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PhD School in Psychology – Cognitive Science

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BEHAVIORAL AND NEURAL EFFECTS OF AUDITORY ENTRAINMENT

PhD Thesis

Thesis Booklet

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Synopse of the presented studies and theses

Auditory entrainment refers to the process whereby brain oscillations in the sensory and motor cortices synchronize and mode-lock to the integer ratios of the related frequencies in an auditory stimulus. The significance of auditory entrainment lies in its potential to modify our perceptual and cognitive processes by affecting communication between neural populations. It is a complex process that involves multiple brain networks, which have different roles in beat encoding and auditory–motor interaction (Fujioka, Trainor, Large & Ross, 2009; Nozaradan, Zerouali, Peretz & Mouraux, 2015; Snyder & Large, 2005). The dissertation presents four studies that characterize auditory entrainment from different neural and behavioral perspectives and examine the link between its neural and behavioral effects.

Auditory entrainment takes time to develop. There is evidence that infants can already perceive beat and time intervals correctly, however sensorimotor synchronization (movement alignment to an auditory stimulus) continues to mature during early childhood. There is very few data regarding the maturation of neural entrainment, and compared to adults, children's data are very elusive. More importantly, previous studies did not control for the level of music education and linguistic abilities, which affect timing processing that underlies beat perception. These issues were addressed in the first study that investigated brain oscillations in different frequency bands in children without formal musical training before they started elementary school and learnt to read.

During synchronization of movement to a periodic auditory stimulus, neural activity in sensory and motor areas mutually inform each other in order to facilitate accuracy of movement alignment to the beat. Auditory representation is enhanced, when movement synchronization accompanies the listening to the stimulus. However, existing data covers mostly adults, and studies testing infants and children yielded controversial results. Furthermore, music training and reading abilities bias interpretation. The second study addressed this issue by investigating the developmental trajectory of the neural processes underlying sensorimotor entrainment in pre-reading elementary school children without formal musical training.

It has been suggested that one of the underlying mechanisms responsible for the transfer effect of music is auditory entrainment (Miendlarzewska & Trost, 2014). This idea is based on the fact that music is embedded in a hierarchical structure, which is best processed when the attention entrains to its periodicities. This attentional mechanism nevertheless benefits other skills that share overlapping brain networks or utilize similar attentional processes. Studies investigating the effect of entrainment found that auditory entrainment benefits different cognitive skills. However, studies yielded conflicting results and different forms of entrainment in music training resulted in different types of effects. Furthermore, children in these studies were measured at different ages having different musical background. These issues were addressed in the third study that measured long-term transfer effects of auditory entrainment in three elementary school classes participating in different entrainment-based and a regular music education.

Periodic auditory stimuli can entrain perceptual processes not only within the auditory but also in another domain, such as vision. It implies that when auditory rhythms are perceived simultaneously with visual stimuli either attended or unattended, it can change the way we visually experience the world. Although there is ample evidence that periodic auditory rhythms facilitate visual perception, it is not known how tempo affects visual coupling to the musical beat. In the fourth study, we investigated the effect of auditory beats in different tempi on eye movements during natural viewing.

The following research questions were addressed in the dissertation:

1. *What are the early developmental manifestations of auditory entrainment throughout different frequency bands in 6-7-year old children?*
2. *How do auditory and motor processes underlying sensorimotor synchronization develop in primary school children?*
3. *How sensorimotor entrainment relates to cognitive, linguistic, musical, and social skills, how do they develop over time, and what are the effects of different forms of entrainment?*
4. *How musical beats in different tempi modulate information sampling during natural viewing?*

Thesis point I.: Entrainment-related auditory and motor processes develop at different rates.

In the first study (Maróti, Honbolygó & Weiss, 2019), we examined auditory and motor processes in beta (15-25 Hz) and gamma (28-48 Hz) oscillations in 6-7-year-old children without formal musical training and before learning to read. First, children listened to isochronous tone sequences in three different tempi to investigate motor preparatory processes in the beta frequency band. The three tempi served to investigate whether children's neural responses can adapt to different timing rates. Second, we used isochronous tone sequences with alternating loud-soft accent patterns, in which the loud tone was occasionally omitted. The accent pattern meant to facilitate a binary metrical percept. Contrary to musically trained adults and children, we did not find tempo dependent fluctuations in the beta oscillatory patterns, and beta desynchronization and rebound were not significant suggesting that these processes are still under development. Pertaining to metrical percept, we found similar tendencies to adults. Induced gamma oscillations remained unaffected by occasional tone omissions and peaked after the omitted tone. The results of this study suggest that auditory processing related to metrical perception evolves earlier than processes that involve auditory-motor interactions, such as auditory-guided motor preparatory mechanisms.

Thesis point II.: The lack of auditory-motor coupling impedes sensorimotor synchronization in primary school children.

In the second study (Maróti, Weiss, Asztalos & Honbolygó, 2019), we investigated the maturity of the interaction between auditory and motor processes and measured changes in SS-EPs (steady-state evoked potentials) during tapping synchronization in children from age 6 to 7. Our results revealed SS-EP peaks at the exact stimulus frequency and at its first harmonic corresponding to auditory regions of the brain. These SS-EPs were significant at each measuring time and did not change significantly throughout measurements. However, SS-EPs corresponding to the target tapping rate and its corresponding cross-modulation frequency (the frequency related to the interaction

between auditory and motor processes) were not significant at any measuring times. Because topographical maps revealed activations around motor areas in the brain relative to the time of the individual tapping onsets but not relative to the target tapping time, it suggests that the movement was not synchronized to the auditory stimulus, therefore auditory-motor coupling could not take place. These findings provide further support to the idea that the interaction between auditory and motor areas is not completely developed at the age of 6-7.

