Long-term music training tunes how the brain temporally binds signals from multiple senses

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AUTHOR SUMMARY

Practicing a musical instrument is a rich, multisensory experience involving the integration of visual, auditory, and tactile inputs with motor responses (1). Although it is well-established that music training induces extensive plasticity in auditory and motor systems in the brain, relatively little is known about its possible effects on the temporal binding of signals from multiple sensory sources (i.e., auditory and visual signals) at a neural level. Because musical performance requires precise timing, musical expertise may particularly fine tune the temporal window in which sensory signals need to co-occur to be considered synchronous and bound into a single coherent percept. This study aimed to investigate how long-term piano practicing shapes the neural processes underlying the temporal binding of auditory and visual signals. Our findings highlight the importance of sensory-motor experience (such as piano practicing) in fine tuning how we temporally bind auditory and visual inputs into a unified percept.

We presented subjects with synchronous and asynchronous speech and music as two highly complex classes of stimuli that are linked to different motor effectors (mouth vs. hand). Comparing the effect of musical expertise on the synchrony perception of speech and music allowed us to dissociate (i) generic and (ii) context-specific mechanisms by which piano practicing can influence audiovisual integration. In support of generic mechanisms, music training has been shown to induce changes in the auditory processing system, leading to listening benefits that generalize from music to speech processing (2). Hence, if music training induces a general sensitization to audiovisual temporal (mis)alignment, we would expect a narrower temporal binding window and increased neural audiovisual (a)synchrony effects in musicians for both music and speech. Context-specific mechanisms may rely on internal forward models that are adapted to specific motor tasks and thought to be represented in a neural system involving the premotor cortex and cerebellum (3). Specifically, piano practicing may fine tune a forward model that maps from the motor plan of piano playing onto visible finger movements and concurrent auditory sounds. Thereby, more precise predictions can be made about the relative timings of auditory and visual signals, leading to a narrower temporal binding window in musicians for music but not for speech. Thus, asynchronous music stimuli that violate these predictions should increase neural activation, indicating a prediction error.

Eighteen amateur pianists and nineteen nonmusicians participated in the study. During the psychophysical part of the study, the subjects explicitly judged the audiovisual synchrony of recorded speech sentences and piano melodies at various stimulus onset asynchronies. We estimated each subject’s temporal binding window from the proportion of synchronous responses at different asynchrony levels. As shown in Fig. P1A, the temporal binding window was narrower for musicians than nonmusicians selectively for music but not speech. These results provide behavioral evidence that piano practicing fine tunes audiovisual synchrony perception in a context-specific manner.

Using a standard technique called functional MRI (fMRI), we next investigated how musical expertise shapes the neural mechanisms underlying audiovisual temporal binding and (a)synchrony perception. The same speech and music stimuli were presented synchronously and asynchronously with a temporal offset that subjects reported as asynchronous in 67% of the trials. The subjects perceived the stimuli without being engaged in any explicit task, enabling us to evaluate automatic (a)synchrony effects in motor and premotor regions of the brain without potential interference from motor responses or task-related processes. First, we identified the neural system that evaluates the temporal (mis)alignment of auditory and visual signals by comparing asynchronous and synchronous conditions. Asynchronous

Fig. P1. (A) The proportion of synchronous responses (across subjects’ mean ± SEM) at different levels of asynchrony for speech (Left) and music (Right) in musicians (black, M+) and nonmusicians (gray, M−); from the psychophysical experiment before the fMRI study. (B, i) Asynchrony effects for music that are enhanced for musicians relative to nonmusicians in the left cerebellum, left premotor cortex, and right posterior superior temporal sulcus. (B, ii) Scatter plot depicting the regression of left premotor neural asynchrony effects for music on perceptual asynchrony sensitivity in musicians (black, M+) and nonmusicians (gray, M−).
music and speech signals commonly increased neural activation in a widespread system encompassing the following brain regions: bilateral superior temporal sulci, occipital and fusiform gyri, and premotor and cerebellar cortices. Thus, audiovisual asynchrony of music and speech is detected not only in the sensory processing areas and classical audiovisual integration areas such as the superior temporal sulcus (STS) but also in a premotor-cerebellar circuitry.

Second, we investigated how musical expertise affects neural responses to asynchronous speech and music. Mirroring the context-specific effects seen at the behavioral level, piano practicing modulated neural asynchrony effects selectively for music but not for speech. In line with humans’ generic speech expertise, both musicians and nonmusicians showed similar responses for asynchronous relative to synchronous speech, whereas asynchrony responses to music were amplified in musicians, indicating that the neural asynchrony effects depended on a prior sensory-motor experience (Fig. P1B, i).

The functional relevance of these asynchrony effects was corroborated by additional regression analyses that used a subject’s perceptual asynchrony sensitivity to predict their asynchrony-induced activation enhancement (Fig. P1B, ii). These analyses revealed that the better that the musicians are at distinguishing synchronous and asynchronous music stimuli, the greater that their neural asynchrony effects are as seen in the left cerebellum and premotor cortex. Collectively, our results suggest that prior sensory-motor experience induces activations in a STS–premotor-cerebellar circuitry as a supplementary mechanism to determine the temporal (mis)alignment of auditory and visual signals. Indeed, previous studies have implicated the cerebellum and premotor cortex in motor and perceptual timing, particularly in the millisecond range (4).

In conclusion, our behavioral and fMRI results collectively provide compelling evidence that piano practicing enables more precise predictions regarding the relative timings of auditory and visual signals through the refinement of a context-specific forward model. Asynchronous speech and music stimuli that violate the predictions made by the model elicit an error signal in the STS–premotor-cerebellar circuitry that is fine-tuned through sensory-motor experience. Hence, music training confers a greater sensitivity to synchronicity of auditory and visual signals specific to music stimuli. Collectively, our findings highlight intimate links between sensory-motor experience and audiovisual synchrony perception, where our interactions with the environment determine whether and how we integrate auditory and visual inputs into a unified percept. They show that action production and audiovisual synchrony perception are closely related. In sum, our sensory-motor experience influences how we bind sensory signals to form a coherent percept of our natural environment.