiting motion capture systems for motor strengthening and rehabilitation.[52,53] In this context, I will focus in particular on rhythm-based serious games. The periodic temporal structure of music, underlined by a regular pulse to which movement can be aligned, is well suited for improving or retraining rhythmic abilities in patient populations such as Parkinson's, dementia, ADHD, dyslexia, and stuttering.[54] In a recent review, we surveyed the existing game interfaces that use music and allow recording movement, to assess their potential to be used in rehabilitation settings (see Table 1 in Bégel *et al.* (2017) for the features of the reviewed games).[54] We selected games and devices involving rhythmic skills, based on their capacity to record the player's temporal performance while considering aspects, such as the peripheral used, the response, and the output provided. Several games on the market might have the potential of training rhythmic skills and auditory–motor processes (e.g., Guitar Hero, Rock Band, Beat Sneak Bandit, Rhythm Heaven Fever, etc.). However, none of the 27 reviewed games at the time is satisfying for rehabilitation purposes. First, in most of the games, the task is to react to visual stimuli with music in the background, with the number of stimuli rather than rhythmic complexity being manipulated to increase the game difficulty. Even though the performance in the games is likely to be affected by the rhythm of musical stimuli, the player's task is not directed toward rhythm per se. Second, the temporal precision of the devices in recording synchronization between the movements and the beat is quite poor, a fact which hinders proper recording of the metrics of rhythmic performance, such as motor variability and the precision of synchronization. In conclusion, the surveyed games include tasks, such as catching objects on the screen or imitating movement sequences, that are not targeted toward training rhythmic abilities. These tasks are rather likely to train more general cognitive and motor skills that may be unrelated to rhythmic abilities per se. The training afforded by these games is thus rather nonspecific and does not allow proper evaluation of the progress in rhythmic abilities during the training, owing to the aforementioned limitations in measurement. Yet, they may still be useful for training temporal prediction in an implicit fashion (implicit timing), though.[55,56] It is well known that the temporal regularity of a stimulus sequence, such as a metronome, can be processed implicitly and thereby improve performance in nontiming tasks (e.g., working memory,[57] pitch judgment,[58] and language[59]). For example, in tasks in which a deviant pitch is detected in a temporally regular or irregular sequence, the regular rhythmic structure of the stimulus typically improves reaction times[60] even though a timing judgment is not required. Interestingly, there is evidence that implicit timing might be more resistant than explicit timing in individuals with rhythm disorders.[61] An appealing possibility is that patients with rhythm disorders can still be trained using dedicated serious games capitalizing on relatively spared implicit timing mechanisms as a way to relearn rhythmic abilities. This possibility awaits further inquiry and evidence-based studies. Notably, some of the aforementioned games and devices enjoy considerable commercial success, and generally, users enjoy playing with them outside of a rehabilitation context. This suggests that the impact of some of these games should undergo thorough scrutiny via a systematic evaluation to identify their potential in terms of near- and far-transfer effects.

With the goal in mind of devising a serious game explicitly targeting rhythmic skills, in particular auditory–motor synchronization, we recently devised the game *Rhythm Workers*.[62] The rationale underlying the creation of this game is that by improving rhythmic skills via finger tapping paced to a musical beat, we are likely to see positive transfer to other motor functions and cognition. This idea is motivated by growing evidence of a tight link between rhythmic skills, motor, and cognitive functions. Tracking the beat of an auditory stimulus is associated with general cognitive functions, such as working memory, attention, executive functions, or language and reading skills.[31,32,63,64] Thus, it is expected that rhythmic training may foster an improvement of functions beyond rhythm per se.

Rhythm Workers is a finger tapping game, in which the player, by tapping on the tablet screen as accurately as possible to the beat of auditory stimuli (metronomes, rhythmic sequences, and music), constructs buildings (Figure 1A,B for a first prototype, and also Bégel *et al.* (2018) for more details).[62] Each auditory stimulus (e.g., a song fragment or a rhythmic sequence) is linked to the construction of a given building. The game includes different levels of difficulty, corresponding to increasing rhythmic complexity of the auditory stimuli, as determined in a previous pilot tapping study.[62] The aesthetic appeal of the building constructed after each tapping trial depends on the player's rhythmic performance, namely on how accurately and consistently the taps are aligned to the beat of the rhythmic stimulus. For example, when tap

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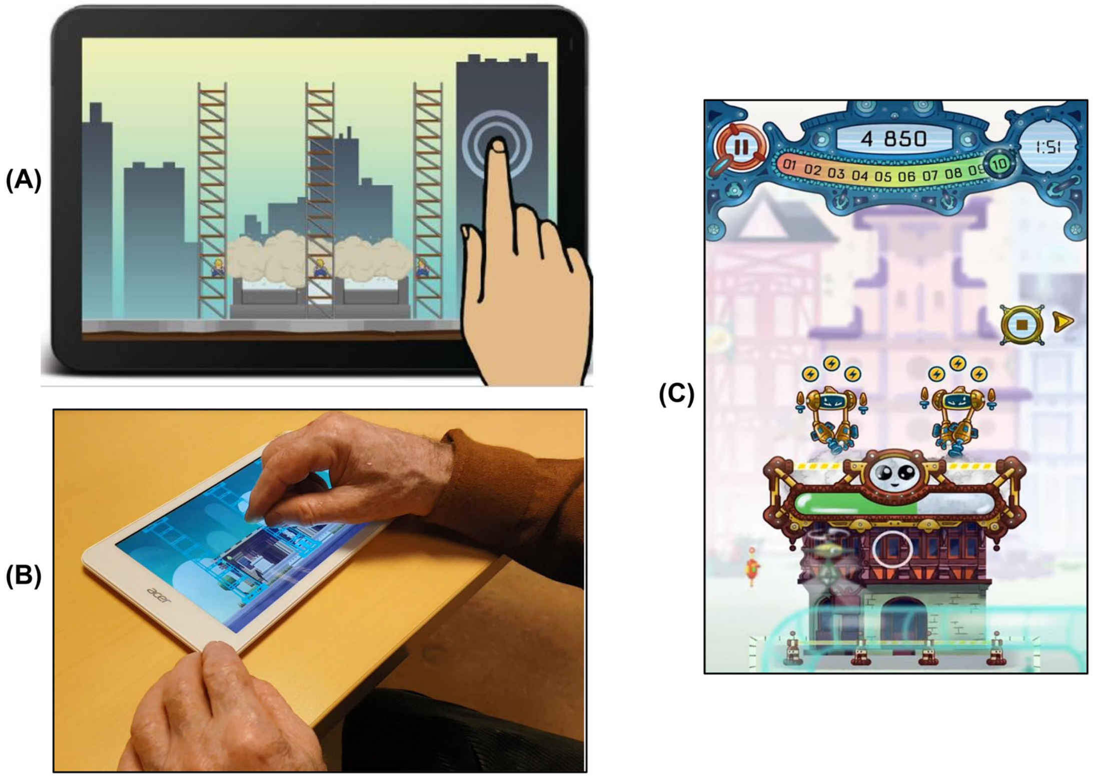

