Do Vision and Audition Influence Bimanual Timing Coordination for In-Phase and Anti-Phase Patterns in a Linear Slide Task?

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Abstract: The purpose of the present study was to investigate the role of vision and audition in the coordination of in-phase and anti-phase movement patterns at increasing frequency of oscillation in a bimanual linear slide task. The dependent variables were mean error of relative phase and standard deviation of relative phase. Results indicated that vision and audition did not influence the accuracy and the variability in performance of the two relative phase patterns, whereas increasing frequency influenced the performance of the anti-phase pattern, but not the in-phase pattern. As a potential explanation of the current findings, it is hypothesized that the bimanual linear coordination task did not rely on vision and audition because the task was perhaps governed by proprioception. With consideration for specific motor tasks, investigating the role of vision, audition, and proprioception on the performance of coordinative movements remains an important question for continued research.

Keywords: Bimanual coordination, vision, audition, relative phase, motor control.

INTRODUCTION

Coordinative movements are believed to be a good representation of how the motor system performs complex movements [1-6]. Rather than rescaling a previously acquired skill through a command function, coordinative movements are self-organized between body segments allowing for emergent movement patterns [7-11]. Kelso [12, 13] developed a task environment to study dual limb coordinative movements in which two stable patterns were identified: 0º relative phase (in-phase) and 180º relative phase (anti-phase). In the in-phase pattern, the limbs move toward and then away from each other symmetrically and continuously using homologous muscle group contractions. In the anti-phase pattern, the limbs move together in an isodirectional fashion with homologous muscle groups contracting in an alternating fashion. Interestingly, if not resisted, when the speed of performing these coordinative patterns increases beyond 2.25 Hz, the anti-phase pattern destabilizes and transitions into the in-phase pattern [12, 13]. If the transition is resisted, the destabilized anti-phase pattern is reflected by highly variable performance [14]. In contrast, the in-phase pattern is unaffected by increased movement frequency.

The coupling between the limbs for the bimanual coordination of in-phase and anti-phase patterns, which gives rise to the dynamics, is informational in nature resulting from multiple sensory sources that provide feedback about the limbs [15]. Sources of information about the limbs may include vision, proprioception, and audition. Assessing precisely the contribution of each source in the total coupling strength is of interest to allow further insight into the dynamics of bimanual coordination. It is generally acknowledged that one requires proprioceptive and visual information to fine tune motor patterns. Proprioceptive information from the periphery allows the central nervous system to monitor the moving limbs and to adjust the movement pattern if necessary. There is evidence that the coordination of ongoing movements uses proprioception in healthy participants [16], while deafferentiated patients exhibit clear coordination deficits [17-21]. Proprioception, however, cannot fully account for all motor coordination phenomena. Coordination deficits in deafferentiated patients become apparent only if vision is absent [17, 18, 20, 21].

Positive evidence for the assumption that vision may play a role in the coupling of the limbs comes from discrete bimanual movements [22-24] and cyclical bimanual movements [25]. Swinnen and colleagues [24] asked healthy adult participants and participants with Parkinson's disease to trace triangles with both upper limbs at the same time across 22 trials. Vision was allowed in the beginning of trials; however, at the middle (i.e., after 10 trials) and at the end (i.e., after 18 trials), two trials were completed in a blindfolded condition. Without vision of the arms, participants with Parkinson's disease showed a drift in tracing performance as compared to healthy age-matched control participants [24]. In a study by Kazennikov and colleagues [23], 16 healthy

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adult participants performed a drawer-pull task with one hand opening the drawer while the other hand picked up a small peg in the drawer with and without vision of the limbs. The no vision condition resulted in a slower movement production with some participants completely changing the coordination pattern to adapt to the lack of sensory information [23]. Cardoso de Oliveira and Barthelemy [22] investigated the role of vision during bimanual coordination involving hitting a small target with both index fingers in fast goal-directed movements with and without vision of the limbs. Absence of vision significantly increased the reaction times of both limbs, whereas vision of the limbs decreased bimanual amplitude coupling [22].

