Abstract

This paper discusses an exciting application of music-based training for neurodevelopmental disorders using digital therapeutics. We focus on Developmental Dyslexia (DD) but examples of applications in other conditions are also presented. Recent theories and empirical evidence suggest that reading deficits in dyslexia stem from poor temporal sampling of speech. Music and rhythmic training is a way to attenuate reading deficits, but designing and conducting training studies is costly. In addition, it remains difficult for people to have access to training protocols. Digital therapeutics offer unprecedented opportunities to implement training protocols, as they engage people in rehabilitative activities via digital mediums, such as mobile applications or motion sensing input devices (i.e., kinect, wii). In addition, it is a powerful means to create game-based training protocols. Gamification has proven capable of keeping users engaged in therapeutic activities more frequently and consistently than classical therapies.

1. Timing and rhythm in Developmental Dyslexia

Developmental Dyslexia (DD) is a very common neurodevelopmental disorder that affects between 5% to 17% of school-aged children (Habib & Giraud, 2013). People with DD suffer from inaccurate word recognition, poor spelling capacities and difficulties in phonological decoding sound-based (Ramus, 2003; Snowling, 2001). These troubles do not stem from limited education and socio-cultural opportunities, a deficit in general intelligence, or a lack of motivation (Démonet, Taylor, & Chaix, 2004; Snowling, 2001). Yet, troubles beyond phonology have been reported in DD, such as motor and sensorimotor control (Chaix et al., 2007; Ramus, 2003), attention (Stoet, Markey, & López, 2007), working memory (Beneventi, Tønnessen, Ersland, & Hugdahl, 2010), and executive functions deficits (Lewandowska, Milner, Ganc, Włodarczyk, & Skarżyński, 2014). In spite of the fact that DD is heterogenous (Chaix et al., 2007), it has been proposed that reading difficulties encountered by dyslexic stem from timing and rhythm deficits (e.g., the Temporal sampling framework, Goswami, 2011; Leong & Goswami, 2014). Dyslexics have difficulties in timing and rhythm perception (Casini, Pech-Georgel, & Ziegler, 2016; Goswami, Huss, Mead, Fosker, & Verney, 2013; Huss, Verney, Fosker, Mead, & Goswami, 2011). For example, they are less accurate than controls in tasks consisting in classifying short and long durations (Casini, Pech-Georgel, & Ziegler, 2016) or detect shifts in regular sequences (Huss, Verney, Fosker, Mead, & Goswami, 2011). They are also more variable and less precise when asked to synchronize their movements with auditory sequences such as a metronome or music (Leong & Goswami, 2014; Thomson et al., 2006). These timing and rhythm deficits are supposed to encroach into reading and language skills (Goswami, 2011). Language is organized as a rule-based systems in which the appropriate sequencing and timing of events is critical (Schwartze & Kotz, 2013). Poor predictive temporal sampling and coding of events, affecting the treatment of phonological information, are central to recent theories of DD such as the temporal (Goswami, 2011). It is also in line with other accounts of DD, such as attention-based theories (Facoetti et al., 2010; Hari & Renvall, 2001; Lallier & Valdois, 2012) that postulate that dyslexic cannot efficiently shift their attention in rapid and sequential stimulus sequences, or the cerebellar hypothesis, in which deficits in automatized skills are thought to be central to DD (Nicolson & Fawcett, 2019; Pernet, Andersson, Paulesu, & Demonet, 2009).

2. Timing and rhythm in other conditions

Interestingly, impaired timing and rhythm is not selectively a hallmark of DD, as timing deficits are found across other neurodevelopmental disorders affecting language and reading skills, such as stuttering (Falk, Müller, & Dalla Bella, 2015; Wieland, McAuley, Dilley, & Chang, 2015) and specific language impairment (Przybylski et al., 2013). Tierney and Kraus (2013) showed that correlations between synchronization with a metronome and reading exist in typically developing adolescents. This further suggests that timing and rhythmic abilities play a major role in language and speech development. Timing and rhythm are also impaired in other neurological and neurodevelopmental disorders such as Parkinson's diseases or ADHD and potential links between timing and rhythm deficits and other impaired functions (motor control, cognitive skills) have been highlighted (Benoit et al., 2014; Grahn & Brett, 2009; Puyjarinet et al., 2017).

