

# Perceptual and Cognitive Enhancement With an Adaptive Timing Partner: Electrophysiological Responses to Pitch Change

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When 2 people tap together, they adjust their timing to their partner. We investigated whether having an adaptive partner leads to better pitch perception and cognition (measured by electrophysiological mismatch negativity [MMN] and N400 responses to pitch change) compared with having a nonadaptive partner. In the nonadaptive condition, people tapped along to 3 tones generated by the computer at a fixed 800 ms interonset interval (IOI). In the adaptive condition, the computer continuously adjusted the IOI of the tones in response to the taps of the subject. Twenty percent of the time, the fourth tone was changed in pitch by 1/48th octave. Results showed that both MMN and N400 were enhanced in response to deviant targets with the adaptive compared to nonadaptive partner, suggesting that having an adaptive partner enables better perception and cognitive processing of the contents of a sound sequence.

*Keywords:* entrainment, timing, ERP, MMN, N400

When two people play music together, they need to control the timing of their own actions while also adjusting their actions in response to those of the other (Nowicki, Prinz, Grosjean, Repp, & Keller, 2013; Wing, Endo, Bradbury, & Vorberg, 2014). Having a partner who adapts can be satisfying. Patients playing a percussion instrument with a music therapist who entrains to them may gain a sense of freedom in expressing their emotion and feel empowered by the experience (Bensimon, Amir, & Wolf, 2008; Winkelman, 2003).

In many species, individuals synchronize their movements together, such as birds that fly in formation, fish that swim in schools, and fireflies that flash at the same time (Buck, 1935, 1937, 1988; Partridge, 1982; Weimerskirch, Martin, Clerquin, Alexandre, & Jiraskova, 2001). More rare, but found in humans and a few vocal learning species, is the ability to synchronize movement to a predictable auditory stimulus, such as the beat in music (Patel & Iversen, 2014; Patel, Iversen, Bregman, & Schulz, 2009; Schachner, Brady, Pepperberg, & Hauser, 2009; Trainor, 2015). This ability is referred to as sensorimotor synchronization (SMS) and is defined as “the coordination of rhythmic movement with an external rhythm” (Repp & Su, 2013).

In a typical musical performance, the underlying beat or tempo produced is not completely steady, with deviations arising from several sources, such as internal time-keeping errors (Torre &

Delignières, 2008; Wing & Kristofferson, 1973a, 1973b), and deliberate deviations for expressive purposes (James, Michel, Britz, Vuilleumier, & Hauert, 2012; Rankin, Large, & Fink, 2009; Repp, 1992). Thus, for two or more people to play music together in synchrony, it necessarily involves mutual adjustments of phase alignment and tempo (period) to achieve SMS.

The study of interpersonal synchrony is particularly important because empirical evidence indicates that synchronous movement promotes a sense of group affiliation. For example, walking or singing in synchrony with others increases cooperation, trust, and ratings of likability among participants (Hove & Risen, 2009; Kirschner & Tomasello, 2010; Valdesolo, Ouyang, & DeSteno, 2010; Wiltermuth & Heath, 2009). Synchronous movement to music even leads to enhanced prosocial instrumental helping in infants (Cirelli, Einarson, & Trainor, 2014; Cirelli & Trainor, 2015). Cirelli, Wan, and Trainor (2014) bounced 14-month-old infants to music facing an experimenter who bounced in synchrony with the infant, or in antiphase (but at the same tempo), or at a different tempo from the infant. After this experience, infants were more likely to help the experimenter by retrieving “accidentally” dropped items needed to complete a task if they had bounced at the same tempo as the experimenter (either in phase or antiphase) compared with if they bounced at a different tempo, whether faster or slower. Of interest to the authors, this increase in helping after synchronous bouncing is targeted to the bouncing partner and not to neutral strangers (Cirelli, Wan, et al., 2014), although it does apply to friends of the synchronous bouncing partner (Cirelli & Trainor, 2015).

It has been proposed that three core cognitive-motor skills are needed for people to engage in real-time interpersonal coordination—(a) propensity to synchronize movements, (b) ability to use anticipatory mechanisms during SMS, and (c) ability to divide attention (reviewed by Keller, Novembre, & Hove, 2014), reviewed in more detail below. In the present study, we investigate perceptual/cognitive consequences of playing with an adaptive partner. In particular, during a difficult SMS task, we expect that

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an adaptive virtual partner that adjusts its onset times so as to place its upcoming tones closer to the expectations of a musically untrained partner will reduce resource demands for that untrained partner compared with a virtual partner that does not adjust, leading to enhanced perceptual and cognitive processing of the music.

Humans have a propensity to synchronize their movements across a wide range of situations. For example, when two people swing pendulums while facing each other, they most often coordinate the phase relationship to become in-phase or antiphase rather than out-of-phase, even when they were instructed not to do so (Schmidt & O'Brien, 1997; Schmidt, Richardson, Arsenault, & Galantucci, 2007). Such drifting toward in-phase or antiphase movement is also observed when pairs of people walk on a treadmill (van Ulzen, Lamoth, Daffertshofer, Semin, & Beek, 2008; van Ulzen, Lamoth, Daffertshofer, Semin, & Beek, 2010).

Basic mechanisms of phase correction and period correction during SMS to an external auditory stimulus have been studied most often with finger tapping paradigms because the simplicity of this paradigm makes it easy to attain precise measurement (Repp, 2005; Repp & Su, 2013). Tapping has also been used to study how two people adapt their movements to each other. It has been found that people mutually adjust their intertap intervals to achieve synchrony with each other, even when the people involved cannot see each other (Himberg, 2006, 2008; Konvalinka, Vuust, Roepstorff, & Frith, 2010; Nowicki et al., 2013). This phenomenon is an example of bidirectional coupling in which there is no evidence that either partner is displaying a leading or following role.

