Auditory Pitch Imagery and Its Relationship to Musical Synchronization

Nadine Pecenka and Peter E. Keller

Music Cognition and Action Group, Max Planck Institute for Human Cognitive and Brain Sciences, Leipzig, Germany

Musical ensemble performance requires precise coordination of action. To play in synchrony, ensemble musicians presumably anticipate the sounds that will be produced by their co-performers. These predictions may be based on auditory images in working memory. This study examined the contribution of auditory imagery abilities to sensorimotor synchronization (SMS) in 20 musicians. The acuity of single-tone pitch images was measured by an adjustment method and by adaptive threshold estimation. Different types of finger tapping tasks were administered to assess SMS. Auditory imagery and SMS abilities were found to be positively correlated with one another and with musical experience.

Key words: **auditory imagery; sensorimotor synchronization; musical training**

Introduction

Auditory imagery plays a major role in musical activities.[1] Musicians often hear with their "mind's ear" when they read musical notation, compose, or memorize music, and they rely on musical images to guide their performances. It has been suggested that the ability to form auditory images is important for interpersonal action coordination in musical ensembles.[2]

To date, only a handful of empirical studies have investigated auditory imagery abilities in musicians. Compared with nonmusicians, musically trained individuals have been found to perform better on musical as well as nonmusical auditory imagery tasks, but not on a visual imagery task.[3] In addition, musicians' auditory images of single-tone pitches stored in working memory are more resistant to verbal and visual interference than nonmusicians' images.[4] A recent magnetoencephalography study showed that imagery of short melodies was strong enough to evoke an imagery mismatch negativity in response to an incorrect (external) continuation of the melody only in musicians.[5] Furthermore, studies of musicians with different amounts of musical training have found that auditory imagery abilities improve with increasing musical experience.[6–8]

Whether improvements in auditory imagery ability benefit actual musical performance has received relatively little empirical attention. One relevant study found a positive correlation between pianists' auditory imagery abilities and success at learning novel piano pieces from notation in the absence of auditory feedback.[6] Another study revealed a relationship between auditory imagery abilities and interpersonal coordination during duet piano performance.[2]

The aim of the present study is to investigate the contribution of auditory imagery abilities to basic sensorimotor synchronization (SMS) processes in musicians. We assume that musicians anticipate future sounds that will be produced by their co-performers and coordinate their own upcoming actions based on these predictions. If such predictions rely on auditory images that are active in working memory, a positive correlation should be observed

Address for correspondence: Nadine Pecenka, Max Planck Institute for Human Cognitive and Brain Sciences, Stephanstrasse 1A, 04103 Leipzig, Germany. Voice: 0049-341 99 40 26 27; fax: 0049-341 99 40 113. pecenka@cbs.mpg.de

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between auditory imagery and synchronization skills.

Methods

Participants

Twenty musicians with varying degrees of musical experience were tested (years of playing summed over all instruments: range = 4–66, mean = 26.8, SD = 14.1).

Materials and Procedure

To assess auditory imagery ability, the acuity of single-tone pitch images was measured by (A1) an adjustment method, and (A2) by adaptive threshold estimation (a two-alternative forced-choice task with a weighted up-down method). Participants were required to maintain the image of a target tone over a 10-s silent interval and subsequently (A1) to adjust the pitch of a probe tone to match the pitch of the imagined target tone, or (A2) to compare the pitch of a probe tone to the target pitch.

In both tasks, targets were complex tones with three base frequencies (261.36 Hz, 392 Hz, and 523.25 Hz), presented in random order. In task A1, probe tone start frequencies were chosen randomly within a range of 200–1200 Hz. Probe tone duration was variable, depending on the individuals' adjustment times (range = 2–40 s), and each frequency was adjusted 10 times. Probe tone frequency in task A2 initially deviated from target tone frequency by 4.5%. The number of trials was dependent on how soon each individual's discrimination threshold was reached. A 1-s burst of white noise was presented between trials in both tasks.

