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Vocal Interaction During Rhythmic Joint Action Stabilizes Interpersonal Coordination and Individual Movement Timing

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Because work songs are ubiquitous around the world, singing while working and performing a task with a coactor is presumably beneficial for both joint action and individual task performance. The present study investigated the impact of interpersonal rhythmic vocal interaction on interpersonal phase relations and on individual motor timing performance, which was evaluated by a synchronization-continuation paradigm requiring whole-body movement with or without visual contact. Participants repeated the syllable "*tah*" or remained silent in a manipulation of vocal interaction, and they were oriented toward or away from their partner to manipulate visual interaction. Results indicated the occurrence of spontaneous interpersonal coordination, evidenced by interpersonal phase relations that were closer to 0° and less variable when participants interacted both visually and vocally. At the individual level, visual interaction increased the variability of synchronization with the metronome but did not modulate the variability of continuation movements, whereas vocal interaction helped to decrease the variability of synchronization and continuation movements. Visual interaction therefore degraded individual movement timing while vocal interaction improved it. Communication via the auditory modality may play a compensatory role in naturalistic contexts where visual contact has potential destabilizing effects.

Keywords: movement timing, spontaneous interpersonal coordination, synchronization-continuation task, vocal interaction

Work songs that are sung while performing collective tasks with coworkers are a feature of many occupations in traditional cultures around the world (Gioia, 2006). This suggests that group singing, a form of rhythmic vocal interaction, facilitates joint action by promoting accurate and stable interpersonal coordination. Moreover, rhythmic vocal interaction may affect not only interpersonal coordination but also individual task performance, for example, by stabilizing the tempo of sequential actions. In the present study, we investigated the effects of simple rhythmic vocal interaction ("*tah*" syllable repetitions instead of singing) on interpersonal phase relations and individual motor timing performance using a synchronization-continuation paradigm requiring whole-body movement in pairs of individuals.

People spontaneously coordinate their movements with a coactor when they interact visually and auditorily (Demos, Chaffin, Begosh, Daniels, & Marsh, 2012; Richardson, Marsh, Isenhower, Goodman, & Schmidt, 2007; Richardson, Marsh, & Schmidt, 2005; Schmidt & O'Brien, 1997; van Ulzen, Lamoth, Daffertshofer, Semin, & Beek, 2008; Varlet, Marin, Lagarde, & Bardy, 2011; Varlet & Richardson, 2015). Nevertheless, studies investigating whether vocal interaction induces spontaneous interpersonal coordination have produced divergent findings (Richardson et al., 2005; Shockley, Santana, & Fowler, 2003). Shockley et al. (2003) investigated the effects of visual and vocal interaction (conversation) on interpersonal postural coordination using a task that required participants to solve puzzles together. The results revealed spontaneous postural coordination when participants in-

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teracted verbally regardless of whether or not visual information about the other person was available. In another study, Richardson et al. (2005) examined the effect of visual and vocal interaction (conversation) on interpersonal coordination while participants solved a puzzle task at the same time as swinging handheld pendulums. The authors found deleterious effects of vocal interaction on the interpersonal coordination of pendulum swinging.

The apparent discrepancy in results across these studies might be attributable to the difference in relations between vocalizations and types of movement that were analyzed. Postural sway is nonstationary (i.e., characterized by drift) and susceptible to the influence of one's own speech because it is a form of proximal motion, whereas swinging a handheld pendulum is relatively stationary (i.e., it has a regular cyclic rhythmic structure) and less likely to be influenced by one's own vocalization because in pendulum swinging the motion is distal. Even if pendulum swinging is influenced by one's own vocalization, the effects can be deleterious because pendulum swinging has a preferred rhythm that is different from speech rhythm.

Another aspect of these earlier studies that may have contributed to divergent results is that conversation was used as the medium for vocal interaction. Phillips-Silver et al. (2010) identified three factors that are important for emerging spontaneous coordination: The ability to perceive stimuli as rhythmic, to produce rhythmic movement, and to integrate the two using sensory feedback. Although conversation is an intrinsically rhythmic form of joint action, it involves complex temporal structures based on turn-taking and prosodic features that emphasize certain syllables and phrase boundaries rather than reflecting a regular periodic accent structure (Cowley, 1998; Wilson & Wilson, 2005). In addition, rhythmic auditory stimuli can serve to stabilize sensorimotor coordination via a process known as *anchoring* (Byblow, Carson, & Goodman, 1994; Fink, Foo, Jirsa, & Kelso, 2000; Kudo, Park, Kay, & Turvey, 2006). These considerations raise the possibility that other forms of rhythmic vocal (i.e., auditory) interaction induce spontaneous interpersonal coordination more strongly than conversation does.

Interpersonal visual interaction affects not only interpersonal phase relations but also individual motor timing control (Miyata, Varlet, Miura, Kudo, & Keller, 2017; Oullier, de Guzman, Jantzen, Lagarde, & Kelso, 2008; Varlet et al., 2011). The preferred frequency of finger tapping, for instance, is influenced when seeing another individual producing finger taps at a different tempo (Oullier et al., 2008). Moreover, interpersonal visual interaction has been reported to increase the variability of visuomotor coordination (Varlet et al., 2011), suggesting that visual coupling can impair individual sensorimotor coordination. Our previous study (Miyata et al., 2017) revealed that interpersonal visual coupling also modulates an individual's capacity to synchronize with an auditory metronome, either facilitating or degrading performance depending on his or her synchronization skills.