Models of SMS can be categorized into linear models (Mates, 1994a, 1994b; Repp & Keller, 2008; Repp, Keller, & Jacoby, 2012; Semjen, Vorberg, & Schulze, 1998; Vorberg & Wing, 1996) and nonlinear dynamic systems models (Large & Jones, 1999; Large & Palmer, 2002; Loehr, Large, & Palmer, 2011; McAuley & Jones, 2003). For both types of models, phase correction and period correction are important components of adaptive processes (Repp & Su, 2013; van der Steen & Keller, 2013; van der Steen, Schwartze, Kotz, & Keller, 2015). Phase correction appears to be an automatic and inflexible response that does not affect the tempo of tapping, whereas period correction is an intentional process that changes the tempo (Repp & Keller, 2004). Phase correction is a mixture of phase resetting to the upcoming stimulus (partner's tone) and to the upcoming tap of one's own tone (Repp, 2005). Period correction appears to be based on perceived asynchronies (defined as the time of the participant's tap minus the time of the corresponding event onset; Schulze, Cordes, & Vorberg, 2005). When systematic tempo fluctuations exceed a given threshold, phase correction is insufficient and period correction is required (van der Steen & Keller, 2013).

SMS with a virtual partner with different anticipatory mechanisms has consequences for timing production. Extending Vorberg's (2005) error correction linear model, Repp and Keller (2008) were the first to examine people's (trained musicians') tapping behavior with auditory pacing signals generated by a computer program (virtual partner) that exhibited different degrees of phase and/or period correction. Repp and Keller (2008) found that when an individual is asked to tap a finger in synchrony with a virtual partner while at the same time trying to maintain the given tempo, synchronization performance (as indicated by measures such as variance and mean asynchronies between the person's taps

and virtual partner's tones) depended on the way the virtual partner adjusted its timing, that is, on the set of phase correction and period correction parameters (Repp & Keller, 2008). For both phase correction and period correction parameters, Repp and Keller (2008) implemented values of 0% to 100% in steps of 10%. When the virtual partner adjusted the next interonset interval (IOI) in the sequence (i.e., phase was modulated) but maintained the tempo-setting period (i.e., period was not modulated), synchronization performance followed a parabolic function with the best performance observed when the next sequence IOI was corrected by 40% or 50% of asynchronies. When the virtual partner adjusted the period but not the phase, average asynchronies were smaller compared with when the virtual partner was nonadaptive (i.e., generating an isochronous tone sequence), across a range of period correcting parameters (10% to 100% of asynchronies). *SDs* of asynchronies, an index of stability (reviewed by Repp & Su, 2013), was larger, however, with period-adjusting than with nonadaptive virtual partners.

Repp and Keller (2008) used 500 ms IOI for the baseline tempo-setting period, which is within the reported range of preferred tempos of 500–550 ms (van Noorden & Moelants, 1999). Research has shown that with longer IOIs, SMS tasks become more demanding and performance gradually deteriorates (Repp & Keller, 2008; Zendel, Ross, & Fujioka, 2011). Participants in the Repp and Keller (2008) study had substantial musical training, and were selected because of their low variability in a previous tapping experiment. Thus, benefits of an adaptive-timing virtual partner for musically untrained individuals during SMS tasks with long IOIs and/or resource demanding situations have not been examined.

SMS with a partner with different anticipatory mechanisms has neurophysiological consequences. Using Repp and Keller's (2008) virtual partner paradigm, Fairhurst, Janata, and Keller (2013) used functional magnetic resonance imaging (fMRI) to measure brain activity during a SMS task. Results revealed that the degree of mutual adaptation in a joint SMS task was associated with activations of different brain regions. With an optimally adaptive virtual partner (virtual partner IOI adjusted in real-time by 25% or 50% of the asynchronies between the computer tone and participant's tap), increased brain activation in ventromedial PFC, hippocampus, SMA, S1/M1, posterior cingulate, and precuneus was identified. These midline regions encompass the default activity mode. Synchronizing with an overly adaptive virtual partner (IOI for the upcoming tone, but not tempo, adjusted by 75% or 100%), led to increased variability in tapping asynchronies and additional increased activation in anterior insula, IFG, superior frontal gyrus (SFG), ventrolateral PFC, and inferior parietal lobe, which are regions associated with cognitive processing, suggesting increased cognitive demand.

SMS with a partner is demanding because one must divide attention between the self and the other, as well as to attend to the relationship between the self and the other (Keller, 2008; Keller, Novembre, & Hove, 2014; Repp & Keller, 2008). The challenge of SMS is further increased at slow tempos (Repp, 2012; Zendel et al., 2011). The virtual adaptive partner's contribution to perceptual and cognitive processing of the music has not yet been studied, but research has shown that detection of pitch changes in tone sequences is more accurate when changes occur at expected than unexpected temporal positions (Jones, Johnston, & Puente, 2006; Jones, Moynihan, MacKenzie, & Puente, 2002). This implies that

an optimal virtual partner might enhance the perceptual and cognitive performance of the participant compared with a nonoptimal virtual partner, and that when real musicians play together in an optimal mutually adaptive way, they are better able to optimally adjust other aspects of their performance. We test this hypothesis in the present paper using electroencephalography (EEG).

The mismatch negativity (MMN) component of the event-related potential (ERP) extracted from EEG is a reliable physiological representation of cortical auditory discrimination processes (Näätänen & Winkler, 1999). MMN reflects a preattentive response to occasional deviations in pitch, duration, loudness, phonemic category, rhythmic pattern, and other abstract features (e.g., Oades & Dittmann-Balcar, 1995; Sussman, Ritter, & Vaughan, 1998), with the peak latency between 150 and 250 ms from the onset of the deviant stimulus. It manifests as a frontal negativity with reversal at the back of the head below the Sylvian fissure, consistent with a source in auditory cortex (for reviews, see Näätänen, Paavilainen, Rinne, & Alho, 2007; Picton, Alain, Otten, Ritter, & Achim, 2000; Schröger, 1998). Of importance for the present study, MMN magnitude to pitch deviants is larger for easier discriminations and larger in musicians than nonmusicians (Brattico, Näätänen, & Tervaniemi, 2001; Desjardins, Trainor, Hevenor, & Polak, 1999; Fujioka, Trainor, Ross, Kakigi, & Pantev, 2004; Koelsch, Schröger, & Tervaniemi, 1999; Tervaniemi, Ilvonen, Karma, Alho, & Näätänen, 1997; Trainor, McDonald, & Alain, 2002).