FIGURE 1 Game interface of the serious game Rhythm Workers. (A) First prototype of the game.[57] (B) The game played by a patient. (C) Most recent version of the game, including additional elements in the gameplay.

times are very close to the beat and there is little variability between the tap times, the player constructs a well-formed and elegant building, gains more points in the game, and thus progresses more swiftly across the different levels. Upon completing each trial in the game, players receive feedback (number of points up to 100, and 1–5 stars), and, conditional on the number of points obtained, they progress or not to the next level. The ultimate goal of the game is to earn as many points as possible. In a proof-of-concept study conducted with healthy young adults subjected to a 2-week training program using the game, the players rated the game as highly motivating across the entire training program.[62] Moreover, they showed high adherence to the training program (approximately 70% of the maximum playing time), and excellent usability of the tablet interface.[62] We found lower adherence in a clinical population (50% of the maximum expected playing time in patients with Parkinson's disease) using the game for a longer period of training (6 weeks), but good to excellent suitability of the game and positive effects of the intervention on rhythmic abilities.[15] Some of these limitations are taken into account in a more recent version of the game (Figure 1C). In order to increase the motivation to play the game while keeping the progression in difficulty, the game now includes only musical stimuli with different degrees of rhythmic complexity, and distractors are added to the game, such as monsters to be destroyed while tapping. This version of the game is being tested at the moment in the lab in children with neurodevelopmental disorders. In the following section, I will describe a domain of application of rhythmic serious games for rehabilitation for patients with neurodegenerative disorders, by taking patients with Parkinson's disease as the target clinical population.

Domain of application of rhythmic serious games: Example of Parkinson's disease

Parkinson's disease is a neurodegenerative disorder that appears to be a good model for testing the efficacy of rhythmic serious games, given the response of patients to rhythmic stimulation. Considered as the most common and serious movement disorder,[65] with about four million patients worldwide,[66] Parkinson's disease is often associated with dysfunctional gait and balance. These deficits, on top of Parkinson's cardinal symptoms, are a major cause of disability, hindering patients' mobility and independence, and a growing economic burden for the healthcare system.[67] Because the response of gait disorders to dopamine replacement therapy is inconstant and decreases over time,[67,68] there is an urgent need for innovative and effective nonpharmacological treatments. Rhythm-based activities (e.g., walking to an auditory beat or dance) are promising in improving patients' gait, quality of life, and social participation.[6,21,69] For example, rhythmic auditory cues are used to provide a temporal scaffolding for action, thus aiding patients in initiating and coordinating movements.[70,71]

Rhythmic cueing involves walking and motor coordination, which alone may improve cognitive and motor functions in older adults.[72] However, there is converging evidence in part from our team

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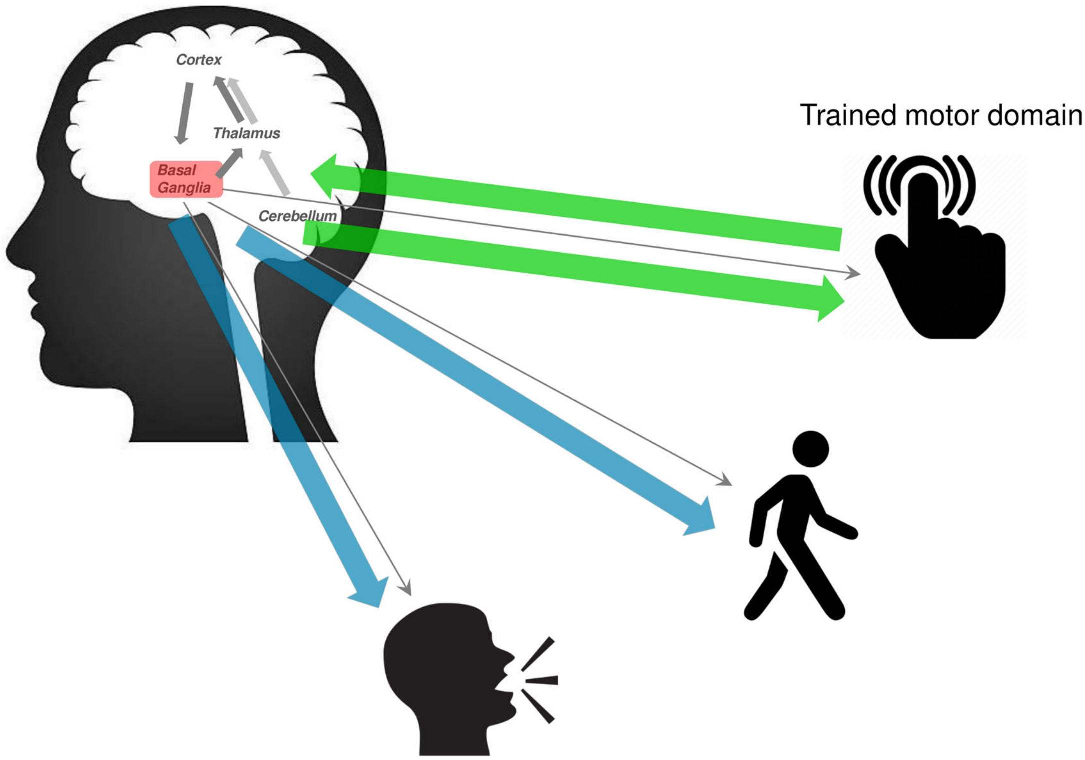