Although vocal interaction is ubiquitous in everyday life, only a few studies have investigated its role in interpersonal coordination. This work has addressed factors that modulate the coordination of voices or finger taps with other's voices (e.g., Lagrois, Palmer, & Peretz, 2019; Palmer, Spidle, Koopmans, & Schubert, 2019), but not the effect of interpersonal vocal interaction on individual motor timing control. This issue is worth examining because vocal interaction might influence individual task performance during dyadic joint action through the interaction of the effects of self-vocalization and the effects of the other individual's voice. Previous studies have suggested that concurrent rhythmic vocalization improves motor timing performance (Harrison, Horin, & Earhart, 2018; Miyata & Kudo, 2014). On the other hand, another individual's vocalizations are not as temporally regular as metronome beats, and this timing variability may degrade motor timing performance. Here, we investigated this possibility using a synchronization-continuation paradigm where participants first coordinate their movements with regular auditory pacing stimuli (synchronization task) and then maintain the tempo in the absence of the pacing signal (continuation task).

The main goal of the present study is to test the degree to which visual and vocal interaction between paired participants (a) results in the occurrence of spontaneous interpersonal coordination and (b) affects motor timing performance at the individual level. We used a whole-body synchronization-continuation paradigm that required participants to bounce via knee bends while maintaining a standing posture. To modulate visual and vocal interaction, participants were asked to stand face-to-face or back-to-back and to repeat the syllable "*tah*" or to remain silent. At the interpersonal level, we expected the occurrence of spontaneous coordination between individuals through both visual and vocal interaction, as indicated by interpersonal phase relations that are closer to 0° and less variable when participants stand face-to-face and repeat the syllable "*tah*" than when they are back-to-back and silent. At the individual level, it was expected that the visual and/or auditory coupling would modulate each participant's capacity to synchronize with the metronome and to maintain regular movement at this instructed tempo during the continuation task. Our previous study (Miyata et al., 2017) showed that the effect of interpersonal visual coupling was prominent at tempi around 90 beat per minute (bpm). However, given that there are individual differences in preferred tempi and that auditory-motor synchronization peaks at around 100–120 bpm (see Burger, Thompson, Luck, Saarikallio, & Toiviainen, 2014; Repp & Su, 2013; Styns, van Noorden, Moelants, & Leman, 2007), we investigated the effects of interpersonal visual and vocal interaction at both 90 and 120 bpm.

Method

Participants

Thirty-two undergraduate and graduate students (mean age = 23.94 years, $SD = 4.32$) from Western Sydney University participated in this experiment. They were allocated to 16 pairs randomly or by virtue of being preexisting friends that signed up together on a case-by-case basis (eight pairs of friends and eight pairs of strangers; seven female pairs, two male pairs, and seven mixed-sex pairs). The mean of within-pair height differences was 10.56 cm ($SD = 6.19$) and the mean of within-pair mass differences was 15.25 kg ($SD = 15.13$). All participants had no self-reported hearing or speech impairments and gave informed consent. The study was approved by the Western Sydney University Human Research Ethics Committee, in accordance with the Declaration of Helsinki. Our sample size was chosen based on an a priori power analysis to detect medium effect sizes ($f = .25$) with at least 80% power, in line with effect sizes previously reported in a study of spontaneous interpersonal coordination (Miyata et al., 2017).

Task and Procedures

The experiment was performed at the motion capture laboratory housed at the MARCS Institute of Western Sydney University, where 12 infrared cameras of a Vicon motion capture system (Vicon Motion Systems Ltd., Oxford, U.K.) were set on a 4-m-high rig positioned over 6 m × 6 m performance area. Participants arrived at the laboratory, were briefly introduced to each other (if they were not already friends), and told that the study was an investigation of individual motor timing performance. After giving their informed consent, participants individually completed questionnaires to control for individual differences that could influence their synchronization performance. Participants completed a musical background questionnaire, as musical expertise has been shown to improve auditory-motor synchronization (Krause, Pollok, & Schnitzler, 2010; Miura, Kudo, Ohtsuki, & Kanehisa, 2011; Repp, 2005; Repp & Su, 2013). They also completed the Liebowitz Social Anxiety Scale (LSAS; Fresco et al., 2001; Heimberg et al., 1999) to evaluates the degree of anxiety and avoidance of social interaction, which has also been shown to modulate interpersonal synchronization (Macpherson, Marie, Schön, & Miles, 2019; Varlet et al., 2014).[1] Reflective markers were then attached on the right side of the hip, knee and ankle joint centers of each participant (see Figure 1).