A later frontal negativity peak around 400 ms (named N400) was first discovered in linguistic contexts (reviewed by Kutas & Federmeier, 2011). Specifically, words that are semantically unexpected or incongruous in a linguistic context (e.g., “The pizza was too hot to cry”) are associated with N400 (Kutas & Hillyard, 1980b). N400 amplitude is also modulated by semantic priming, so that an unexpected word related to the best sentence completion (e.g., “drink” when the expected word is “eat”) elicits a smaller N400 than a completely unexpected word. Within linguistic contexts, N400 effects are found across input modalities, including spoken words and American Sign Language signs, language-like nonwords (van Petten & Rheinfelder, 1995), and even semantic incongruities in drawings, pictures, and environmental sounds (van Petten & Rheinfelder, 1995). A recent study, however, suggests that N400 is elicited by association relationships and not semantic relationships. Rhodes and Donaldson (2008) noted that presence of semantic relationships has often been confounded with associations, where one word calls to mind another based on free association (Postman & Keppel, 1970). By presenting word pairs that shared an association alone (e.g., *traffic-jam*), an association + semantic relationship (e.g., *lemon-orange*), a semantic relationship alone (e.g., *cereal-bread*), or were unrelated (e.g., *bread-tower*), Rhodes and Donaldson (2008) found that modulation of the N400 relative to unrelated word pairs was observed only for conditions involving association (i.e., association only and association plus semantic relationship). The presence of N400 has also been identified with music primes and word targets (Koelsch et al., 2004) as well as with word primes with music targets (Daltrozzo & Schön, 2009). N400 is also larger when attention is heightened (McCarthy & Nobre, 1993) and can be modulated by internally generated events, such as predicting an upcoming sound (Kutas & Federmeier, 2011). Furthermore, N400 can be used as an index for the depth of cognitive processing, such that target tones preceded by

related sounds elicit smaller N400 components than those preceded by unrelated sounds (van Petten & Rheinfelder, 1995). With musical stimuli, Besson, Fäita, and Requin (1994) found late negative components in the 200 to 600 ms range to both standard and deviant targets and that the magnitude of these negative components was significantly larger with unfamiliar than familiar melodies for musically untrained individuals. These studies suggest that N400 may be a good index for cognitive processing of auditory features in unfamiliar tone sequences.

With respect to synchronizing with an adaptive partner, we hypothesized that a good adaptive partner who produces events at expected times will ease the cognitive load of synchronizing, thereby enabling deeper processing of the input stimuli compared with a poor adaptive partner. In the present study, we examined such perceptual and cognitive consequences of temporal adjustment by a virtual partner during SMS task by measuring EEG responses to occasional wrong notes in the stimulus input. We predicted that a good adaptive virtual partner would enhance responses to pitch deviation at both perceptual (measured by MMN) and cognitive (measured by N400) levels.

## Method

### Participants

Eleven right-handed undergraduate students (1 woman, ages 20–22 years) with no hearing deficits participated after providing written informed consent. All participants had no musical training except for music courses taken as part of the school curriculum. Seven additional participants were excluded because of (a) failure to train in the SMS task in 30 min ( $n = 2$ ). Training during the practice session was considered successful when participants produced five or more target tones in sequence, (b) failure to achieve 60% or higher success rate in synchronizing with the virtual partner during test trials ( $n = 4$ ). These participants produced too few trials to reliably measure MMN, or (c) excessive EEG artifacts ( $n = 1$ ). The study was approved by the Future University Hakodate Research Ethics Committee.

### Apparatus

The experiment took place in a sound-attenuating booth (2.55 m in length  $\times$  1.7 m in width  $\times$  1.85 m in height). In the booth, electrical interference was detected only for the noise from the power-line (50 Hz). Presentation of audio stimuli with real-time interval adjustment, transmission of trigger codes to the EEG amplifier and recording of time stamps of key presses on MIDI keyboard (Roland, PC80) were achieved by a program written in MAX 5.0 (Cycling '74) on a computer running Windows XP. Audio stimuli and audio feedback were presented from a loud speaker (Yamaha Soavo 900M). The MIDI keyboard was placed on the arm supports of the reclining chair where participants were seated.

### Stimuli

On each trial, three 110-Hz (A2) tones (leading tones) were presented. Participants tapped along by pressing a key on a MIDI keyboard, and received an auditory feedback tone at 1,046 Hz (C6)

for each tap that was within the range of  $\pm 200$  ms from the time of occurrence of each of the three leading tones. When participants successfully produced all three auditory feedback tones in a trial, a fourth target tone was produced either at 1,046 Hz (standard occurring at 80% of the time) or at 1,061 Hz (deviant occurring at 20% of the time). This represents a small pitch change of 1/48 octave or 1/4 semitone (see Figure 1). All tones were pure tones of 200 ms in duration with 20-ms onset/offset ramps. Sound intensities measured at the position of the participant's ears were 52 decibels (dB) (C) SPL for the 110 Hz tones and 70 dB (C) SPL for the 1,046 and 1,061 Hz tones.

In the nonadaptive condition, the leading and target tones were separated by 800-ms IOIs. In the adaptive condition, the initial IOI was 800 ms, but was adjusted in real-time by the virtual partner algorithm outlined in Repp and Keller (2008). Specifically, we used a period correction parameter of 0.4 and no additional phase correction, defined as follows:

$$t_{n+1} = t_n + T_n + 0.4 \times asy_n$$

$$T_{n+1} = T_n + 0.4 \times asy_n$$

where  $t_n$  is time when  $n$ th tone is produced,  $T_n$  is the current IOI,  $T_{n+1}$  is the next IOI, and  $asy_n$  is the asynchrony between the participant's tap and  $n$ th tone computed by subtracting time when the participant pressed the key for  $n$ th event by  $t_n$ . The asynchrony value was, therefore, negative when participants tapped too early and positive when they tapped too late. This model denotes that in response to asynchrony, the computer makes an immediate phase adjustment and that the amount of phase adjustment also changes the future period. Figure 1 presents a schematic illustration of the phase and period correction response in the adaptive condition.

When participants succeeded in producing a target tone, the subsequent trial started after an interval of 300% of the IOI between the third leading tone and the target tone. When participants did not succeed in producing a target tone, this interval was 400% of the IOI between the second and third leading notes. Because this procedure could lead to considerable drift in the tempo, after every six trials, a "reset" six-tone sequence (tones were 63 dB (C) SPL, 200 Hz; IOIs 800 ms) was played in both the adaptive and nonadaptive conditions. During these reset sequences, no auditory feedback was given for any key presses on the MIDI keyboard.