SMS ability was assessed with three finger tapping tasks: (S1) on-beat tapping with a stable metronome (500 ms inter-onset interval [IOI]), (S2) on-beat tapping with a tempo-changing pacing signal (400–600 ms IOI range), and (S3) off-beat tapping in antiphase with a stable metronome (500 ms IOI). Tasks S1 and S3 consisted of ten 20-s trials. Task S2 comprised twelve 40-s trials in which tempo transitions followed sigmoidal functions resembling tempo changes found in music. Metronome beats were articulated by a sampled bell sound. Finger-tapping performance was recorded using a MIDI percussion pad. No feedback sounds were delivered.

Results

Auditory Imagery

In the adjustment task (A1), auditory imagery acuity was assessed by computing the mean adjusted difference between target and probe tone frequencies. Probe tone settings differed markedly across individuals, with the majority of individuals' images being mistuned upward (Table 1). In the adaptive threshold estimation task (A2), auditory imagery acuity was assessed by calculating the just noticeable difference (75% correct threshold) for target-probe frequency discrimination (Table 1).

Pitch images were less accurate in the adjustment task compared to the adaptive threshold estimation task, $t(19) = -5.49$, $P < 0.001$, perhaps because of interference caused by the adjustment procedure itself. The two tasks were only moderately correlated [$r(18) = 0.42$, $P = 0.06$], suggesting that they measure different aspects of imagery ability. While both tasks measure the acuity of auditory images, the adjustment task additionally assesses the susceptibility to interference by sounds associated with probe tone adjustments. For each musician, a composite score representing the combination of these different aspects of auditory imagery was computed (by averaging z-transformed single scores). Significant correlations were found with aggregated instrumental experience but not with current amount of practice (Table 2).

Sensorimotor Synchronization

To estimate SMS ability, mean absolute asynchronies (i.e., the absolute time difference

TABLE 1. Summary Statistics for the Two Auditory Imagery and Three SMS Tasks

		Mean	SD	Range
Auditory imagery tasks				
A1	Deviation	10.95	9.64	−0.17–30.89
A2	Deviation	1.34	1.63	0.24–5.04
SMS tasks				
S1	Mean absolute asynchrony	26	15	15–62
	Variance of asynchronies	449	254	175–1362
S2	Mean absolute asynchrony	37	15	21–78
	Variance of asynchronies	1744	1441	699–6332
	Prediction/tracking ratio	0.91	0.17	0.64–1.37
S3	Mean absolute asynchrony	51	41	10–132
	Variance of asynchronies	4794	6241	141–18017

Note: Units in auditory imagery tasks are in % Hz. A deviation of 6% corresponds to ∼100 cent (i.e., one semitone on a Western musical scale). Units in the SMS tasks are in milliseconds.

TABLE 2. Correlations between Musical Experience and Measures of Auditory Imagery and SMS

	Auditory imagery			SMS	
	A1	A2	Composite score	Mean absolute asynchrony	Variance of asynchronies
Years of instrument playing[a]	−0.52*	−0.54*	−0.63**	−0.50*	−0.51*
Current practice[b]	−0.08	−0.18	−0.15	−0.33	−0.30

*$P < 0.05$; **$P < 0.01$; $df = 18$ for all analyses.
[a]Summed over all instruments.
[b]Hours per week.

between each metronome beat and the corresponding finger tap) and variance of asynchronies (i.e., the variability of signed within-trial asynchronies) were computed. The three tapping tasks differed significantly on these two measures: $F(2,18) = 12.39$, $P < 0.001$ for mean absolute asynchrony; and $F(2,18) = 9.91$, $P < 0.01$ for variance of asynchronies. SMS decreased in precision and increased in variability from task S1 through S2 to S3 (Table 1). Performance was positively correlated between the tasks on both measures and therefore composite scores were computed (by averaging z-transformed single scores from the three tasks). Correlations between SMS and musical experience were qualitatively similar to those found for auditory imagery (Table 2).

Task S2 allowed us to analyze the degree to which individuals were predicting versus tracking tempo changes in the pacing signal. Prediction and tracking indices were computed based on lag-0 and lag-1 cross-correlations between inter-tap intervals and metronome IOIs.[9] The lag-1/lag-0 ratio reflects whether individuals were predicting (ratio < 1) or tracking (ratio > 1) ongoing tempo changes. The mean of observed ratios was 0.91, indicating that the majority of individuals predicted tempo changes. Prediction/tracking ratios did not correlate with musical experience. However, participants who engaged in more prediction tapped more precisely in tasks S1 [$r(18) = 0.51$, $P < 0.05$] and S2 [$r(18) = 0.66$, $P < 0.01$].