FIGURE 2 Simplified schema to illustrate the cross-effector transfer effects of rhythmic training in Parkinson's disease. Three motor domains are represented (manual, gait, and orofacial). Training of the motor domain via a rhythmic serious game on a tablet is expected to induce improved performance in the trained domain (manual). Moreover, transfer of the improvement to rhythmic performance in other motor domains is also expected, in keeping with the *general dysrhythmia* hypothesis.[67,75]

suggesting that the effect of rhythmic cueing in Parkinson's is likely to be mediated by rhythm mechanisms. Motor disorders in Parkinson's patients are often observed across motor domains. Rhythmic features of gait and speech are correlated,[73] and motor rhythmic variability across different effectors—upper and lower limbs (finger tapping and gait)—and the oromotor system are tightly related.[74] Interestingly, we recently demonstrated that variability in rhythmic tasks across motor domains (walking, finger tapping, and speaking) in patients with Parkinson's disease can be predicted by impaired beat perception.[74] Impairment of a central mechanism devoted to rhythm processing, independent of motor control per se, can partly explain rhythm motor disorders across domains. Moreover, the response to rhythmic cues varies significantly from one patient to the other (positive, null, or negative), and can be accounted for by individual rhythmic abilities.[75–77] These findings point toward a central disorder underpinning rhythmic deficits across effectors and tasks ("general dysrhythmia").[73,74,78] This parsimonious explanation of general rhythm disorders in Parkinson's disease is in keeping with the neuronal basis of the disease, involving basal–ganglia–cortical circuitries,[79] which play a role in rhythm processing and temporal prediction.[28,48] Parkinson's disease is notoriously associated with deficits in the perception and production of temporal intervals,[80,81] as well as in beat perception and synchronization.[28,29]

The possibility that rhythm disorders across motor domains in Parkinson's disease may have a common source is appealing. Causal evidence supporting this hypothesis is missing, though. One way to test this hypothesis is to provide rhythmic training via a motor channel, and observe beneficial effects in one of the other channels (cross-domain motor transfer; see Figure 2). We examined this possibility using training of the manual domain with a tapping rhythmic serious game, while testing transfer effects onto motor skills in other domains (gait and orofacial).[82] We used the rhythmic training game Rhythm Workers, implemented as a tablet app,[62] to train rhythmic abilities via finger/hand tapping to the beat of rhythmic stimuli. In a previous study,[15] we showed good to excellent suitability of this game in patients with Parkinson's disease (score >29, Suitability Evaluation Questionnaire[83]) in the context of a self-rehabilitation program, and the feasibility of this type of training in this population. In a pilot study, one group of patients with Parkinson's disease (n = 12) played with Rhythm Workers at home for 6 weeks. A second group of patients (n = 11) played with a nonrhythmic video game (active control condition)—Tetris[84,85]—and a third group (n = 10) did not receive any training. We tested motor performance (i.e., motor variability) in three different domains, using tests that showed sensitivity to individual differences in this patient population.[74] Rhythmic motor performance was assessed in the orofacial domain by asking patients to perform an oral diadochokinesis task (i.e., repeat the tri-syllable pseudoword *pataka* for 30 s), tapping to a rhythmic stimulus (task taken from the BAASTA battery on tablet[31,86]), and walking along a computerized walkway at their preferred rate, for a distance of 8 m. Rhythm perception was also assessed with the Beat Alignment Test (BAT;[87] version implemented

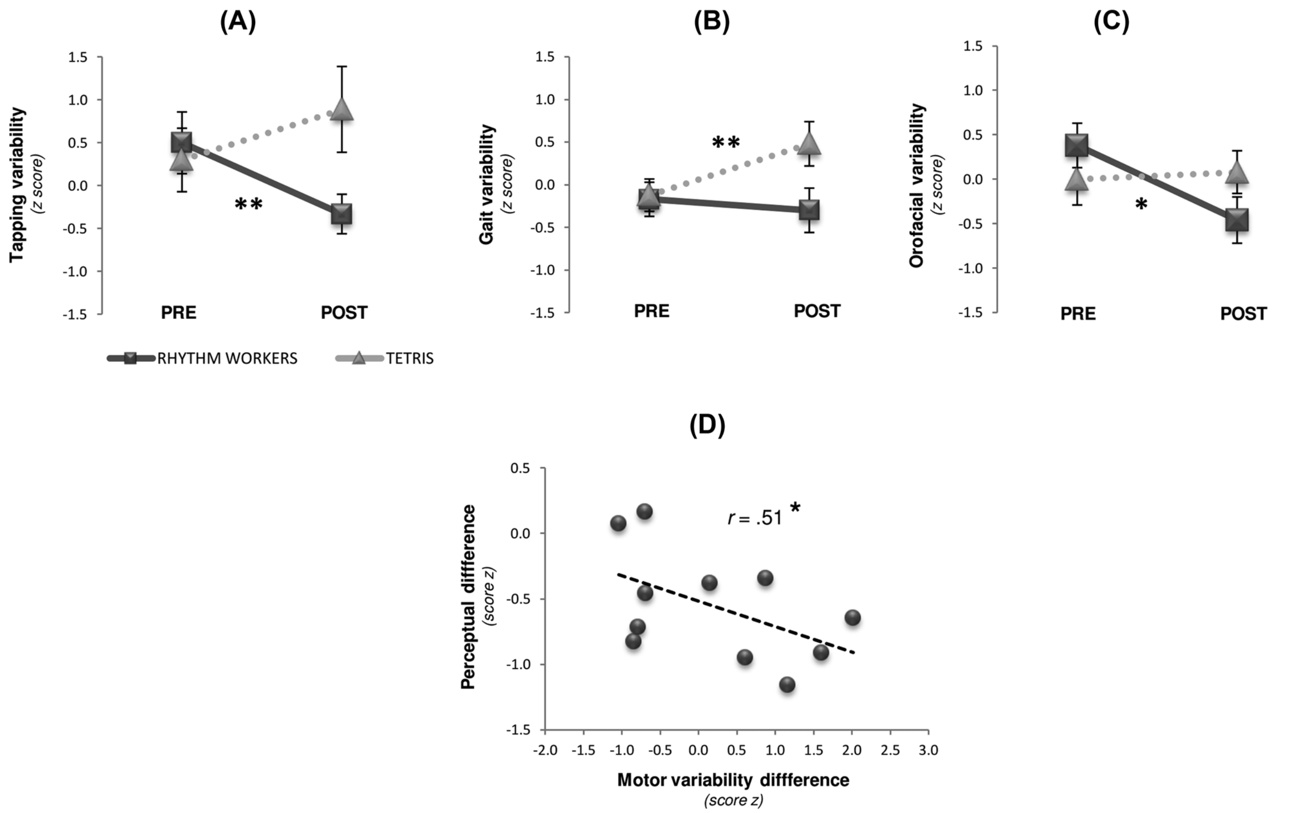

FIGURE 3 Results of training patients with Parkinson's disease with a rhythmic serious game (Rhythm Workers) and a control active game (Tetris). Performance is expressed in *z*-scores relative to the performance of a control group that did not receive any training. Variability pre- and post-intervention in the (A) tapping task, (B) gait task, and (C) orofacial task. (D) Relation between the change in performance in the motor tasks (difference in motor variability, averaged across the three motor domains) and the change in performance in the rhythm perception task (Beat Alignment Test). Lower difference (sometimes negative) in motor variability indicates an improvement of motor performance after the intervention, while a positive perceptual difference indicates an improvement.[75] Error bars indicate SEM. $*p < 0.05$, $**p < 0.01$.

in BAASTA[26]). In this test, the patients judged whether a sequence of tones was aligned or not with the beat of short musical excerpts.