## Procedure

Participants sat in a comfortable reclining chair in a sound-attenuating booth facing a speaker positioned approximately 1 m

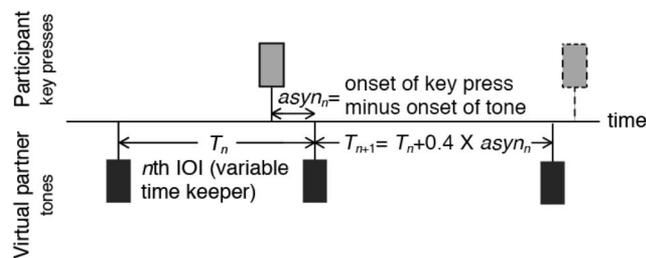


Figure 1. Schematic illustration of the phase and period correction response in adaptive condition.

away. A practice session preceded the experimental session. The experimenter first played several three-tone sequences without any target tone. Participants were then asked to press a key on the MIDI keyboard with their right thumb in synchrony with the three-tone sequences. A schematic illustration of the experimental design is shown in Figure 2.

The experimenter then asked participants to produce the fourth (target) tone. The target tone was self-produced when a MIDI key was pressed within  $\pm 200$  ms from the time of tone occurrence. Auditory feedback was given when this criterion was met. The experimental session began after participants successfully produced five or more target tones in a row. The experimental session consisted of 400 trials in four blocks of 100 trials each, with alternating blocks of the two adaptability types (adaptive, nonadaptive), and with first adaptability type counterbalanced across participants. An oddball paradigm was used in which a random 20% of target tones were pitch deviants.

## EEG Data Recording and Analysis

We recorded EEG with Ag-AgCl electrodes from 32 scalp locations in the 10–20 system (Fz, Cz, Pz, Oz, Fp1, Fp2, AF3, AF4, F7, F8, F3, F4, FC1, FC2, FC5, FC6, C3, C4, T7, T8, CP5, CP6, CP1, CP2, P7, P8, P3, P4, PO3, PO4, O1, and O2) and a Common Mode reference location using a BioSemi Active Two System, keeping impedances below 5 k $\Omega$ . For the purpose of detecting eye movements and blinks, the electrooculogram (EOG) was also recorded using flat-type active electrodes placed 1 cm to the left and right of the external canthi, left and right mastoids, tip of nose, and 1 cm beneath the right eye. EEG and EOG were recorded online at 512 Hz by BIOSEMI amplifiers referencing to the Common Mode electrode, and filtered between 0.01 and 40 Hz. Offline processing of the EEG data was then conducted using Matlab (The Mathworks, USA) and EEGLAB (Delorme & Makeig, 2004). EEG data were re-referenced to the algebraic average of the left and right mastoids, as well as to the nose recordings, and filtered between 1 and 30 Hz. The electrode on the nose was used as a reference to check for the presence of the typical MMN inversion between Fz and the mastoid electrodes that differentiates the MMN from other negative components such as N1 and N2 (see Näätänen et al., 2007 for a review). For the rest of the analyses the mastoids were used as the reference. The data were segmented to 1,000-ms epochs with a baseline starting 200 ms before the onset of the target tone of each trial. Trials that contained ocular movement artifacts, amplifier saturation or high levels of noise were removed using a threshold of 50 micro volts (mean rejection rate was 12%). For each electrode site, EEG single epochs were first corrected relative to their 200 ms baseline by a subtraction procedure and subsequently averaged across trials for each stimulus combination, participant, and channel.

To examine the scalp distribution, in addition to midline locations at Fz, Cz, and Pz, MMN and N400 values were averaged across channels in lateral locations according to selected regions of interest (ROIs)—left frontal (FC1, F3, and F7), right frontal (FC2, F4, and F8), left central (C3, CP1, and CP5), right central (C4, CP2, and CP6), left parietal (PO3, P3, and P7), and right parietal (PO4, P4, and P8)—for analysis of variance. Because adaptivity condition order (adaptive block first vs. nonadaptive block first) yielded no significant main effect or interaction involving adap-

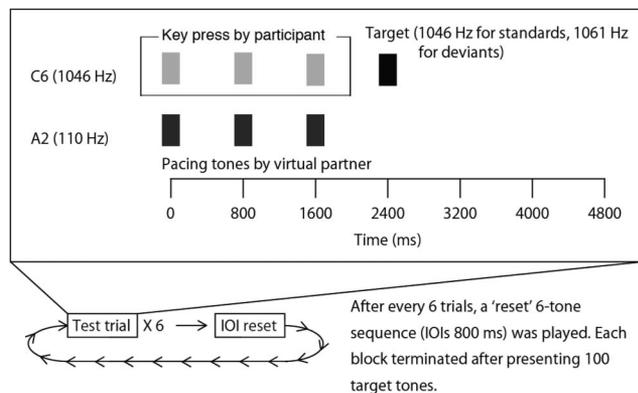


Figure 2. Schematic illustration of the experimental design. SMS with a virtual partner and subsequent target tone presentation.

tivity or target type in preliminary analyses on MMN and N400, the factor adaptivity condition order was excluded from the analyses below.

## Results

### Behavioral Data

Table 1 lists descriptive statistics of SMS performance from trials that met the criterion of obtaining the target tone. Because of technical errors in saving behavioral data in the MAX program, behavioral data from two participants were not available so the analyses are based on the remaining nine participants. The first three behavioral measures in Table 1 are based on commonly reported measures of asynchrony (Repp & Su, 2013). On each

trial, asynchrony is defined as the time of key press by the participant minus the time of tone production by the computer. While mean asynchrony shows whether participants were generally ahead or behind the beats of the adaptive partner, the *SD* of asynchrony is a commonly used index of SMS stability (see Repp & Su, 2013 for review) and mean absolute asynchrony is computed as an index of SMS accuracy (e.g., Pecenka & Keller, 2011). The average proportion of error trials, defined by failure to press the MIDI key within 200 ms on one or more of the three auditory pacing tones, did not differ significantly between adaptive and nonadaptive conditions (mean proportion of trials = .40 (*SD* = .11) in the adaptive condition and .35 (*SD* = .07) in the nonadaptive condition). All reported *p* values were adjusted with Bonferroni corrections.