3. Music and rhythmic therapy for Dyslexia

Given the tight link between rhythmic skills and DD, it is not surprising that there have been several attempts to implement music and rhythmic training in dyslexia. In 2008, Dr. Besson's team assembled two groups of 8-year old's and assigned each group to a music or painting program (each designed to be engaging and motivating). The results showed that 6 months of musical learning increased children's ability to discriminate between height variations in language and read phonologically complex words (Molinaro et al., 2016).

The direct link between rhythmic skills and reading was first explored in a 1951 paper by Mira Stamback (Stambak, 1951). A 2009 study with 1,028 children aged 5 and 6 years old used the rhythmic patterns established by Stamback to show that the simple reproduction of rhythm was predictive of reading in early grades (Dellatolas et al., 2009). Another study that looked specifically at dyslexic children found that they improved their reading skills, phonological processing and written transcription skills after a 15 week program that trained rhythm and timing skills (pitch skills were inconsequential) (Overy, 2003).

As a follow-up to their 2011 experiment with non-dyslexic children, Dr. Besson's team placed dyslexic and non-dyslexic children into a musical training protocol or a visual arts training program. They measured the impact of these programs on sensitivity to voice onset time by having the children watch cartoons on mute, playing them a series of syllables of different durations and measuring their brains' responses to the audible stimulus (the cartoons were meant to distract them). Prior to the training programs the team had found that the brains of the dyslexic children were less sensitive to variations in the duration and timing of stimuli but did not differ from controls in detecting height (pitch) variations (Chobert et al., 2012). After the six month program dyslexic children's perception of voice onset time had normalized and their perception of sound duration had improved (Chobert & Besson, 2012).

A study by Dr. Nina Kraus' team found that one year of musical instruction for 8 year old children benefited the rhythmic skills of those considered at risk of a learning disability significantly more than controls (Slater et al., 2013). Two very interesting studies looked at dyslexic and dysphasic children's ability to identify incorrect syntax in sentences before and immediately after listening to a rhythmic primer and found a significant improvement (Przybylski et al., 2013; Bedoin et al., 2016).

In another study that compared systematic rhythmic training to visual arts practice, musical training was found to have a more significant effect on auditory attention and several auditory perception and reproduction skills (Flaugnacco et al., 2015). The visual arts program was designed to promote visual-spatial skills, dexterity and creativity through painting whereas the music program emphasized use of percussion, syllabic rhythms (ta..ta..ti.ti.ti.) and rhythmic body movements accompanied by music. In the end, the rhythm production ability was the best predictor of performance in phonemic fusion and segmentation tasks which are used in assessments of dyslexia to provide measures of phonemic awareness.

Using this scientific insight, Dr. Michel Habib and his colleagues in France proposed new methods for using music to rehabilitate learning differences. The core of their method was the integration and consistent practice of multi-modal musical interactions that could activate brain plasticity and achieve the anatomical changes observed in the brains of musicians (Commeiras et al., 2014). This also allowed them to target cognitive and executive functions influenced by the same type of practice. The method was intended as a complement and not a substitute to any requisite speech therapy work. Dr. Habib and his team compared their method to a visual arts program over 6-weeks and found improvements in phonemic awareness and working memory (Millet et al., 2015). A year later they tested the method in two different settings, an intensive 3-day program that met 6 hours per day, and a 6-week program that met 4 times a week for a total of 3 hours per week (Habib et al., 2016). The children who participated were severely dyslexic. In both settings, those who practiced music improved their abilities to perceive the duration of sounds and categorize phonemes. The longer setting also measured reading, phonemic awareness and auditory attention. They saw improvements in all three and found that these effects were maintained up to 6 weeks after the program had ended.