The results of this pilot study[82] showed that the rhythmic game led to a reduction of motor variability in the trained motor domain, as expected (Figure 3A). We observed no effect of the active control condition on tapping variability, thus showing that only the rhythm game is effective in training rhythmic abilities. The effects of the training extended also to the oromotor task (Figure 3B), with a reduction of motor variability selectively after the rhythm intervention, and allowed keeping the performance stable in the gait task (Figure 3C). Interestingly, the reduction of motor variability across motor tasks was linked to the improvement of the performance in rhythm perception (Figure 3D). The patients who benefitted the most from the rhythmic training in the motor tasks were those who also displayed the largest improvement in rhythm perception consequent to the intervention. These effects persisted after taking into account the patients' clinical characteristics (e.g., severity) and cognition. These findings are very promising and provide the first causal evidence in support of the hypothesis of a general dysrhythmia in Parkinson's disease. They are also very encouraging from a clinical standpoint, suggesting that training rhythmic abilities in one motor domain (i.e., with a given effector) can bring about beneficial effects in tasks involving other effectors.

One caveat of the training program is that in spite of the fact that patients generally enjoyed the game, adherence to the program was still below our expectations (patients played on average about 60% of the required playing time). The next step of this project will be to run a larger-scale randomized clinical trial with a new version of the game taking into account these issues, as a way to confirm the results obtained in the pilot study.

CONCLUSIONS

Technologies, such as dedicated apps on smartphone and tablet devices, coupled with external sensors,[88,89] are recent additions to the methods for music-based interventions.[9] Implementing music-based interventions as serious games has several advantages, such as making them particularly motivating and rewarding, allowing performance monitoring and individualization, which all should add to the potential of music as a tool for rehabilitation. Serious games, with their capacity to engage multisensory processes (auditory perception, haptics, and movement) provide flexible solutions for music-based interventions. The gamification of rehabilitation protocols is likely to maximize their rewarding features; the gameplay and game properties aimed at

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increasing motivation and adherence can be flexibly manipulated in dedicated apps and tested in pilot studies before the deployment of a full-fledged large-scale clinical trial. Increasing motivation associated with rehabilitation protocols is paramount, given the increasing role of reward mechanisms, under dopaminergic control and their possible interaction with the success of the therapy and brain plasticity.[90] Moreover, serious games can be devised to target specific musical features or processes (e.g., pitch vocal training, rhythm perception, and auditory–motor synchronization), thus allowing to test specific hypotheses in experimental or theory-driven clinical studies.

Owing to their wide access and low costs, serious games are also inclusive tools ideally suited for remote at-home training using music in a variety of populations. The focus of this article has been in particular on interventions based on auditory–motor training using rhythmic stimuli, given the potential of this form of intervention for patients with neurological disorders.[91] A domain of application for rhythmic serious games is rehabilitation for patients with motor disorders.[6] I presented first evidence from a recent proof-of-concept study[82] showing that an at-home protocol using a rhythmic video game using finger tapping has beneficial effects on motor performance across motor domains in Parkinson's disease. This evidence, albeit preliminary and awaiting validation in a larger-scale clinical trial, shows that rhythmic serious games can be used with success in patients with motor disorders in remote protocols. This possibility is particularly appealing in situations where the movement of a given effector is hindered (e.g., in stroke or aphasia), while other effectors or motor domains are untouched by the disease, thus opening up innovative perspectives for motor rehabilitation.[6]

The use of serious rhythmic games for rehabilitation can be extended to a larger spectrum of disabilities beyond patients with movement disorders. Neurodevelopmental disorders, such as speech and language disorders (e.g., developmental dyslexia), autism spectrum disorder (ASD), developmental stuttering, and ADHD, are potential candidates for this type of intervention. These disorders are characterized by poor timing or rhythmic abilities (developmental dyslexia, and speech and language impairments;[32,92,93] stuttering;[30] ASD;[94] and ADHD[31,95]). For example, there is evidence that rhythmic stimulation or auditory–motor synchronization can improve speech perception in dyslexia and Specific Language Impairment,[59,96,97] reduce motor dysfunctions and improve social communication in autism,[98,99] and foster fluency-enhancing effects in stuttering (the "rhythm effect").[100,101] Moreover, because training of auditory–motor synchronization was found to improve executive functions (e.g., inhibition control) in typical development,[102–104] rhythmic training may be generally beneficial for a range of disorders. In most of the cases, the assessment of the benefits of auditory–motor synchronization in neurodevelopmental disorders awaits randomized control trials, including a comparable active control condition.[18] Rhythmic serious games can be instrumental for this purpose by providing a viable alternative to implement training protocols by taking advantage of their motivating and inclusive properties.

In spite of all these advantages and the general excitement surrounding technologies as tools for rehabilitation, the use of serious games and apps is not without dangers. A few words of caution are in order. One of the challenges is that the accessibility of serious games especially as apps on a mobile device may encourage patients to use them to self-monitor their progress without the supervision of a clinician. The fast development of apps promoting self-monitoring of performance using sensors, such as accelerometers or physiology trackers, in the absence of proper clinical validation, adds to this risk. Moreover, because serious games can be played at home without supervision, they may also encourage isolation and reduce social interactions. The bottom line is that serious games for music-based interventions should not be treated as a replacement of a therapist but rather as an additional element to be added to the clinician's toolbox. Integration of the serious games in a well-structured clinical protocol, supervision by a clinician during the implementation of the protocol, and clinical validation via randomized clinical trials are all critical elements.[9] Moreover, further development of serious games in the years to come may be directed to increase their interactive component, thus making patients fully benefit from the social reward afforded by music interventions.

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COMPETING INTERESTS

The author declares that he is a board member of the BeatHealth company devoted to the design and commercialization of rhythm-based cognitive therapies, including the Rhythm Workers serious game.