Paired participants were instructed to perform a synchronization-continuation task by flexing and extending their knees while keeping a standing posture (Miura, Kudo, & Nakazawa, 2013; Miura et al., 2011). The distance between two participants in each pair was 2 m. Participants were asked to coordinate knee flexion with auditory metronome beats during the first half of a trial and maintain the tempo from the first half during the last half of a trial after the metronome ceased until a beep sound occurred. Participants performed this task in two orientation conditions (Face-to-Face and Back-to-Back) and two vocalization conditions (Vocalization and Silent) as shown in Figure 1. In all conditions, paired participants were not explicitly instructed to coordinate with each other but asked to look forward and coordinate their movement with the metronome beats and to maintain the tempo as stably as possible when the metronome stopped. In the Vocalization conditions, participants were asked to repeat syllable "*tah*" in time with knee flexion in a loud voice (and to breathe whenever they needed to).

The synchronization task of each trial comprised 33 auditory metronome beats presented at rates of 90 or 120 bpm. Four additional beats served as a "ready" cue at the beginning of each trial. The metronome beat consisted of a pure tone (80 ms duration, 440 Hz) generated using LabVIEW (National Instruments, Austin, TX) and delivered via an analogue-to-digital converter (NI USB-6218 BNC, National Instruments) and four speakers. To record at least 33 movement cycles, the duration of continuation section was approximately 25 and 19 s for the 90 and 120 bpm tempi, respectively. Trial durations were about 50 s (90 bpm) and 38 s (120 bpm). A beep signaled the end of the trial. We did not tell participants how many beats there were nor how many times they had to vocalize the "*tah*" syllable to make sure that they remained focused on the task without the additional cognitive demand of keeping track of the number of beats. Participant pairs completed 40 trials (2 orientation conditions × 2 vocalization conditions × 2 beat rates × 5 repetitions) in a randomized order. The opportunity to practice the task in each condition was given for a few minutes at the beginning of the experiment.

Data Acquisition and Analysis

Knee angular displacement was recorded as a representative index of whole-body vertical movement based on the three reflective markers attached to participants' right hip, knee, and ankle joints using the Vicon motion capture system. Voice data were recorded using a head-mounted unidirectional microphone (WH20XLR, SHURE Inc., Niles, IL). Audio signals of the metronome and participants' voices were amplified (AT-MA2, Audio-Technica, Tokyo, Japan), digitized at 1,000 Hz using an analogue-to-digital converter (NI USB-6218 BNC, National Instruments), and recorded in synchrony with the motion capture data.

Displacement data were low-pass filtered with a bidirectional second-order Butterworth filter (cut-off frequency = 7 Hz). The first three movement cycles of each synchronization and continuation section of the task were discarded to remove transient effects associated with the change from rest to movement and from metronome-paced to self-paced movement.

To calculate the relative phase angles between paired participants, and between each individual's movements and metronome beats, we obtained the continuous phase of each participant's movement time-series using the Hilbert transform (Gabor, 1946; Varlet & Richardson, 2011). The Hilbert transform was calculated after the low-pass filtering and before discarding the first three movement cycles and the last movement cycle. The real and imaginary parts of displacement data were normalized by calculating *z* values. The mean relative phase angle between participants and the *SD* of these phase angles were then calculated using circular statistics (Batschelet, 1981). Because leader and follower relations were not relevant to the aims of this study, the mean relative phase angle was converted to an absolute (unsigned) value.

Audio signals of the metronome were analyzed to determine the beat onset times, as in accordance with a method established in a previous study (Fujii et al., 2011). Circular statistics were then used to calculate the relative phase between the rhythmic movement and the beat timing. The mean phase angle of beat time and *SD* of beat phase angles were calculated and averaged across trials for each participant.

For the continuation section of the task, the mean and *SD* of time intervals between knee flexion peaks (I_{knee}) within each trial were calculated for each participant. The mean I_{knee} was normalized by dividing by the reference interval (667 ms at 90 bpm and 500 ms at 120 bpm). The coefficient of variance (CV) was computed as the *SD* divided by the mean I_{knee}. These mean and CV values were then averaged across trials for each participant. The individual variables in both the synchronization and continuation tasks were averaged across paired participants prior to statistical analyses

[1] We examined potential confounds of musical background and social factors, specifically partner familiarity (friends vs. strangers) and social anxiety, by conducting ANOVAs including musical background and the familiarity as factors and regression analyses of the LSAS score, and found no significant interactions involving these factors.