4. Music training and music therapeutics in other conditions

The application of music to therapeutic practices was in part inspired by studies that compared the brain and cognitive development of musicians and non-musicians. One early study identified above average development in musicians' corpus callosum, the mass of white fibers uniting the left and right hemispheres of the brain. Authors speculated that the intensive two hand coordination exercise of playing an instrument caused a massive flow of information between the two hemispheres (Schlaug et al., 1995). A few years later another study discovered that areas in the left hemisphere of the brain involved in auditory perception and the assignment of meaning to sound were more developed in musicians (Schlaug, 2001). More recently, diffusion tensor imaging or tractography, which can measure the diffusion of water molecules, has allowed neuroscientists to visualize the path and directionality of fibers in the brain. Using this technology, one group of researchers found that cortical thickness between musicians and non-musicians differed most in the frontal-temporal areas, and that activity in the two regions were more highly correlated among musicians (Bermudez et al., 2008). Such stark contrasts in brain development resonated with research that compared cognitive abilities between the two groups. Studies conducted with large groups of children concluded that musical training improved verbal IQ, motor learning, non-verbal reasoning, and executive functions (Forgeard et al., 2008; Moreno et al., 2011). The importance of music in verbal cognition was highlighted in research by Dr. Nina Kraus which identified the common processes underlying verbal and "musical" language and highlighted the effect of musical learning on the auditory characteristics of speech (Kraus & Chandrasekaran, 2010). Dr. Mireille Besson expanded on this and focused on the idea that improving the perception of music could improve the perception of speech (Besson et al., 2007; Besson, Chobert, & Marie, 2011).

5. Cognitive Consequence of Gaming

In this paper, we propose that implementing promising musical and rhythmic training protocols can be done via digital games. Gaming has proven capable of keeping users engaged in all sorts of activities frequently and consistently, but it is only useful in therapeutic contexts when players are able to transfer new skills outside of gaming environments. The theory of the specific transfer of general skills suggests that the best way to transfer skills out of a training environment is with repeated exercise of that skill, immersion in a variety of contexts, and increasingly difficult challenges (Singley & Anderson, 1989). The field of cognitive consequence gaming seeks to empirically determine how theories of skill transfer apply to gaming (Mayer, 2014). Most recently, studies have examined games that claim to train executive functions and other cognitive skills. A 2018 study that looked at the self-described "brain training" application Lumosity ran two experiments, one short-term study where 72 participants aged 18 to 30 played for 3 hours over 2 weeks and a long-term study where 51 participants played for 20 hours over 16 weeks. They found that players improved in their application of the targeted cognitive skills within the Lumosity games, but that they were unable to transfer these levels of performance to other outside tests (Bainbridge & Mayer, 2018). Cogmed, a game that claimed to train executive functions, was found to produce short-term positive effects that did not generalize. It was able to train visuo-spatial working memory but had no effect on verbal working memory (Melby-Lervåg & Hulme, 2013). In the area of popular consumer games, Tetris was found to improve the spatial skills involved in mental rotation with 2-d but not 3-d shapes, and with Tetris shapes only (Pilegard & Mayer, 2008). Authors concluded that despite continuous training, skill improvements did not transfer because the games failed to provide diverse contexts which would have forced players' to develop the cognitive resources to make their skills generalizable . The most extensively studied games have been first person shooters. These types of games were found to be capable of improving players' perceptual attention skills (Bediou et al., 2018). Critically, their core mechanic repetitively rewarded and punished players based on their perceptual attention skills, and did so in innumerable contexts (e.g. objects, environments, stories, social) (Wang et al., 2016). Some authors highlighted the importance of these games' intuitive, discovery based systems which afforded players the ability to avoid overwhelming frustration and stay engaged longer (Powers & Brooks, 2014). Researchers used lessons from this field to build games with the explicit purpose of inducing cognitive changes. A game called Neuroracer dynamically adapted its difficulty to players' skill levels and reduced multitasking costs in older adults (aged 60 to 85) below the levels of those achieved by untrained 20 year old's. The effect lasted for up to six months () Anguera et al., 2013). Teams at the University of California, Santa Barbara and New York University were able to significantly improve children's' mental shifting ability with a game called " All You Can ET " in which players fed aliens based on rules that constantly changed (Parong et al., 2017). These authors highlighted the importance of strategically balancing focus on the cognitive task at hand with diverse and engaging contextual elements.