Not surprisingly, synchronizing the first tap with the computer tone was imprecise as it occurred after a wait of 2,400 ms for the nonadaptive condition and 300% of the last updated IOI (initial value was 800 ms) for the adaptive condition. For the first tone, participants adopted a reactive approach as indicated by positive mean asynchronies (i.e., they pressed the key after pacing tone). Following Miyake, Onishi, and Pöppel (2004) and Repp and Doggett (2007), the proportion of reactive responses was defined as the proportion of asynchronies larger than 100 ms (i.e., they pressed the key more than 100 ms after the tone). The proportion of reactive responses was .43 (*SD* = .10) for the first tone, and this large value is consistent with previous findings that SMS becomes difficult when IOIs exceed about 1,800 ms (Bååth & Madison, 2012; Engström, Kelso, & Holroyd, 1996; Mates, Müller, & Radil, Pöppel, 1994; Miyake et al., 2004), in which case a reactive strategy is effective to reduce variability (Repp & Su, 2013). Participants then switched to predictive SMS for the remaining tones and displayed a typical negative mean asynchrony (i.e.,

Table 1  
Contrast of Key Pressing Performances Between Adaptive and Nonadaptive Conditions

	Adaptive		Nonadaptive		<i>t</i> (8)	<i>p</i> -value
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>		
Mean asynchronies						
Tone 1	47.25	18.65	38.64	31.19	1.34	.66
Tone 2	20.70	4.77	-27.09	21.53	.89	1.00
Tone 3	-39.57	9.27	-49.43	26.96	1.13	.87
Mean absolute asynchronies						
Tone 1	93.57	8.74	89.85	9.51	1.50	.51
Tone 2	35.85	4.98	47.31	11.86	-3.10*	.05
Tone 3	54.55	6.63	59.22	19.78	-.65	1.00
<i>SD</i> of asynchronies						
Tone 1	99.33	5.42	95.23	4.10	1.86	.30
Tone 2	39.13	5.06	48.66	7.99	-5.32**	.003
Tone 3	52.61	6.70	45.34	7.26	2.65†	.09
IOI of key presses						
Tone 1 to 2	716.75	22.62	734.27	15.28	-2.35†	.094
Tone 2 to 3	757.52	32.33	777.66	16.33	-2.19	.12
IOI of pacing tones						
Tone 1 to 2	784.70	30.80	800.00	.00	n/a	
Tone 2 to 3	776.39	31.24	800.00	.00	n/a	
Adaptation index (%)						
Tone 1 to 2	91.40	2.31	91.78	1.91	-.78	1.00
Tone 2 to 3	97.56	1.11	97.21	2.04	.74	1.00

† *p* < .10. \* *p* < .05. \*\* *p* < .01, two-tailed and Bonferroni-adjusted.

pressed the key before the pacing tone), drifting toward shorter IOIs between the second and the third tones. This commonly observed phenomena has been explained by resonance theory (van Noorden & Moelants, 1999) for IOIs less than 1,800 ms (Repp & Su, 2013). Reactive responses at Tone 1 were reflected in positive asynchronies and anticipatory responses at Tones 2 and 3 were evident from negative asynchronies. The adaptation index (Novembre, Ticini, Schütz-Bosbach, & Keller, 2014), obtained by dividing the IOI produced by participant by the IOI produced by virtual partner, quickly approaches to 1 (the value denoting that periods produced by participant and virtual partner are identical) from the first interval (IOI between Tone 1 and Tone 2) to the second interval (IOI between Tone 2 and Tone 3; see Figure 3). A within-subject analysis of variance (ANOVA) on the adaptation index with tone interval pair (IOI between the first and second tones and IOI between the second and third tones) and adaptivity type as within-subject factors showed a main effect of tone interval pair, with the adaptation index increasing from the first interval pair ( $M = .92$ ,  $SD = .02$ ) to the second interval pair ( $M = .97$ ,  $SD = .01$ ),  $F(1, 8) = 54.29$ ,  $p < .001$ ,  $\eta^2 = .872$ . Of importance for our research question, a pairwise  $t$  test showed that the  $SD$  of asynchronies to the second pacing tone was significantly smaller in the adaptive condition than in the nonadaptive condition (see Figure 4),  $t(8) = -5.36$ ,  $p < .005$ . Although the difference did not reach the .05  $p$  level by pairwise  $t$  tests, shorter IOIs between the first and second tones, as well as between second and third tones, with the adaptive compared with nonadaptive partner ( $p = .094$ ,  $\eta^2 = .408$  for the IOI between Tone 1 and Tone 2 and  $p = .12$ ,  $\eta^2 = .376$  for the IOI between Tone 2 and Tone 3) suggests that the drift toward shorter IOIs was more prominent with the adaptive than nonadaptive partner. Results from all other comparisons between the two adaptivity conditions were nonsignificant after Bonferroni corrections.

### Electrophysiological Data

The standard and deviant grand average waveforms for both adaptivity conditions are shown in Figure 5. Difference waveforms

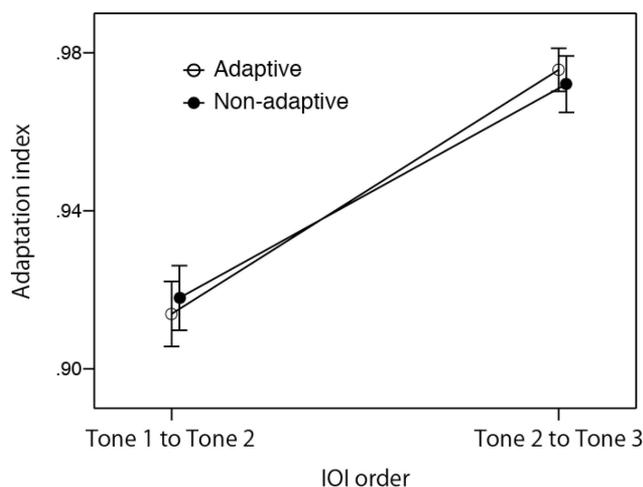


Figure 3. Adaptation index as a function of tone interval and adaptivity type. Error bars indicate SEs.

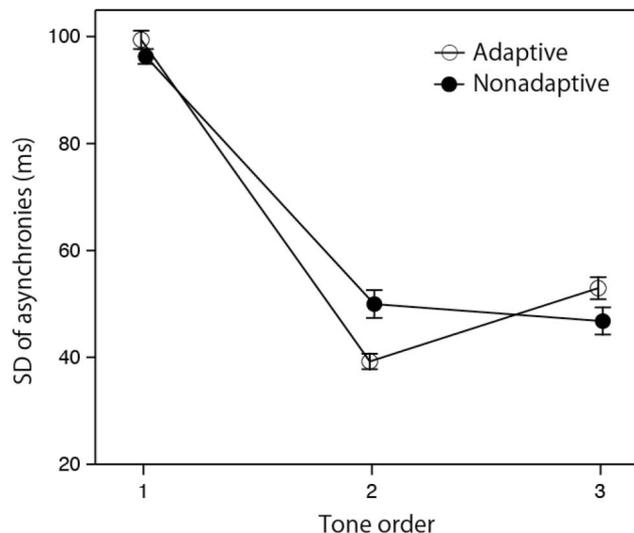


Figure 4.  $SD$  of asynchronies as a function of the three leading tones on each trial and adaptivity type. Error bars indicate SEs.