REFERENCES

1. Sihvonen, A. J., Särkämö, T., Leo, V., Tervaniemi, M., Altenmüller, E., & Soinila, S. (2017). Music-based interventions in neurological rehabilitation. *Lancet Neurology*, *16*, 648–660.
2. Herholz, S. C., & Zatorre, R. J. (2012). Musical training as a framework for brain plasticity: Behavior, function, and structure. *Neuron*, *76*, 486–502.
3. Zatorre, R. J. (2013). Predispositions and plasticity in music and speech learning: Neural correlates and implications. *Science*, *342*(6158), 585–589.
4. Dalla Bella, S. (2016). Music and brain plasticity. In S. Hallam, I. Cross, & M. (Eds.), *The Oxford handbook of music psychology - Second edition* (pp. 325–42). Oxford University Press.
5. Nombela, C., Hughes, L. E., Owen, A. M., & Grahn, J. A. (2013). Into the groove: Can rhythm influence Parkinson's disease? *Neuroscience & Biobehavioral Reviews*, *37*, 2564–2570.
6. Dalla Bella, S. (2020). The use of rhythm in rehabilitation for patients with movement disorders. In L. Cuddy, S. Belleville, & A. Moussard (Eds.), *Music and the aging brain* (pp. 383–406). Elsevier.
7. Särkämö, T. (2018). Cognitive, emotional, and neural benefits of musical leisure activities in aging and neurological rehabilitation: A critical review. *Annals of Physical and Rehabilitation Medicine*, *61*(6), 414–418.
8. Salimpoor, V. N., Zald, D. H., Zatorre, R. J., Dagher, A., & McIntosh, A. R. (2015). Predictions and the brain: How musical sounds become rewarding. *Trends in Cognitive Sciences*, *19*, 86–91.

17496632, 2022, 1, Downloaded from https://nyaspubs.onlinelibrary.wiley.com/doi/10.1111/nyas.14878 by Colorado State University, Wiley Online Library on [06/05/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

9. Agres, K. R., Schaefer, R. S., Volk, A., van Hooren, S., Holzapfel, A., Dalla Bella, S., Müller, M., de Witte, M., Herremans, D., Ramirez Melendez, R., Neerincx, M., Ruiz, S., Meredith, D., Dimitriadis, T., & Magee, W. L. (2021). Music, computing, and health: A roadmap for the current and future roles of music technology for health care and well-being. *Music & Science*, *4*, 1–32.
10. Schneider, S., Münte, T., Rodriguez-Fornells, A., Sailer, M., & Altenmüller, E. (2010). Music-supported training is more efficient than functional motor training for recovery of fine motor skills in stroke patients. *Music Perception*, *27*, 271–280.
11. Scholz, D. S., Rohde, S., Nikmaram, N., Brückne, H.-P., Grossbach, M., Rollnik, J. D., & Altenmüller, E. (2016). Sonification of arm movements in stroke rehabilitation — A novel approach in neurologic music therapy. *Frontiers in Neurology*, *7*, 106.
12. de Kok, R., Rothweiler, J., Scholten, L., van Zoest, M., Boumans, R., & Neerincx, M. (2018). Combining social robotics and music as a non-medical treatment for people with dementia. *Proceedings from RO-MAN 2018 - 27th IEEE International Symposium on Robot and Human Interactive Communication*, 465–467.
13. Annetta, L. A. (2010). The “I's” have it: A framework for serious educational game design. *Review of General Psychology*, *14*(2), 105–113.
14. Kato, P. M. (2012). Evaluating efficacy and validating games for health. *Games for Health Journal*, *1*(1), 74–76.
15. Dauvergne, C., Bégel, V., Gény, C., Puyjarinet, F., Laffont, I., & Dalla Bella, S. (2018). Home-based training of rhythmic skills with a serious game in Parkinson's disease: Usability and acceptability. *Annals of Physical and Rehabilitation Medicine*, *61*, 380–385.
16. Leman, M. (2008). *Embodied music cognition and mediation technology*. MIT Press.
17. Cancer, A., Sarti, D., de Salvatore, M., Granocchio, E., Chieffo, D. P. R., & Antonietti, A. (2021). Dyslexia telerehabilitation during the COVID-19 pandemic: Results of a rhythm-based intervention for reading. *Children*, *8*(11), 1011.
18. Grau-Sánchez, J., Jamey, K., Paraskevopoulos, E., Dalla Bella, S., Gold, C., Schlaug, G., Belleville, S., Rodriguez-Fornells, A., Hackney, M. E., & Särkämö, T. (2022). Putting music to trial: Consensus on key methodological challenges investigating music-based rehabilitation. *Annals of the New York Academy of Sciences*, *XXXX*, XX–XX.
19. Zatorre, R. J., Chen, J. L., & Penhune, V. B. (2007). When the brain plays music: Auditory–motor interactions in music perception and production. *Nature Reviews Neuroscience*, *8*(7), 547–558.
20. Trainor, L. J., & Cirelli, L. (2015). Rhythm and interpersonal synchrony in early social development. *Annals of the New York Academy of Sciences*, *1337*, 45–52.
21. Dalla Bella, S., Benoit, C.-E., Farrugia, N., Schwartze, M., & Kotz, S. A. (2015). Effects of musically cued gait training in Parkinson's disease: Beyond a motor benefit. *Annals of the New York Academy of Sciences*, *1337*, 77–85.