6. Digital Music Therapy

Reading disabilities are most effectively treated early in a child's life, preferably while they are still learning to read. Music therapy delivered through digital games is promising because children of all ages actively engage in digital play. Thus, digital music therapy games have the potential to frequently engage children in therapeutic activities outside of formal treatment settings. Ultimately, the elements that make digital cognitive training effective are the same ones that make neurologic music therapy effective. The Handbook of Neurologic Music Therapy written by Dr. Michael Thaut set the elementary rules for learning-oriented motor-therapy: repetition, feedback, cueing, task orientation (instruction), active learning, ecological validity (functional relevance), shaping (adaptive difficulty) and motivation (Thaut & Hoemberg, 2014).

Repetition, functional relevance and adaptive difficulty are all paramount to skill acquisition. Designers spend countless hours engineering intuitive feedback, instruction, cueing and active learning mechanisms for high quality games. Similarly, therapists tailor these elements into their session with remarkable consideration. Both mediums employ a myriad of different strategies to keep individuals motivated but an engaging musical element is always among them. To combine these two technologies into a therapeutic solution that supports the treatment of reading disabilities, rehabilitative practice should target players' perception of the temporal aspects of sound. Earlier sections described why rhythmic training is suggested as the most effective method to accomplish this. The objective in rhythmic training is for the player achieve synchronization (entrainment) with a beat or its period (time between beats). A player's ability to entrain with complex rhythmic patterns reflects a higher ability to perceive things in time (temporal perception). However, to achieve long-term improvements in temporal perception the training must be capable of activating plastic changes in the brain. The earlier discussion around the impact of music echoes a robust literature that supports the use of multimodal interaction to activate brain plasticity and enhance perception in the long-term (Shams & Seitz, 2008). In one direction, repetitive physical movement helps refine anticipation by tying spatial distance to the period of a beat. In the opposite direction, anticipation of audible cues primes motor neurons for more effective movement (Nozaradan et al., 2011). This approach leverages the reflexive link between auditory and motor neurons to gradually strengthen cortical connections between the relevant areas of the brain (Thaut, McIntosh, & Hoemberg, 2015). Thus, a therapeutic game should elicit a physical response from players using audible cues while simultaneously allowing for players to adjust or otherwise correct their physical interactions using audible feedback. This feedback process, otherwise known as sonification, is critical for effective acquisition of audio-motor skills (Wolpert, Daniel M., Diedrichsen, & Flanagan, 2011).

The next step would be to design an experience that meets the criteria necessary for skill transfer in digital games. Digital platforms cannot engage the players' senses as directly as instrumental play with another human being. Hence, the importance placed on context diversity in the earlier section on cognitive consequence gaming. In this regard, "context" in gaming is akin to functional relevance in neurologic music therapy and should be understood to include everything from visual and audible aesthetics to rules of play and interaction diversity referred to as game aesthetics and mechanics, respectively (Hunicke, Leblanc, & Zubek, 2004). The utilization of diverse game mechanics is an effective way to engage players in active learning and expose them to different applications of the target cognitive skills. Diversity is also important when considering game aesthetics and interactions. Engaging the senses through different visual, audible and tactile elements (i.e. vibration, device tilt, positioning, or movement) should avoid specialization to a limited set of gaming environments and interactions. With all of this in mind it is important that repetition remain a priority and diversity be appropriately sequenced with difficulty and mastery. The prioritization of repetition implies targeting the same cognitive skill (in this case temporal perception) constantly. However, achieving entrainment with rhythmic sequences while splitting focus with another task reflects greater ability because it reduces the mental resources available to achieve synchronize with a rhythm. These additional cognitive tasks may also be part of a "diverse context" and contribute to functional relevance by allowing the player to experience synchronization with music where they previously might not have been able to due to distractions.