(deviant–standard) are presented in Figure 6. Preliminary  $t$  tests comparing difference waves (deviant–standard) between nonadaptive and adaptive condition across time revealed enhanced MMN and N400 components in the adaptive condition (see Figure 6 for details). Significant MMN was present in the adaptive condition in the right frontal region, and in both hemispheres for central and parietal regions. N400 components were also identified in both hemispheres in frontal, central, and parietal regions. Note that Figure 7 shows nose referenced difference waveforms for the two conditions to confirm that the first negative response was consistent with MMN and not N200 or any other negativity responses.

Based on visual inspection of the grand average across the 6 ROIs identified in the preliminary analyses and previous reports that used MMN as a response variable (Brattico, Tervaniemi, Näätänen, & Peretz, 2006), average voltage amplitude in 150–250 ms time window was computed as the estimate of MMN. This window for MMN covered all individual negativity peaks obtained from all participants. The average amplitude of the difference wave during this window was calculated for each subject for each region and used as an index of MMN (the dependent variable) in the following analyses. Based on visual inspection of the grand average waveform and previous reports (review by Kutas & Federmeier, 2011) that used N400 as a response variable, N400 was calculated as the average of each waveform between 300 and 600 ms after the target onset (Kutas & Hillyard, 1980a). MMN and N400 components were analyzed by separate within-subject ANOVA with adaptability (adaptive, nonadaptive), target type (standard, deviant), anteroposterior (frontal, central, and parietal) and hemisphere (left, right) as within-subject factors. All  $p$  values reported were adjusted by the Greenhouse-Geisser for ANOVAs and the Bonferroni adjustment for post hoc comparisons using pairwise  $t$  tests.

### Missmatch Negativity

An ANOVA revealed significant main effects of adaptivity condition,  $F(1, 10) = 5.71$ ,  $p = .04$ ,  $\eta^2 = .36$  and target type,

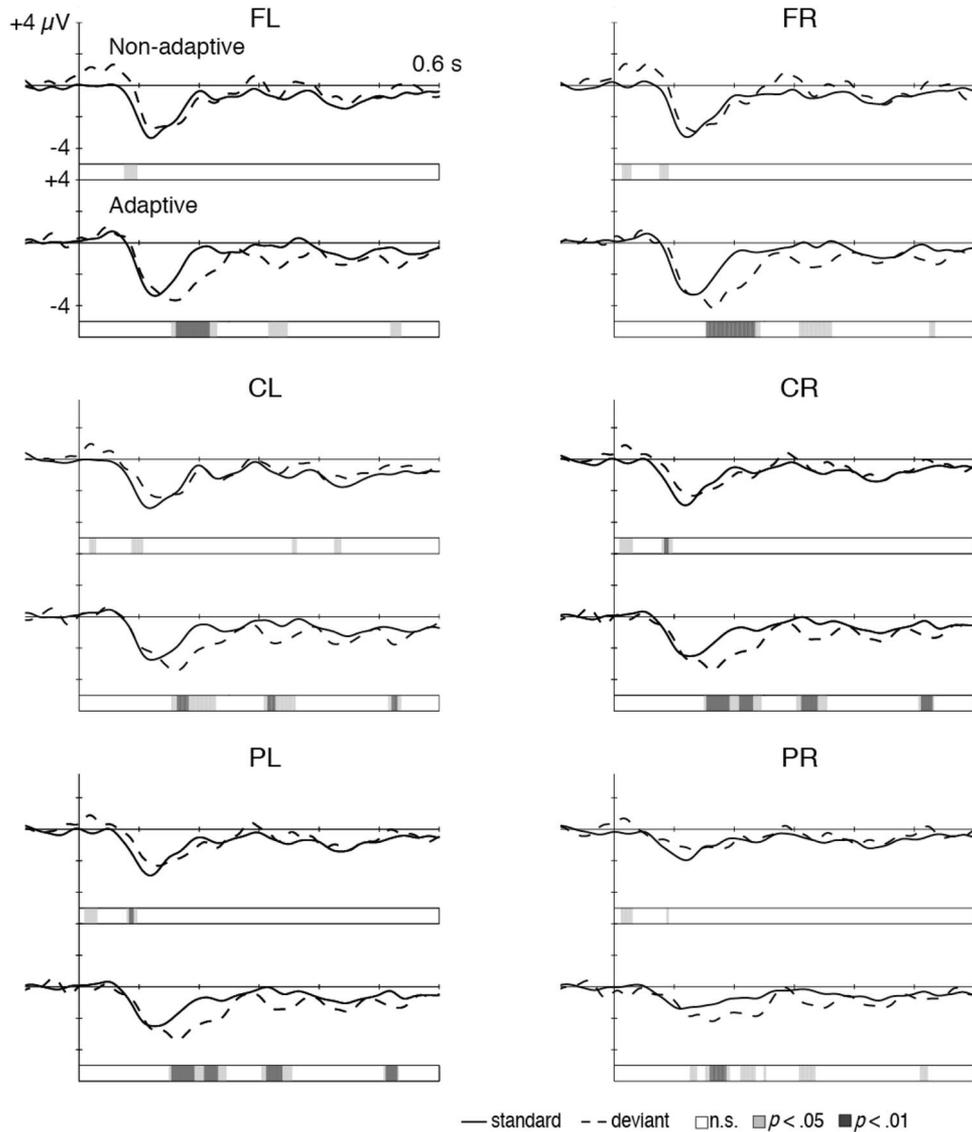


Figure 5. Grand average waveforms of standards (black lines) and deviants (dashed lines) in each condition and in each region. FL, FR, CL, CR, PL, and PR specify Frontal-Left cluster, Frontal-Right cluster, Central-Left cluster, Central-Right cluster, Parietal-Left cluster, and Parietal-Right cluster, respectively. Boxes underneath each waveform indicate the significance level of  $t$  tests conducted on the difference between standard and deviant waves at each time point. The y-axis marks the onset of the target note.