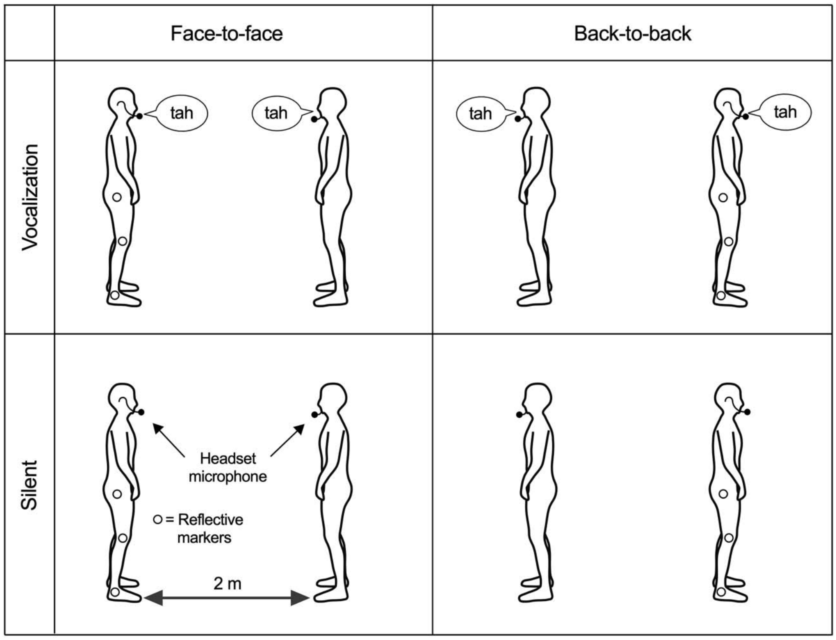

Figure 1. Experimental conditions. Paired participants performed the task in two orientation conditions (Face-to-Face and Back-to-Back) and two vocal conditions (Vocalization and Silent). Participants stood 2 m apart in the center of a room and were asked to look forward in both orientation conditions. Three reflective markers attached on the right side of the hip, knee, and ankle joint centers were recorded by a Vicon 12-camera motion capture system to analyze knee angular displacement as a representative measure of whole-body vertical movement. Syllable ("*tah*") repetition was recorded using a headset microphone.

because individual data within pairs are not statistically independent.

To ensure that participants vocalized at the instructed tempo, we calculated the vocalizations per minute and the percentage of missing vocalizations. Voice data were preprocessed with a band-pass filter (from 100 Hz to 350 Hz) using FDATool in MATLAB with full-wave rectification. Voice onset times were defined in accordance with the general procedure from a previous study (Fujii et al., 2011), with the threshold set at 120% of the average signal intensity. When the interval between successive vocalizations exceeded 150% of the median interval value, a missing vocalization was registered. The percentage of missing vocalizations was 0.48% in the synchronization task and 0.75% in the continuation task, calculated based on the number of missing vocalizations over the total expected number of vocalizations. The number of vocalizations per minute was calculated after excluding missing vocalizations. Participants produced 91.6 vocalizations per minute at the 90 bpm tempo and 119.80 vocalizations per minute at the 120 bpm tempo. These data indicate that participants successfully performed the syllable repetition component of the task at the instructed rates.

Statistics

Separate four-way repeated-measures analyses of variance (ANOVAs) with the within-subject factors Task (synchronization and continuation), Orientation (Face-to-Face and Back-to-back), Vocal condition (Vocalization and Silent), and Beat rate (90 and 120 bpm) were performed on (a) the mean relative phase and (b) the *SD* of relative phase between participants. Separate three-way ANOVAs with the within-subject factors Orientation, Vocal condition, and Beat rate were performed on (a) the mean phase angle of beat time and (b) the *SD* of beat phase angles for the synchronization task, and (c) the mean I_{knee} and (d) the CV of I_{knee} for the continuation task. When three-way interactions of Task × Orientation × Vocal condition were significant, separate ANOVAs were performed at each level of Task or Orientation. Significant two-way interactions were followed up with pairwise contrasts corrected for multiple comparisons using the Holm correction. The statistical significance level was set at $p < .05$.

Results

Interpersonal Phase Relations

Consistent with previous work, the relative phase angles between paired participants were closer to 0° and less variable when participants interacted visually during the synchronization (Figure 2A) and continuation tasks (Figure 2B). These effects were also found with vocal interaction but were modulated depending on the availability of visual information.

The four-way ANOVA on mean interpersonal relative phase angle showed significant main effects of Task, $F(1, 15) = 8.58$, mean squared error (*MSE*) = 262.83, $p = .010$, $\eta^2_G = .03$, Orientation, $F(1, 15) = 113.30$, $MSE = 346.47$, $p < .001$, $\eta^2_G = .35$, and Vocal condition, $F(1, 15) = 24.26$, $MSE = 319.48$, $p < .001$, $\eta^2_G = .10$. Because neither main effect of Beat rate, $F(1, 15) = 0.93$, $p =$

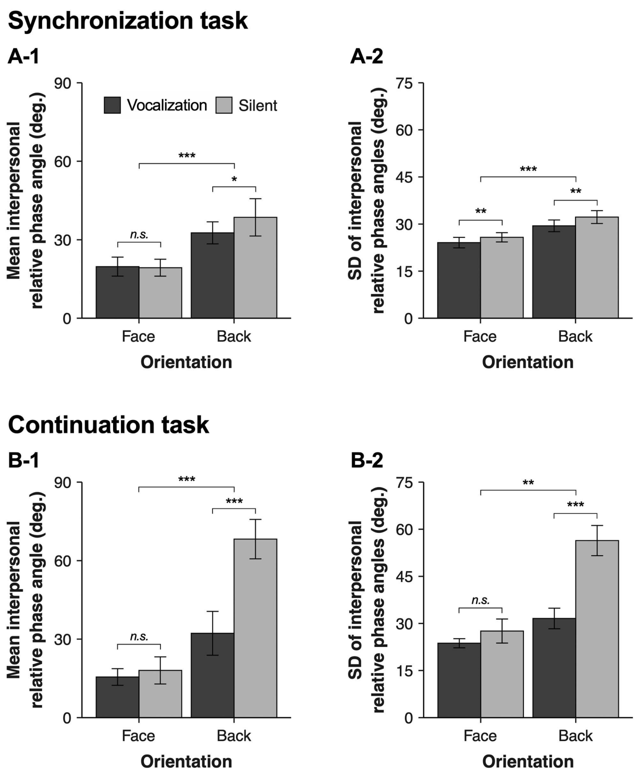

Figure 2. Mean and standard deviation of interpersonal relative phase angles in the synchronization task (A) and the continuation task (B) averaged across the two beat rates (90 and 120 bpm). Error bars represent 95% within-pairs confidence intervals (Morey, 2008). Face = Face-to-face condition; Back = Back-to-back condition; *ns* = not significant. $^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$.