There is one more set of considerations that is critical to the aesthetic design of digital musical therapy games. These are the alternative cognitive strategies afforded by the aesthetic designs themselves. For example, a 2017 study that looked at existing musical games and examined their potential for rhythmic training found most games relied heavily on reactions to visual cues rather than prediction via entrainment (Bégel et al., 2017). This afforded the players the opportunity to cheat themselves by avoiding strict exercise of auditory-temporal perception and audio-motor coordination.

7. Mila : Musical Interactions for Learning Activities

This paper has reviewed the foundations and considerations necessary to design an effective digital music therapy game. This last section will present strategies that can be deployed to meet the requirements discussed in the previous section. These will draw from existing video games, music instruction, educational technology, therapeutic insight and applications of artificial intelligence. Since interventions for reading disabilities are most effective in early childhood, these examples can be assumed to apply to a children's game.

Repetition and Motivation

The reason motivation is fundamental to effective therapy is that repetitive practice, which is necessary for skill acquisition, can induce boredom, frustration and eventually complete abandonment. Other elementary rules like adaptive difficulty and content diversity can help improve motivation. However, one motivational advantage that digital games have over most in-person therapy practices is their ability to engage players in discovery, exploration, and storytelling (Swaak, De Jong, & Wouter, 2004). Reading disabilities are life-long conditions and music therapy must be constant in order to support long-term improvements, yet few gaming styles are capable of sustaining players' attention for such time-spans. Among these are online role-playing games that allow players to explore worlds and grow their own customized characters in the process. Many of these also use online components to reinforce engagement whether it be cooperative or competitive. Whatever the design, it is important to strike a balance that satisfies basic psychological needs (such as self-expression and confidence) to a degree that motivates frequent and continuous play but avoids obsessive and unhealthy habits (Przybylski et al., 2009).

Cueing

Game designers of both educational and recreational products use strategies to develop cueing systems that reinforce temporal perception and prediction based on audio cues rather than visual cues. Visual cues can be presented and then iteratively subtracted during testing in order to recognize the values at which each cue is an aid and not a dependency. Players may reach a skill level that allows them to operate completely independent from visual cues. This gradual testing can reveal how visual cues may be used to facilitate active learning and early stage skill acquisition.

Game Mechanics

Resources for music instruction produced by companies such as Hall Leonard, McGraw-Hill or World Music Drumming share an array of games that instructors all over the world use in their classrooms. One excellent source is the Art and Learning Guide funded by the Erasmus+ program of the European Union. These can be used to inspire digital games that 3 demand different strategies to apply temporal perception. Most of these games are social and played in groups. Thus, developers may want to emulate the dynamic nature of these games using in-game characters or animated environments. Mechanics can also leverage diverse aesthetics to layer cognitive challenges atop practice of the target skill. For instance, a player can be asked to perceive a rhythmic sequence, hold it, change it in their mind based on the specific sound cues in the sequence, and then reproduce the modified version with temporal precision. This example adds a working memory task that promotes audio-motor coordination to an exercise that is still dependent on exercising temporal perception. In particular, this strategy can be used to diversify the dimensions of difficulty that players encounter.