$F(1, 10) = 18.70, p = .002, \eta^2 = .65$ , as well as an interaction of target type X adaptivity,  $F(1, 10) = 5.86, p = .04, \eta^2 = .37$ . Subsequent analyses of simple main effects revealed that MMN amplitude was significantly below zero in the adaptive condition ( $M_{deviant - standard} = -1.31 \mu V, SD = .96, p = .002$ ), but not in the nonadaptive condition ( $M_{deviant - standard} = -.22 \mu V, SD = .94, ns.$ ). Another set of post hoc  $t$  tests comparing simple effects of adaptivity separately for standards and deviants showed that while for standards there was no difference across adaptivity conditions,  $ns$ , for deviants, MMN was larger with adaptive than nonadaptive partners,  $p = .04$ , indicating that the adaptive partner enhanced the encoding of the repeated tone only for deviants. Correlation analyses showed that the IOI

between the 2nd and the 3rd auditory pacing signal was not significantly correlated with the magnitude of MMN,  $p > .05$ .

#### N400

Analyses on N400 revealed a significant target type X adaptivity interaction,  $F(1, 10) = 8.43, p = .02, \eta^2 = .46$ . The N400 effect was significantly larger in the adaptive condition ( $M_{deviant - standard} = -.38 \mu V, SD = .52$ ) than in the nonadaptive condition ( $M_{deviant - standard} = .27 \mu V, SD = .47$ ),  $p = .01$ . Enhancement of N400 was distributed over the scalp and no three way or four way interactions were found.

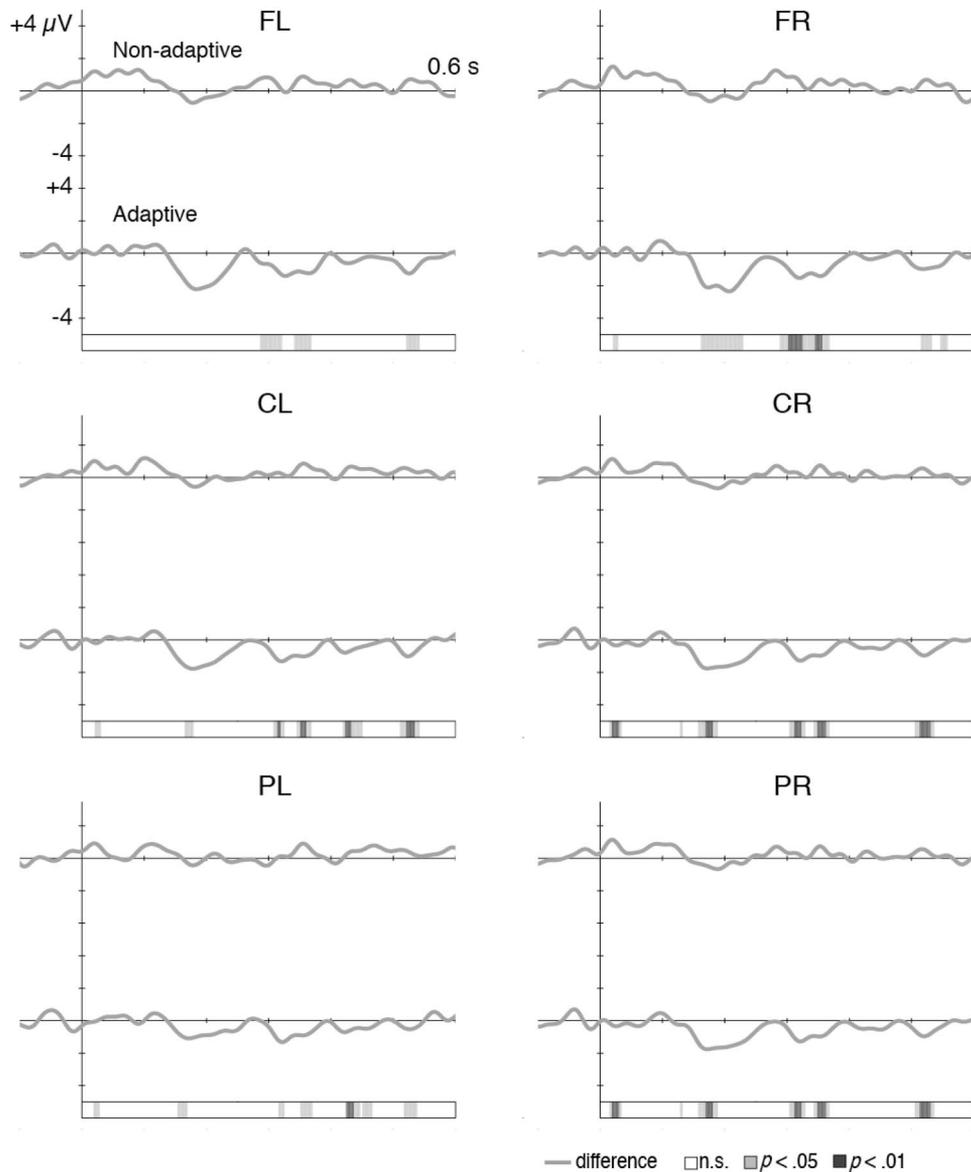


Figure 6. Averaged difference waves (deviant–standard; gray lines) in each condition and each region. FL, FR, CL, CR, PL, and PR specify Frontal-Left cluster, Frontal-Right cluster, Central-Left cluster, Central-Right cluster, Parietal-Left cluster, and Parietal-Right cluster, respectively. Boxes underneath each waveform indicate the significance level of *t* tests conducted on the difference between adaptive and nonadaptive waves at each time point. The y-axis marks the onset of the target note.

Similar analyses of MMN and N400 were also conducted with midline electrodes Fz, Cz, and Pz, but because findings were similar to results found from lateral sites, we have not presented them here.

Pearson's correlation coefficients between MMN and N400 were nonsignificant for each of the six laterality by hemisphere ROIs separately and for the average of the 6 ROIs for both the adaptive condition and the nonadaptive condition (all *ps* > .05).