.350, nor interactions related to Beat rate were significant, data for the two tempi were averaged in Figure 2A. There was a significant three-way interaction of Task × Orientation × Vocal condition, $F(1, 15) = 28.63$, $MSE = 103.01$, $p < .001$, $\eta^2_G = .04$, whereas other interaction effects were not significant. We broke down the Task × Orientation × Vocal condition interaction with separate two-way analyses of Task × Vocal condition for each level of Orientation and of Orientation × Vocal condition for each task.

There was a significant interaction of Task × Vocal condition in the Back-to-back condition, $F(1, 15) = 23.18$, $MSE = 156.08$, $p < .001$, $\eta^2_G = .16$. Post hoc tests revealed that the mean interpersonal phase relations were closer to 0° in the synchronization task than in the continuation task when participants were silent, $t(29.9) = 6.53$, $p < .001$, but there was no significant difference during vocal interaction, $p = .927$. In the Face-to-face condition, there was no significant main effect of Task, $F(1, 15) = 3.16$, $p = .096$, nor interaction of Task × Vocal condition, $F(1, 15) = 1.71$, $p = .211$. These results indicate that the spontaneous interpersonal coordination that occurs in the synchronization task due to the common pacing signal significantly decreased in the continuation task when participants had no visual and/or auditory information about each other.

The two-way interactions of Orientation × Vocal condition were significant for both the synchronization task, $F(1, 15) = 7.21$, $MSE = 22.28$, $p = .017$, $\eta^2_G = .01$, and the continuation task, $F(1, 15) = 46.05$, $MSE = 97.42$, $p < .001$, $\eta^2_G = .24$. Post hoc tests revealed that mean interpersonal phase relations were closer to 0° when participants could see each other irrespective of Vocal condition in both the synchronization task, $ts(19.6) > 4.04$, $ps < .001$, and continuation task, $ts(29.8) > 4.61$, $ps < .001$. The tests also indicated that vocalization led to mean interpersonal phase relations closer to 0° in the Back-to-back condition in both the synchronization task, $t(25.4) = 2.69$, $p = .025$, and continuation task, $t(25.8) = 7.97$, $p < .001$, but not in the Face-to-face condition, $ps > .58$. Taken together, these results show that participants synchronized their movements with closer to 0° phase relations while interacting visually, and that vocalization led to interpersonal phase relations closer to 0° only when participants could not see each other.

The four-way ANOVA on the *SD* of interpersonal relative phase angles yielded significant main effects of Task, $F(1, 15) = 33.79$, $MSE = 90.77$, $p < .001$, $\eta^2_G = .11$, Orientation, $F(1, 15) = 186.49$, $MSE = 50.45$, $p < .001$, $\eta^2_G = .27$, and Vocal condition, $F(1, 15) = 82.97$, $MSE = 53.06$, $p < .001$, $\eta^2_G = .15$. The main effect of Beat rate was nonsignificant, $F(1, 15) = 0.32$, $p = .583$, and therefore data of the two tempi were averaged together, as depicted in Figure 2B. There was a significant two-way interaction of Orientation × Beat rate, $F(1, 15) = 4.75$, $MSE = 26.43$, $p = .046$, $\eta^2_G = .00$, and a significant three-way interaction of Task × Orientation × Vocal condition, $F(1, 15) = 26.39$, $MSE = 59.62$, $p < .001$, $\eta^2_G = .06$ (whereas other interactions were not significant). Again, we broke this interaction down with separate two-way analyses of Task × Vocal condition and Orientation × Vocal condition.

The interaction of Task × Vocal condition was significant in the Back-to-back condition, $F(1, 15) = 42.19$, $MSE = 45.99$, $p < .001$, $\eta^2_G = .24$. Post hoc tests revealed that the interpersonal phase relations were less variable in the synchronization task than in the continuation task when participants were silent, $t(29.1) = 10.95$, $p < .001$, but there was no significant difference during vocal interaction, $p = .339$. The interaction and main effect of Task were not significant in the Face-to-face condition, $ps > .26$. These results further show that spontaneous interpersonal coordination significantly decreased in the continuation task compared with the synchronization task when participants had no shared visual and/or auditory information.