22. Rodriguez-Fornells, A., Rojo, N., Amengual, J. L., Ripollés, P., & Altenmüller, E. (2012). The involvement of audio–motor coupling in the music-supported therapy applied to stroke patients. *Annals of the New York Academy of Sciences*, *1252*, 282–293.
23. Grondin, S. (2010). Timing and time perception: A review of recent behavioral and neuroscience findings and theoretical directions. *Attention, Perception & Psychophysics*, *72*(3), 561–582.
24. Sowiński, J., & Dalla Bella, S. (2013). Poor synchronization to the beat may result from deficient auditory-motor mapping. *Neuropsychologia*, *51*, 1952–1963.
25. Tranchant, P., Vuvan, D. T., & Peretz, I. (2016). Keeping the beat: A large sample study of bouncing and clapping to music. *PLoS One*, *11*(7), e0160178.
26. Dalla Bella, S., Farrugia, N., Benoit, C.-E., Bégel, V., Verga, L., Harding, E., & Kotz, S. A. (2017). BAASTA: Battery for the Assessment of Auditory Sensorimotor and Timing Abilities. *Behavior Research Methods*, *49*, 1128–1145.
27. Fujii, S., & Schlaug, G. (2013). The Harvard Beat Assessment Test (H-BAT): A battery for assessing beat perception and production and their dissociation. *Frontiers in Human Neuroscience*, *7*, 771.
28. Grahn, J. A., & Brett, M. (2009). Impairment of beat-based rhythm discrimination in Parkinson's disease. *Cortex*, *45*, 54–61.
29. Benoit, C.-E., Dalla Bella, S., Farrugia, N., Obrig, H., Mainka, S., & Kotz, S. A. (2014). Musically cued gait-training improves both perceptual and motor timing in Parkinson's disease. *Frontiers in Human Neuroscience*, *8*, 494.
30. Falk, S., Müller, T., & Dalla Bella, S. (2015). Non-verbal sensorimotor timing deficits in children and adolescents who stutter. *Frontiers in Psychology*, *6*, 847.
31. Puyjarinet, F., Bégel, V., Lopez, R., Dellacherie, D., & Dalla Bella, S. (2017). Children and adults with attention-deficit/hyperactivity disorders cannot move to the beat. *Scientific Reports*, *7*, 11550.
32. Bégel, V., Dalla Bella, S., Devignes, Q., Vandenbergue, M., Lemaître, M. P., & Dellacherie, D. (2022). Rhythm as an independent determinant of developmental dyslexia. *Developmental Psychology*, *58*(2), 339–358.
33. Webster, D., & Celik, O. (2014). Systematic review of Kinect applications in elderly care and stroke rehabilitation. *Journal of Neuroengineering and Rehabilitation*, *11*, 108.
34. Bonnechere, B., Jansen, B., Omelina, L., & Van Sint Jan, S. (2016). The use of commercial video games in rehabilitation : A systematic review. *International Journal of Rehabilitation Research*, *39*(4), 277–290.
35. Harris, D. M., Rantalainen, T., Muthalib, M., Johnson, L., & Teo, W.-P. (2015). Exergaming as a viable therapeutic tool to improve static and dynamic balance among older adults and people with idiopathic Parkinson's disease: A systematic review and meta-analysis. *Frontiers in Aging Neuroscience*, *7*, 167.
36. Sun, T. L., & Lee, C. H. (2013). An impact study of the design of exergaming parameters on body intensity from objective and gameplay-based player experience perspectives, based on balance training exergame. *PLoS One*, *8*(7), e69471.
37. Abd-Alrazaq, A., Alajlani, M., Alhuwail, D., Toro, C. T., Giannicchi, A., Ahmed, A., Makhlouf, A., & Househ, M. (2022). The effectiveness and safety of serious games for improving cognitive abilities among elderly people with cognitive impairment: Systematic review and meta-analysis. *JMIR Serious Games*, *10*(1), e34592.
38. Rego, P., Moreira, P., & Reis, L. (2010). Serious games for rehabilitiation: A survey and classification towards a taxonomy. *Proceedings from the 5th Iberian Conference on Information Systems and Technologies (CISTI)*, Santiago de Compostela.
39. Rego, P., Moreira, P., & Reis, L. (2018). Proposal of an extended taxonomy of serious games for health rehabilitation. *Games for Health Journal*, *7*(5), 302–309.
40. Di Loreto, I., Lange, B., Seilles, A., Dyce, W., & Andary, S. (2013). Game design for all: The example of hammer and planks. *Proceedings from the 4th International Conference on Serious Games Development and Applications (SGDA)* .
41. Saposnik, G., Teasell, R., Mamdani, M., Hall, J., McIlroy, W., Cheung, D., Thorpe, K. E., Cohen, L. G., & Bayley, M., Stroke Outcome Research Canada (SORCan) Working Group. (2010). Effectiveness of virtual reality using Wii gaming technology in stroke rehabilitation: A pilot randomized clinical trial and proof of principle. *Stroke*, *41*(7), 1477–1484.
42. Fernández, E., Bringas, M. L., Salazar, S., Rodriguez, D., Garcia, M. E., & Torres, M. (2012). Clinical impact of RehaCom software for cognitive rehabilitation of patients with acquired brain injury. *MEDICC Review*, *14*(4), 32–35.
43. Martinez-Pernia, D., Núñez-Huasaf, J., Del Blanco, Á., Ruiz-Tagle, A., Velásquez, J., Gomez, M., Blesius, C. R., Ibañez, A., Fernández-Manjón,