Relationships between Auditory Imagery and SMS

Individuals who formed more accurate single-tone pitch images tapped with greater precision [$r(18) = 0.63$, $P < 0.01$] and less variability [$r(18) = 0.62$, $P < 0.01$] (Fig. 1). Importantly, this relationship between auditory

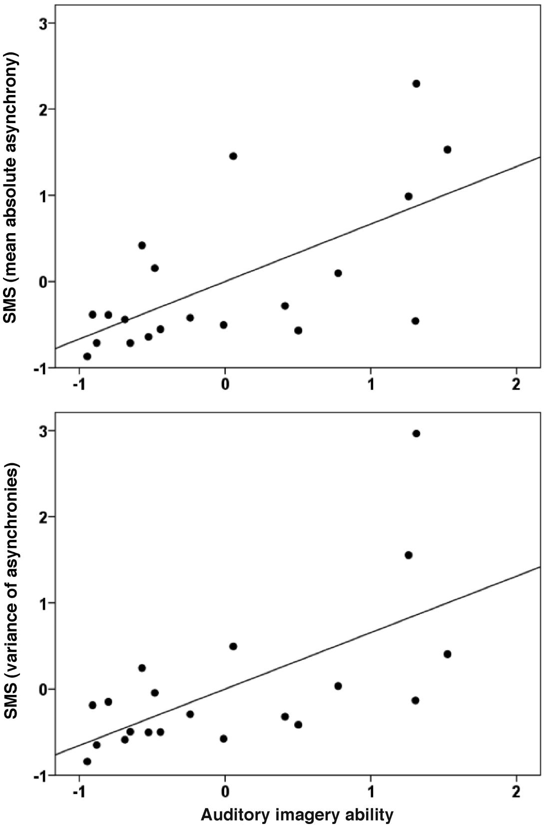

Figure 1. Scatter plots of auditory imagery and SMS composite scores shown separately for mean absolute asynchronies (upper panel) and variance of asynchronies (lower panel).

imagery and synchronization ability was not completely mediated by musical experience. When controlling for experience (years of instrument playing), the correlation is reduced but remains significant for mean absolute asynchrony [$r(18) = 0.48$, $P < 0.05$] and for variance of asynchronies [$r(18) = 0.46$, $P < 0.05$].

Examination of the three tapping tasks separately revealed that correlations with auditory imagery were highest for the more prediction-demanding tapping task: task S2 [$r(18) = 0.67$, $P < 0.01$] versus tasks S3 [$r(18) = 0.56$, $P < 0.05$] and S1 [$r(18) = 0.46$, $P < 0.05$], although these differences in correlation strength were not significant. Furthermore, prediction/tracking ratios were positively correlated with auditory imagery composite scores [$r(18) = 0.47$, $P < 0.05$].

Conclusions

The results of the present study add to a growing body of work showing that auditory imagery ability improves with increasing musical experience. Moreover, this work was extended by showing that individuals who perform well on auditory imagery tasks are more precise and less variable than others when tapping in synchrony with stable and tempo-varying metronomes. Importantly, this relationship between auditory imagery and SMS ability was only partially mediated by musical experience.

The current findings are consistent with the proposal that auditory imagery plays a role in musical synchronization. Ensemble musicians may establish and maintain synchrony by using such imagery to predict the time course of each others' actions. Evidence for a link between auditory imagery and anticipatory processes comes from our finding that individuals with relatively good imagery abilities engaged in more prediction when tapping in time with tempo-changing pacing signals. Further support comes from the finding that the correlation between auditory imagery and SMS abilities was numerically strongest with these signals.

It is an open question whether the observed relationship between pitch-based auditory imagery and SMS accuracy stems from general musical ability (independent of music training), domain-general working memory capacity and intelligence, or the interaction of domain-specific cognitive and motor predictive processes. Ongoing studies are designed to clarify this issue and to investigate other varieties of auditory imagery (e.g., imagery in the temporal domain) that may be relevant to musical synchronization.

Conflicts of Interest

The authors declare no conflicts of interest.

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