The two-way interaction of Orientation × Vocal condition was only significant for the continuation task, $F(1, 15) = 34.10$, $MSE = 51.36$, $p < .001$, $\eta^2_G = .20$. Post hoc tests indicated less variable interpersonal phase relations in the Face-to-face condition compared with the Back-to-back condition irrespective of Vocal condition, $ts(28.2) > 3.49$, $ps < .002$, and with vocalization compared with silence in the Back-to-back condition, $t(30) = 9.78$, $p < .001$, but not in the Face-to-face condition, $p = .135$. In the synchronization task, the main effects of Orientation, $F(1, 15) = 73.07$, $MSE = 7.60$, $p < .001$, $\eta^2_G = .13$, and Vocal condition, $F(1, 15) = 15.06$, $MSE = 5.33$, $p = .001$, $\eta^2_G = .02$, were both significant. Together, these results indicate that the variability of interpersonal relative phases decreased due to visual interaction in all conditions and due to vocal interaction in all conditions except in the continuation task when participants could see each other.

Phase Angle of Beat Time in the Synchronization Task

As shown in Figure 3, participants coordinated the maximum flexion position of their individual movements more closely with metronome beats during interpersonal visual and vocal interactions than in the absence of such interaction. However, interpersonal visual interaction increased the variability of synchronization with metronome beats, whereas vocal interaction contributed to decreased variability.

The three-way ANOVA on the mean phase angle of beat time revealed significant main effects of Orientation, $F(1, 15) = 25.87$, $MSE = 419.60$, $p < .001$, $\eta^2_G = .06$, Vocal condition, $F(1, 15) = 4.55$, $MSE = 363.86$, $p = .050$, $\eta^2_G = .01$, and Beat rate, $F(1, 15) = 109.89$, $MSE = 518.53$, $p < .001$, $\eta^2_G = .27$. There was a significant interaction between Orientation and Beat rate, $F(1, 15) = 33.99$, $MSE = 71.51$, $p < .001$, $\eta^2_G = .02$. Other interaction effects were not significant. Mean phase angles were closer to 0° with visual interaction than without, $ts(20) > 2.48$, $ps < .02$, and at 90 bpm than 120 bpm, $ts(19.1) > 7.80$, $ps < .001$. Thus, both interpersonal visual and vocal interaction led to phase angles of the maximum flexion position being closer to beat times (Figure 3A). In addition, mean phase angles were generally closer to 0° at 90 bpm than 120 bpm.

Figure 3B shows the *SD* of beat phase angles. The main effect of Orientation was significant, $F(1, 15) = 15.87$, $MSE = 12.67$, $p = .001$, $\eta^2_G = .02$, indicating that visual interaction increased the variability of synchronization with metronome beats. Although the main effect of Vocal condition, $F(1, 15) = 2.46$, $p = .138$, and Beat rate, $F(1, 15) = 0.98$, $p = .337$, were not significant, there was a significant interaction of these factors, $F(1, 15) = 5.37$, $MSE = 13.13$, $p = .035$, $\eta^2_G = .01$. Post hoc tests revealed a significant decrease of the *SD* of beat phase angles with vocalization at 90 bpm, $t(29.1) = 2.69$, $p = .023$, but not at 120 bpm, $p = .772$. In the silent condition, the *SD* of beat phase angles tended to be smaller at 120 bpm compared with 90 bpm, though this numerical difference was not significant, $p = .129$. Other interaction effects were not significant.

Knee Flexion Intervals in the Continuation Task

Effects of visual and vocal interaction on knee flexion interval data are shown in Figure 4. The three-way ANOVA on mean knee flexion intervals (I_{knee}) revealed significant main effects of Orientation, $F(1, 15) = 47.93$, $MSE = .00025$, $p < .001$, $\eta^2_G = .12$, and Beat rate, $F(1, 15) = 333.35$, $MSE = .00015$, $p < .001$, $\eta^2_G = .37$, and a significant interaction of these factors, $F(1, 15) = 9.36$, $MSE = .00006$, $p = .008$, $\eta^2_G = .01$, whereas the main effect of Vocal condition was nonsignificant, $F(1, 15) = 3.44$, $p = .084$. Other interaction effects were not significant. Mean I_{knee} was shorter with visual interaction than without, $ts(21.7) > 4.90$, $ps < .001$, and at 90 bpm than 120 bpm, $ts(25.2) > 13.85$, $ps < .001$. The three-way ANOVA on the CV of I_{knee} revealed significant main effects for Vocal condition, $F(1, 15) = 7.28$, $MSE = .00003$, $p = .017$, $\eta^2_G = .02$, and Beat rate, $F(1, 15) = 19.06$, $MSE = .00002$, $p < .001$, $\eta^2_G = .05$, but not for Orientation, $F(1, 15) = 0.01$, $p = .923$. All interaction effects were not significant. This suggests that vocal interaction, but not visual interaction, decreased the variability of knee flexion intervals.

Discussion

This study investigated the effects of interpersonal visual and vocal interaction on interpersonal phase relations and individual movement timing in a task that required paired participants first to synchronize vertical bouncing movements (involving knee flexion and extension) with a metronome and then to continue moving at the same tempo. The main finding was that visual and vocal interaction both resulted in spontaneous coordination between participants' movements but had differential effects on individual motor timing performance. On one hand, visual interaction increased the variability of auditory-motor synchronization and did not affect the temporal variability of rhythmic movements during the continuation task. On the other hand, vocal interaction decreased the variability of auditory-motor synchronization at the slower of two tempi (90 bpm, compared with 120 bpm) and decreased the variability of continuation movement intervals at both tempi.