17496632, 2022, 1, Downloaded from https://nyaspubs.onlinelibrary.wiley.com/doi/10.1111/nyas.14878 by Colorado State University, Wiley Online Library on [06/05/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

B., & Slachewsky, A. (2017). Using game authoring platforms to develop screen-based simulated functional assessments in persons with executive dysfunction following traumatic brain injury. *Journal of Biomedical Informatics*, *74*, 71–84.
44. Doumas, I., Everard, G., Dehem, S., & Lejeune, T. (2021). Serious games for upper limb rehabilitation after stroke: A meta-analysis. *Journal of Neuroengineering and Rehabilitation*, *18*(1), 100.
45. McCallum, S., & Boletuses, C. (2013). A taxonomy of serious games for dementia. *Proceedings of the 3rd European Conference on Gaming and Playful Interaction in Health Care*, 219–232.
46. Takagi, A., Hirashima, M., Nozaki, D., & Burdet, E. (2019). Individuals physically interacting in a group rapidly coordinate their movement by estimating the collective goal. *eLife*, *8*, e41328.
47. Mandanici, M., Altieri, F., Rodà, A., & Canazza, S. (2018). Inclusive sound and music serious games in a large-scale responsive environment. *British Journal of Educational Technology*, *49*(4), 620–635.
48. Grahn, J. A., & Brett, M. (2007). Rhythm and beat perception in motor areas of the brain. *Journal of Cognitive Neuroscience*, *19*, 893–906.
49. Grahn, J. A. (2012). Neural mechanisms of rhythm perception: Current findings and future perspectives. *Topics in Cognitive Science*, *4*, 585–606.
50. Cannon, J. J., & Patel, A. (2021). How beat perception co-opts motor neurophysiology. *Trends in Cognitive Sciences*, *25*(2), 137–150.
51. Friedman, N., Chan, V., Zondervan, D., Bachman, M., & Reinkensmeyer, D. J. (2011). MusicGlove: Motivating and quantifying hand movement rehabilitation by using functional grips to play music. *Proceedings of the 2011 Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, 2359–2363.
52. Agres, K., & Herremans, D. (2017). Music and motion-detection: A game prototype for rehabilitation and strengthening in the elderly. *Proceedings from the IEEE International Conference on Orange Technologies (ICOT 2017)*, 95–98.
53. Beveridge, S., Cano, E., & Agres, K. (2018). Rhythmic entrainment for hand rehabilitation using the leap motion controller. *Proceedings of the 19th International Society of Music Information Retrieval (ISMIR) Conference*. Paris, France.
54. Bégel, V., Di Loreto, I., Seilles, A., & Dalla Bella, S. (2017). Music games: Potential application and considerations for rhythmic training. *Frontiers in Human Neuroscience*, *11*, 273.
55. Nobre, K., & Coull, J. T. (2010). *Attention and time*. Oxford University Press.
56. Coull, J. T., Cheng, R. K., & Meck, W. H. (2011). Neuroanatomical and neurochemical substrates of timing. *Neuropsychopharmacology*, *36*, 3–25.
57. Cutanda, D., Correa, Á., & Sanabria, D. (2015). Auditory temporal preparation induced by rhythmic cues during concurrent auditory working memory tasks. *Journal of Experimental Psychology: Human Perception and Performance*, *41*(3), 790.
58. Jones, M. R., Moynihan, H., MacKenzie, N., & Puente, J. (2002). Temporal aspects of stimulus-driven attending in dynamic arrays. *Psychological Science*, *13*(4), 313–319.
59. Przybylski, L., Bedoin, N., Krifi-Papoz, S., Herbillon, V., Roch, D., Léculier, L., Kotz, S. A., & Tillmann, B. (2013). Rhythmic auditory stimulation influences syntactic processing in children with developmental language disorders. *Neuropsychology*, *27*(1), 121.
60. Sanabria, D., Capizzi, M., & Correa, Á. (2011). Rhythms that speed you up. *Journal of Experimental Psychology: Human Perception and Performance*, *37*(1), 236–244.
61. Bégel, V., Benoit, C.-E., Correa, Á., Cutanda, D., Kotz, S. A., & Dalla Bella, S. (2017). "Lost in time" but still moving to the beat. *Neuropsychologia*, *94*, 129–138.
62. Bégel, V., Seilles, A., & Dalla Bella, S. (2018). Rhythm Workers: A music-based serious game for training rhythm skills. *Music and Science*, *1*, 1–16.
63. Tierney, A. T., & Kraus, N. (2013). The ability to tap to a beat relates to cognitive, linguistic, and perceptual skills. *Brain and Language*, *124*(3), 225–231.
64. Woodruff Carr, K., White-Schwoch, T., Tierney, A. T., Strait, D. L., & Kraus, N. (2014). Beat synchronization predicts neural speech encoding and reading readiness in preschoolers. *Proceedings of the National Academy of Sciences of the United States of America*, *111*(40), 14559–14564.
65. Hirtz, D., Thurman, D. J., Gwinn-Hardy, K., Mohamed, M., Chaudhuri, A. R., & Zalutsky, R. (2007). How common are the "common" neurologic disorders? *Neurology*, *68*, 326–337.
66. Andlin-Sobocki, P., Jönsson, B., Wittchen, H. U., & Olesen, J. (2005). Cost of disorders of the brain in Europe. *European Journal of Neurology*, *12*(Suppl 1), 1–27.
67. Grabli, D., Karachi, C., Welter, M.-L., Lau, B., Hirsch, E. C., Vidailhet, M., & François, C. (2012). Normal and pathological gait: What we learn from Parkinson's disease. *Journal of Neurological, Neurosurgery and Psychiatry*, *83*(10), 979–985.
68. Sethi, K. (2008). Levodopa unresponsive symptoms in Parkinson disease. *Movement Disorders*, *23*(Suppl 3), S521–S533.
69. Predovan, D., & Bherer, L. (2020). Effects of physical activity with and without music and dance on cognition. In L. Cuddy, S. Belleville, & A. Moussard (Eds.), *Music and the aging brain* (pp. 277–291). Elsevier.
70. Spaulding, S. J., Barber, B., Colby, M., Cormack, B., Mick, T., & Jenkins, M. E. (2013). Cueing and gait improvement among people with Parkinson's disease: A meta-analysis. *Archives of Physical Medicine and Rehabilitation*, *4*, 562–570.
71. Ghai, S., Ghai, I., Schmitz, G., & Effenberg, A. O. (2018). Effect of rhythmic auditory cueing on parkinsonian gait: A systematic review and meta-analysis. *Scientific Reports*, *8*(1), 506.
72. Voelcker-Rehage, C., & Niemann, C. (2013). Structural and functional brain changes related to different types of physical activity across the life span. *Neuroscience and Biobehavioral Reviews*, *37*(9), 2268–2295.
73. Cantiniaux, S., Vaugoyeau, M., Robert, D., Horrelou-Pitek, C., Mancini, J., Witjas, T., & Azulay, J. P. (2010). Comparative analysis of gait and speech in Parkinson's disease: Hypokinetic or dysrhythmic disorders? *Journal of Neurology, Neurosurgery and Psychiatry*, *81*, 177–184.
74. Puyjarinet, F., Bégél, V., Gény, C., Driss, V., Cuartero, M.-C., Kotz, S. A., Pinto, S., & Dalla Bella, S. (2019). Heightened orofacial, manual, and gait variability in Parkinson's disease results from a general rhythmic impairment. *NPJ Parkinson's Disease*, *5*, 19.
75. Dalla Bella, S., Benoit, C.-E., Farrugia, N., Keller, P. E., Obrig, H., Mainka, S., & Kotz, S. A. (2017). Gait improvement via rhythmic stimulation in Parkinson's disease is linked to rhythmic skills. *Scientific Reports*, *7*, 42005.
76. Cochen De Cock, V., Dotov, D. G., Ihalainen, P., Bégel, V., Galtier, F., Lebrun, C., Picot, M. C., Driss, V., Landragin, N., Gény, C., Bardy, B., & Dalla Bella, S. (2018). Rhythmic abilities and musical training in Parkinson's disease: Do they help? *NPJ Parkinson's Disease*, *4*(1), 8.
77. Dalla Bella, S., Dotov, D. G., Bardy, B., & Cochen de Cock, V. (2018). Individualization of music-based rhythmic auditory cueing in Parkinson's disease. *Annals of the New York Academy of Sciences*, *1423*, 308–317.
78. Tolleson, C. M., Dobolyi, D. G., Roman, O. C., Kanoff, K., Barton, S., Wylie, S. A., Kubovy, M., & Claassen, D. O. (2015). Dysrhythmia of timed movements in Parkinson's disease and freezing of gait. *Brain Research*, *1624*, 222–231.
79. Factor, S. A., & Weiner, W. J. (2008). *Parkinson's disease. Diagnosis and clinical management*. Demos Medical Publishing.
80. Allman, M. J., & Meck, W. H. (2012). Pathophysiological distortions in time perception and timed performance. *Brain*, *135*, 656–677.
81. Jones, C. R., & Jahanshahi, M. (2014). Motor and perceptual timing in Parkinson's disease. *Advances in Experimental Medicine and Biology*, *829*, 265–290.