### Discussion

In the present study, we examined effects of adaptive-timing virtual partners on behavioral and electrophysiological responses

to pitch changes during SMS tasks. Consistent with our hypotheses, both MMN, reflecting sensory encoding, and N400, reflecting cognitive evaluation, were larger when synchronizing with an adaptive than with a nonadaptive virtual partner. Thus, we have shown that synchronizing with an adaptive partner can enhance sensory and cognitive processing. The adaptive partner in this study updated its IOIs for upcoming tones and the subsequent period by adding 40% of the asynchrony between the time of the individual's key press and the time of the adaptive partner's tone onset, a proportion that previous studies have established as leading to optimal synchronization (Repp & Keller, 2008), while the nonadaptive virtual partner did not respond to the asynchronies

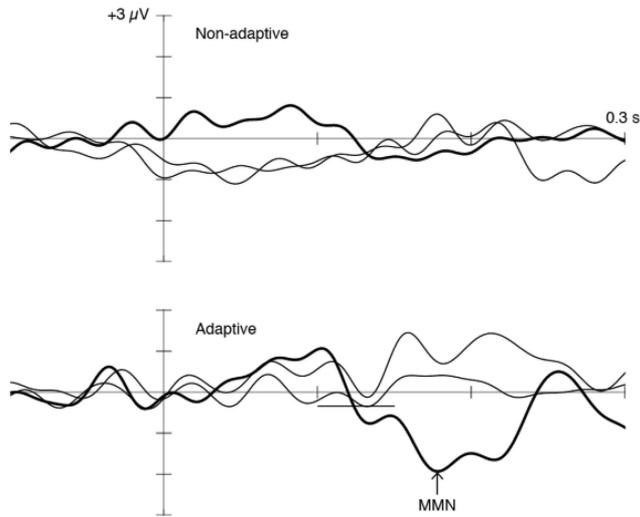


Figure 7. Grand mean difference waveforms (deviant–standard). Thick lines are recordings at Fz and thin lines are recordings at the mastoids. The y-axis marks the onset of the target note.

and its IOI was fixed. Future studies could examine effects of nonoptimal adaptive partners.

Participants were individuals with no music training outside of the regular school curriculum. The SMS task in the present study was difficult for these nonmusicians as shown by high average proportion of errors (35–40%) in achieving successful SMS to the three pacing tones. Most likely because of the long IOIs between the presentation of the target tone and the first pacing tone in the subsequent trial (300% of the most recently updated IOI, approximately  $800 \times 3 = 2,400$  ms), responses to the first pacing tone were reactive. On average, this key press was 47 ms behind the tone of the adaptive virtual partner and 39 ms behind the tone of the nonadaptive virtual partner.

Behavioral measures of the timing of the second and third leading tones suggest that the adaptively timed partner may have facilitated pitch processing of auditory patterns by promoting predictive SMS. According to dynamic attending theory (Large & Jones, 1999; Large & Palmer, 2002; Loehr et al., 2011; McAuley & Jones, 2003), an external periodic pattern, such as the auditory pacing tones in the present study, drives internal periodic attending patterns such that attention is heightened when the external and internal periodic cycles synchronize. In some situations, pitch changes in tone sequences are more easily detected when they occur at expected rather than unexpected temporal positions (Jones et al., 2002, 2006). For the second and the third pacing tones, with IOIs around 800 ms, participants showed typical negative mean asynchronies (i.e., they pressed their key before the pacing tone) drifting toward a 2 Hz frequency (500 ms IOI) as predicted by the resonance theory (van Noorden & Moelants, 1999). Significantly smaller *SDs* of the asynchronies to the second pacing tone with the adaptive compared with nonadaptive virtual partner suggests that SMS became less effortful when the virtual partner adaptively timed the upcoming tone onset and period.

The pitch deviance in this study was small (1/48th octave). Indeed, when the virtual partner was nonadaptive, MMN and N400 were not significantly present. On the other hand, both MMN and

N400 were present in the case of the adaptive partner, and both components were significantly larger in the adaptive than nonadaptive condition. Thus, the EEG results revealed enhanced perceptual and cognitive processing when the partner was adaptive. It is likely that the high demand on cognitive resources required for the difficult SMS task with the nonadaptive virtual partner lowered perceptual sensitivity (reflected in MMN) for detecting changes in auditory features whereas SMS was easier in the case of the adaptive virtual partner, thereby freeing attentional resources that could be applied to processing the pitch.

N400 is typically used as an index for semantic processing in language (Kutas & Federmeier, 2011). However, previous work has also identified that N400 reliably represents the strength of memory associations using word pairs (Rhodes & Donaldson, 2008) and tone and pitch label pairs (Elmer, Sollberger, Meyer, & Jäncke, 2013). With respect to our stimuli, the three leading tones primed an associative expectation with target tones (prime and target being the same pitch in standard trials vs. different in deviant trials). The presence of N400 only in the case of the adaptive partner indicates that participants were able to process this associative relationship only with the adaptive partner, presumably because this made the SMS easier, freeing attentional resources for the associative task.

During the SMS task, people had two goals, which were potentially conflicting (Fairhurst, Janata, & Keller, 2013; Repp, 2008). The first goal was to establish synchronization with the partner. The second goal was to maintain a steady or intended tempo. The analyses of the behavioral data described above suggest that participants in the present study generally focused on establishing synchronization and had a limited sense of being able to maintain the intended tempo. This suggests that our finding of enhanced perceptual and cognitive processing of pitch with the adaptive compared with nonadaptive partner likely resulted from the adaptive partner assisting to establish SMS by placing its tone closer to the predicted time of the participant. However, further studies could examine more directly the separate effects of establishing and maintaining SMS with an adaptive versus nonadaptive partner on sensory and cognitive processing.

After experiencing maintained SMS during joint music making, people from infancy to adulthood become more cooperative, trusting, and show increased liking toward in-group members (Cirelli, Einarson, et al., 2014; Cirelli & Trainor, 2015; Hove & Risen, 2009; Kirschner & Tomasello, 2010; Valdesolo et al., 2010; Wiltermuth & Heath, 2009). The present results show that SMS also makes us become more sensitive to details of the sounds we are jointly producing. In turn, this jointly enhanced perceptual and cognitive processing may increase our sense of affiliation with our synchronization partners.

Many additional questions remain. For example it is likely that in a context of mutual temporal adaptation there may be effects of the performers' knowledge about the music, performers' familiarity with other performers, their use of regulatory strategies to facilitate coordination, and performers' personality traits (Keller, 2008, 2014).

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