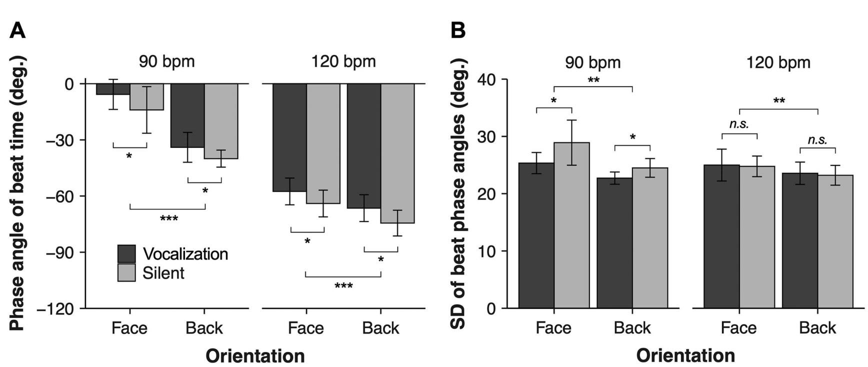

Figure 3. Mean phase angle of beat time (A) and the standard deviation of beat phase angles in the synchronization task (B) at the two beat rates. The maximum flexion point is indicated as 0° and the velocity peak of flexion as −90°. Error bars represent 95% within-pairs confidence intervals (Morey, 2008). Face = Face-to-face condition; Back = Back-to-back condition; *ns* = not significant; bpm = beat per minute. * $p < .05$, ** $p < .01$, *** $p < .001$.

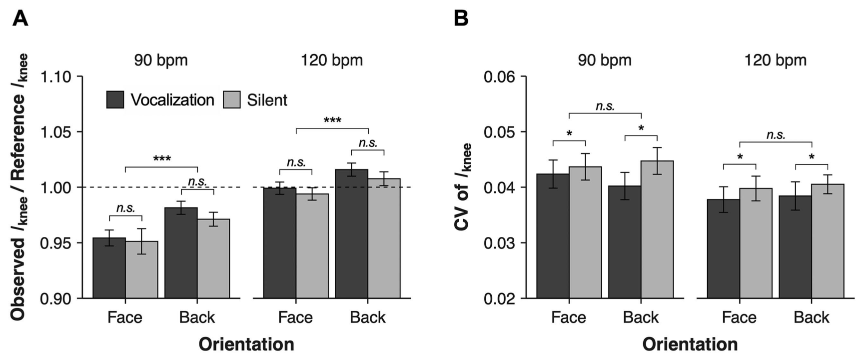

Figure 4. Mean and coefficient of variance (CV) of knee flexion intervals in the continuation task. Mean I_{knee} was normalized by dividing with reference interval (667 ms in 90 bpm and 500 ms in 120 bpm). Error bars represent 95% within-pairs confidence intervals (Morey, 2008). Face = Face-to-face condition; Back = Back-to-back condition; *ns* = not significant; bpm = beats per minute. * $p < .05$.

Spontaneous Interpersonal Coordination

As predicted, we found that bouncing with a visually and vocally coupled partner elicited spontaneous interpersonal coordination in both synchronization and continuation tasks. Numerous previous studies have reported that spontaneous interpersonal coordination emerges through visual and auditory interaction (Demos et al., 2012; Richardson et al., 2007; Richardson et al., 2005; Schmidt & O'Brien, 1997; van Ulzen et al., 2008; Varlet et al., 2011; Varlet & Richardson, 2015). However, there are few studies examining spontaneous coordination via vocal interaction, and some that do report deteriorative effects on interpersonal coordination (Richardson et al., 2005; Shockley, Richardson, & Dale, 2009). This may be because of the type of task that these studies employed (conversation). Our study demonstrated that rhythmic vocal interaction (syllable repetition) leads to spontaneous interpersonal coordination for rhythmic body movements. This result is broadly consistent with a previous study reporting that spontaneous coordination between participants seated in rocking chairs was facilitated by auditory interaction (the sound of the chairs; Demos et al., 2012).

For the synchronization task in our study, the variability of interpersonal phase relations was smallest when participants interacted both visually and vocally. However, a corresponding effect was not observed in the continuation task or for mean interpersonal phase relations in both tasks. During visual interaction, vocal interaction did not affect interpersonal phase relations reliably. This may be attributable to a floor effect. Assuming that there is a limit to how close to 0° and how much lower in variability interpersonal phase relations can be through informational interaction, visual coupling may have brought participants to this limit. Visual interaction gives direct and continuous information about interpersonal phase relations whereas vocal interaction does so indirectly and intermittently in discrete form (Varlet, Marin, Issartel, Schmidt, & Bardy, 2012). Therefore, vocal interaction did not have benefits on interpersonal synchrony, as measured by interpersonal phase relations, over and above the beneficial effects of visual interaction when both modalities were available.