17496632, 2022, 1, Downloaded from https://nyaspubs.onlinelibrary.wiley.com/doi/10.1111/nyas.14878 by Colorado State University, Wiley Online Library on [06/05/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

82. Puyjarinet, F., Bégél, V., Gény, C., Driss, V., Cuartero, M.-C., Cochen de Cock, V., Pinto, S., & Dalla Bella, S. (2022). At-home training with a rhythmic video game for improving orofacial, manual, and gait abilities in Parkinson's disease: A pilot study. *Frontiers in Neuroscience*, *16*, 874032.
83. Gil-Gómez, J.-A., Gil-Gómez, H., Lozano-Quilis, J.-A., Manzano-Hernández, P., Albiol-Pérez, S., & Aula-Valero, C. (2013). SEQ: Suitability Evaluation Questionnaire for virtual rehabilitation systems. Application in a virtual rehabilitation system for balance rehabilitation. *Proceedings of the 7th International Conference in Pervasive Computing Technologies in Healthcare – ICST* , 335–338.
84. Green, C. S., & Bavelier, D. (2003). Action video game modifies visual selective attention. *Nature*, *423*, 534–537.
85. Nouchi, R., Taki, Y., Takeuchi, H., Hashizume, H., Akitsuki, Y., Shigemune, Y., Sekiguchi, A., Kotozaki, Y., Tsukiura, T., Yomogida, Y., & Kawashima, R. (2012). Brain training game improves executive functions and processing speed in the elderly: A randomized controlled trial. *PLoS One*, *7*, e29676.
86. Zagala, Z., Foster, N., & Dalla Bella, S. (2021). Commentary: A tablet-based assessment of rhythmic ability. *Frontiers in Psychology*, *12*, 607676.
87. Iversen, J. R., & Patel, A. D. (2008). The Beat Alignment Test (BAT): Surveying beat processing abilities in the general population. *Proceedings of the 10th International Conference on Music Perception and Cognition*, 465–468.
88. Dotov, D. G., Cochen de Cock, V., Gény, C., Ihalainen, P., Moens, B., Leman, M., Bardy, B., & Dalla Bella, S. (2019). The role of interaction and predictability in the spontaneous entrainment of movement. *Journal of Experimental Psychology: General*, *148*(6), 1041–1057.
89. Cochen de Cock, V., Dotov, D. G., Damm, L., Lacombe, S., Ihalainen, P., Picot, M. C., Galtier, F., Lebrun, C., Giordano, A., Driss, V., Gény, C., Garzo, A., Hernandez, E., Van Dick, E., Villing, R., Bardy, B., & Dalla Bella, S. (2021). BeatWalk: Personalized music-based gait rehabilitation in Parkinson's disease. *Frontiers in Psychology*, *12*, 655121.
90. Grau-Sánchez, J., Münte, T. F., Altenmüller, E., Duarte, E., & Rodriguez-Fornells, A. (2020). Potential benefits of music playing in stroke upper limb motor rehabilitation. *Neuroscience & Biobehavioral Reviews*, *112*, 585–599.
91. Hove, M. J., & Keller, P. (2015). Impaired movement timing in neurological disorders: Rehabilitation and treatment strategies. *Annals of the New York Academy of Sciences*, *1337*(1), 111–117.
92. Corriveau, K. H., & Goswami, U. (2009). Rhythmic motor entrainment in children with speech and language impairments: Tapping to the beat. *Cortex*, *45*(1), 119–130.
93. Corriveau, K., Pasquini, E., & Goswami, U. (2007). Basic auditory processing skills and specific language impairment: A new look at an old hypothesis. *Journal of Speech, Language, and Hearing Research*, *50*(3), 647–666.
94. Allman, M. J., Pelphrey, K. A., & Meck, W. H. (2012). Developmental neuroscience of time and number: Implications for autism and other neurodevelopmental disabilities. *Frontiers in Integrative Neuroscience*, *6*, 7.
95. Noreika, V., Falter, C. M., & Rubia, K. (2013). Timing deficits in attention-deficit/hyperactivity disorder (ADHD): Evidence from neurocognitive and neuroimaging studies. *Neuropsychologia*, *51*(2), 235–266.
96. Flaugnacco, E., Lopez, L., Terribili, M., Montico, M., Zoia, S., & Schön, D. (2015). Music training increases phonological awareness and reading skills in developmental dyslexia: A randomized control trial. *PLoS One*, *10*(9), e0138715.
97. Schön, D., & Tillmann, B. (2015). Short- and long-term rhythmic interventions: Perspectives for language rehabilitation. *Annals of the New York Academy of Sciences*, *1337*(1), 32–39.
98. Hardy, M. W., & Lagasse, A. B. (2013). Rhythm, movement, and autism: Using rhythmic rehabilitation research as a model for autism. *Frontiers in Integrative Neuroscience*, *7*, 19.
99. Sharda, M., Tuerk, C., Chowdhury, R., Jamey, K., Foster, N., Custo-Blanch, M., Tan, M., Nadig, A., & Hyde, K. (2018). Music improves social communication and auditory–motor connectivity in children with autism. *Translational Psychiatry*, *8*(1), 231.
100. Hutchinson, J. M., & Norris, G. M. (1977). The differential effect of three auditory stimuli on the frequency of stuttering behaviors. *Journal of Fluency Disorders*, *2*(4), 283–293.
101. Frankford, S. A., Heller Murray, E. S., Masapollo, M., Cai, S., Tourville, J. A., Nieto-Castañón, A., & Guenter, F. H. (2021). The neural circuitry underlying the "rhythm effect" in stuttering. *Journal of Speech, Language, and Hearing Research*, *64*, 2325–2346.
102. Miendlarzewska, E. A., & Trost, W. J. (2014). How musical training affects cognitive development: Rhythm, reward and other modulating variables. *Frontiers in Neuroscience*, *7*, 279.
103. Frischen, U., Schwarzer, G., & Degé, F. (2019). Comparing the effects of rhythm-based music training and pitch-based music training on executive functions in preschoolers. *Frontiers in Integrative Neuroscience*, *13*, 41.
104. Slater, J., Ashley, R., Tierney, A., & Kraus, N. (2018). Got rhythm? Better inhibitory control is linked with more consistent drumming and enhanced neural tracking of the musical beat in adult percussionists and nonpercussionists. *Journal of Cognitive Neurosciences*, *30*(1), 14–24.

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