Interactions

There are many interaction options available to the widely accessible universe of touch screen devices. These include tapping, tracing, clapping (via microphones), speaking/singing, device tilt, orientation and even device height. Body movement detected by camera was excluded because of latency. It was found that 20ms was enough to affect trained musicians' performance, meaning that beginners are likely to be even more sensitive to this issue. [56] 4 Focusing on period entrainment may be beneficial and provide an easy strategy for adjusting to latency (when it is constant) (Thaut, Miller, & Schauer, 2998). However, barring specialized hardware or specialized lightweight computer vision models, latency will restrict the interactions available to designers. Nevertheless, interaction difficulty mainly deals with motor control, and complex movements that require physical multitasking are common in musical practice. The interaction complexity demanded from players can be increased by requiring brain-teaser-like motion or keeping track of multiple rhythms with different actions (e.g. tapping and voice). Furthermore, it has been shown that it is easier to entrain to the period of a beat using continuous movement rather than discrete movement such that interaction difficulty can be tailored sensitively to players' skill level (Hogan & Sternad, 2007; Smits-Engelsman, Swinnen, & Duysens, 2006). The ability to layer difficulty gradually is very important when 5 engaging players with reading difficulties since they are more likely to struggle with rhythmic tasks.

Feedback

When playing an instrument, players receive feedback through the sound and vibrations of their instruments. A pianist can observe how deeply they press each key and how it correlates to the volume they hear. Digital mediums may not be able to provide feedback in the same way, they are nonetheless capable of providing intricate feedback in other ways. For example, sonification was shown to be more effective than natural sound in correcting rowers' physical performance (Effenberg et al., 2016). Consider a continuous interaction such as the tilt of a device. Each tilt direction can be tied to the volume of a specific continuous soundtrack that makes a discrete noise beyond a tilt threshold. This can be adapted to a temporal perception exercise that provides players continuous feedback to correct their movement and momentum. Furthermore, if it is suggested by the game this type of activity could elicit full body movement to increase player control.

Adaptive Learning

In contrast with in-person therapy, games can measure players' in-activity performance with precision every time they play. This advantage is monumental because precise measurement affords game designers the opportunity to deploy machine learning infrastructure that continuously tests how any given element affects players' performance. The most fundamental element to measure is rhythmic complexity as this provides a direct measure of temporal perception. The earliest guide for rhythmic complexity originated in a benchmark 1951 paper by Mira Stambak (Stambak, 1951). Some instructional resources also provide guidance on rhythmic complexity. These may be good starting points, but the flow of data provided by a widely used digital music therapy game could allow for the creation of a rhythmic topology that provides a continuous path of difficulty. Different paths could emerge that could reflect distinct cognitive profiles for players with respect to rhythmic skills. Machine learning could also afford the opportunity to measure how endogenous elements (interactions, game mechanics or complementary cognitive tasks) accelerate or delay mastery of rhythmic complexity. These measurements provide the building blocks for pacing and remediation that keeps the players engaged in continuous play that is challenging enough to remain entertaining but not so challenging that it leads to abandonment. Ultimately, in game performance metrics can be benchmarked to formal evaluations of temporal perception like the BAASTA and, eventually, measures of reading proficiency (Dalla Bella et al., 2017).

Final Thoughts

The knowledge and technology available is sufficient to begin guided efforts and expand our knowledge of skill acquisition through digital medium. Music provides much of the leverage necessary to combine the best parts of in-person therapy and digital gaming. It is important to learn the lessons of past failures and keep gameplay focused on one cognitive skill under the conditions that maximize the likelihood of that skill transferring out of the gaming environment. Examples like RockBand provide models of success for interactions that were able to change players' perceptual abilities. Examples like Neuroracer provide models of success for adaptive infrastructures that make for effective training. Prioritizing accessibility and developing under the hardware constraints of widely accessible devices is both a creative challenge and potential advantage since it will afford players the chance to engage in rehabilitative activities consistently. The development of remote diagnostic tools for dyslexia is already a large and organized effort. A future in which children play a game on their parents' device to tangibly improve their cognitive abilities may be closer than we think.

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