Effects of Visual and Vocal Interaction on Individual Motor Timing Performance

In accordance with a previous study (Varlet et al., 2011), our results showed that visual interaction increased the variability of auditory-motor synchronization, although this effect might depend on the individual's synchronization skill (Miyata et al., 2017). (We did not analyze individual differences during solo performance because it was not relevant to the aims of this study.) It is well known that there are certain phase relations between movement and rhythmic auditory stimuli that are especially stable (e.g., 0° and 180°) whereas other phase relations tend to be much more variable (Kelso, 1984, 1995). Our previous results indicate that stable phase relations occur at around −47° for the auditory-motor synchronization of whole-body movements, with slight differences depending on the movement frequency (Miyata et al., 2017). The present results showed that visual interaction led to the phase angle of beat times being shifted (closer to 0°) from that in the Back-to-back condition. Thus, in the current context, it is assumed that participants synchronized with metronome beats with less stable phase relations due to spontaneous coordination with their partner.

This interpretation is supported by the results of previous studies on a bimodal target-distracter synchronization paradigm (Hove, Iversen, Zhang, & Repp, 2013; Iversen, Patel, Nicodemus, & Emmorey, 2015) and interference paradigms (Cracco, De Coster, Andres, & Brass, 2015; Kilner, Paulignan, & Blakemore, 2003; Press, Bird, Flach, & Heyes, 2005). These studies found that visual-motor coupling is stronger than auditory-motor coupling when the visual stimulus consists of continuous biological movement. Specifically, previous research using a bimodal target–distracter synchronization paradigm demonstrated that visuomotor coupling is weaker than auditory-motor coupling when visual stimuli were presented as flashing lights but equivalent in strength to audio-motor coupling when visual stimuli were presented as continuous trajectories (Hove et al., 2013; Iversen et al., 2015). Furthermore, previous studies using interference paradigms have found that human movement is more sensitive to visual stimuli of biological movement than nonbiological movement (Cracco et al., 2015; Kilner et al., 2003; Press et al., 2005). The visual stimulus in the current study was biological motion (a partner's movement) and hence might have been more influential compared with nonbiological metronome sounds, leading to a situation where interpersonal visual coupling was stronger than auditory-motor coupling. These findings are consistent with a cross-modal competition effect in which auditory-motor coupling becomes weaker due to strong visuomotor coupling between individuals.

On the other hand, vocal interaction reduced the variability of auditory-motor synchronization at the relatively slow tempo in the synchronization task and generally decreased the variability of movement intervals in the continuation task. An individual can monitor her own movement timing via auditory information and, for instance, detect differences between the phase of one's own movement and an externally generated beat. According to the modality appropriateness hypothesis (Welch & Warren, 1980), the auditory modality is dominant for temporal processing whereas the visual modality is dominant for spatial processing. It follows that motor timing control should be superior when one can monitor one's own movements via the auditory channel.

Furthermore, research taking a dynamical systems approach has shown that an interaction between vocalization and other active effectors can be understood as coupled systems (Kelso, 1995; Kelso, Tuller, & Harris, 1983; Miyata & Kudo, 2014; Treffner & Peter, 2002). Previous studies have reported the stabilization of coupled systems in which a group of neuromuscular components act as a collective unit referred to as a coordinative structure (Bernstein, 1967; Drewing & Aschersleben, 2003; Helmuth & Ivry, 1996; Miyata & Kudo, 2014). Miyata and Kudo (2014) found that rhythmic vocalization and vertical bouncing movements (involving knee flexion and extension) are coupled in a flexion-on-the-voice pattern that is less variable when performed concurrently than when performed independently. This suggests that vocalization and movement are stabilized by acting as a coordinative structure.

The stabilizing effect of vocal interaction was limited to 90 bpm for the *SD* of beat phase angles in the synchronization task, whereas it occurred at both tempi for the CV of I_{knee} in the continuation task. This result might be attributable to higher movement variability occurring at slower tempi and in the continuation task (McPherson, Berger, Alagapan, & Fröhlich, 2018; Repp, 2005), leaving more room for the beneficial effects of vocalization. Because participants tended to perform the synchronization task with greater stability at 120 bpm than at 90 bpm (albeit only marginally), there might have been relatively little room for stabilization by vocalization at 120 bpm, hence limiting the effect to 90 bpm.

Although the effect of vocal interaction could be attributable to one's own vocalization and/or the vocal sounds of one's partner, the current study was not designed to tease apart these potential effects. Maitra et al. (2003) have reported that both self-vocalization and external (experimenter) vocalization make hand reaching for a cup faster and smoother. Future work would be needed to address the degree to which one's own vocalization and the vocal sounds of one's partner modulate individual movement timing.

Conclusions

The findings of the current study suggest that vocal interaction while performing a rhythmic task with a coactor, as exemplified by the widespread tradition of work songs, is beneficial for both the joint action outcome and individual task performance. To accomplish a range of joint actions that we perform successfully every day, information about movement timing needs to be shared among coactors. Joint rhythmic vocalization provides a medium for such sharing and thereby facilitates interpersonal coordination. Moreover, communication via the auditory modality may play a compensatory role in naturalistic contexts where visual contact has potentially destabilizing effects. This explains why the work songs that are ubiquitous around the world make teamwork not only more enjoyable but also boost productivity.

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