Thesis point III.: Entrainment-based music education enhances cognitive skills related to specific elements of the teaching method.

In the third study (Maróti, Barabás, Deszpot, Farnadi, Nemes, Szirányi & Honbolygó, 2018), we compared the transfer effects of two different entrainment-based methods (one with fixed movement patterns, the other with free movement) and a singing-based (control) music education method on cognitive, linguistic musical and social skills in 6-7-year-old children. On the initial assessment, there were no significant differences in performance between the three groups. After 8 months, we found significant improvement for the entrainment-based methods compared to the singing-based method in pitch discrimination, working memory, phonological processing and verbal skills, and the singing-based method improved executive functions more compared to the entrainment-based methods. Additionally, we found significant correlations between sensorimotor entrainment, attention, working memory and phoneme awareness. Finally, we showed that different teaching methods of sensorimotor entrainment (fixed movement vs. free movement) affected cognitive, linguistic, musical, and social skills to a different degree that could be attributed to particular elements of the methods.

Thesis point IV.: Musical beats in different tempi modulate information sampling during natural viewing.

In the fourth study (Maróti, Knakker, Vidnyánszky, Weiss, 2017), we investigated how listening to naturalistic drum grooves in two different tempi as opposed to silence affects

eye movements of participants viewing natural scenes on a computer screen. We used drum stimuli in two different genres (funky and techno) to explore possible effects of different musical styles, and we applied a tapping synchronization test to measure the degree of auditory entrainment. We found that the beat frequency of the drum grooves modulated the rate of eye movements across all participants: fixation durations were increased at the lower beat frequency (1.7 Hz) as compared to the higher beat frequency (2.4 Hz) and no music conditions. Correspondingly, estimated visual sampling frequency decreased as fixation durations increased with lower beat frequency. Regarding musical genre, all participants rated tapping easier to the techno grooves compared to the funky grooves, however, this difference did not show up in the eye movements. Our results imply that the tempo of musical beats commonly affects eye movements during natural viewing, and slow musical beats can retard sampling of visual information by increasing fixation durations.

Discussion

Auditory and motor processes involved in auditory entrainment are influenced by the maturity of the underlying neural networks. The finding that the pattern of beta oscillations and SS-EP responses were different from musically trained adults and older children suggests that age and music training highly affects auditory-guided motor preparatory processes and auditory-motor coupling. Compared to adults, children have a narrower tempo range to which they can effectively synchronize, and this range gradually broadens each year between age 6 and 10 (van Noorden & Moelants, 1999). However, neural activity related to auditory stimulus processing and metrical percept was in a more mature state. Efficient auditory processing is vital in newborn babies for communication. The perception of higher-order periodicities of sound sequences is necessary for speech segmentation and for adapting to different speech rhythms, and previous studies found evidence that the perception of meter is innate (Háden, Honing, Török & Winkler, 2015; Stefanics, Háden, Huotilainen, Balázs, Sziller, Beke, Fellman & Winkler, 2007; Winkler, Háden, Ladinig, Sziller & Honing, 2009).

We have shown that children that received entrainment-based music education showed larger improvement in phonological awareness, vocabulary and in working memory span after 8 months compared to children that received the singing-based method. Our results extend previous research by showing that sensorimotor entrainment has a long-term effect that is different from other aspects of music training. Producing or perceiving a rhythm leads to formation of expectations that facilitates orienting of attentional resources (Bolger, Trost & Schön, 2013). These attentional processes are utilized in language processing and working memory (for a review, see Gruber & Goschke, 2004). We have additionally found that different teaching forms of sensorimotor entrainment resulted in different transfer effects. Fixed movement patterns resulted in more accurate sensorimotor entrainment and greater improvement in phonological speed compared to free movement. Fixed movement patterns as opposed to free movement allows bodily synchronization to be predictable, therefore auditory-motor integration could be processed faster. This temporal advantage might result in better performance in phonological speed and sensorimotor entrainment.

Finally, we have shown that the effect of auditory entrainment can transfer to the visual domain. Eye movements, through which visual information is acquired, became entrained to the auditory stimulus, which entailed a tempo dependent change in fixation duration and in sampling frequency. It implies that when auditory rhythms are perceived simultaneously with visual stimuli, it can change the way we visually experience the world. This idea lies in the theory of dynamic attending, which proposes that our information processing is most effective when our attention is enhanced at times when important input is expected (Jones & Boltz, 1989).

Publications attached to the thesis points:

1. Maróti, E., Honbolygó, F., & Weiss, B. (2019). Neural entrainment to the beat in multiple frequency bands in 6–7-year-old children. *International Journal of Psychophysiology*, *141*, 45-55.

2. Maróti, E., Weiss, B., Asztalos, K., & Honbolygó, F. (2019). Age-related changes of frequency-specific brain responses underlying tapping to the beat. *Proceedings of the 18th PEME PhD Conference*, 193-204.
3. Maróti, E., Barabás, E., Deszpot, G., Farnadi, T., Norbert Nemes, L., Szirányi, B., & Honbolygó, F. (2019). Does moving to the music make you smarter? The relation of sensorimotor entrainment to cognitive, linguistic, musical, and social skills. *Psychology of Music*, *47*(5), 663-679.
4. Maróti, E., Knakker, B., Vidnyánszky, Z., & Weiss, B. (2017). The effect of beat frequency on eye movements during free viewing. *Vision research*, *131*, 57-66.

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