Additionally, in a study by Serrien and colleagues [25], vision and proprioception were manipulated during the production of in-phase and anti-phase patterns for young adult participants and older adult participants at a slow speed (1 Hz). Results indicated that the young adult participants demonstrated decreased stability for the in-phase pattern with no vision of the limbs and during the altered proprioceptive conditions, whereas with no vision of the limbs, the young participants produced more stable anti-phase patterns. Even though the younger participants demonstrated more of a decrease in pattern stability during in-phase coordination as compared to the older participants, both groups were sensitive to proprioceptive influences during the anti-phase coordination as demonstrated by decreased pattern stability. This finding led the authors to suggest that the integration of afferent information may have a more prominent influence in the anti-phase pattern than in the in-phase pattern [25].

Although the noted studies do suggest a role of vision and proprioception in the coupling of the limbs for bimanual coordination, the contribution of such information to the coordination of a bimanual limb task involving relative phase has not been fully evaluated. Specifically, the bimanual tasks discussed in the preceding studies did not involve linear bimanual movements at increasing frequency of oscillation from a slow speed (i.e., 1Hz) to a fast speed (i.e., 3Hz). Considering Kelso's [12, 13] work, it is important to replicate the increasing speed of relative phase production for bimanual linear movements. It is not clear if vision would play a role in the coordination of relative phase patterns exposed to a different task environment involving linear bimanual movements from a slow speed to a fast speed. In addition, audition was not controlled in the preceding studies. Perhaps audition could also be influencing the coupling of the limbs for coordination of bimanual movements as the sounds produced by the bimanual linear slide may provide information about performance. In fact, there has been recent interest in understanding the link between the auditory and the motor systems during musical performance of bimanual tasks [see 26, for a review]. For example, when auditory feedback was manipulated by changes in pitch, motor performance of a piano task for both pianists and nonpianists was significantly altered [27]. In contrast, when auditory feedback of a piano task was absent, performance for both the pianists and nonpianists was not affected [27]. It is interesting to note that auditory feedback influenced the coupling of the limbs for the bimanual piano task only when pitch was manipulated. In the absence of audition, no changes in performance of the bimanual piano task were noted. The results suggest that altered auditory feedback (i.e., changes in pitch) influences the bimanual task when the goal of the movement is musical.

Based on the results in the study by Pfordresher [27], an interesting question is posed. How would these results translate to a bimanual linear task that does not involve a musical goal but rather a pure movement goal? The bimanual linear task of relative phase for the in-phase and the anti-phase patterns can arguably be considered a pure, simplistic movement goal. The current study attempted to answer this question by manipulating audition during relative phase performance of a bimanual linear slide task. Consistent with the study by Pfordresher [27], manipulation of audition involved alterations in pitch by presentation of white noise (i.e., 20Hz-20,000Hz at equal amplitude for each frequency). During relative phase production, white noise was presented so that sounds from the bimanual linear slides were masked. The metronome was still heard through the white noise to ensure appropriate speed of movement production. The intent was to alter the audition of the movement goal itself not the speed of movement production.

The following study, therefore, was conducted to examine the influence of vision and audition on the in-phase and anti-phase patterns at increasing frequency of oscillation for a bimanual linear task. Based on previous findings [25], it was hypothesized that participants in the present study would produce destabilized in-phase patterns and more stable anti-phase patterns without vision and with masked audition by white noise.

METHODS

Participants and Procedures

First, participants read and signed the consent form, which had been approved by Wilfrid Laurier University's Ethics Board and the University of Pittsburgh's IRB. Second, participants answered questions to meet the recruitment criteria for participation. Participants were 15 females, ages 18-35 years with a mean age of 21 years. Inclusion criteria included self-report of normal vision with or without correction by glasses or contacts and self-report of normal audition. Twelve of the 15 participants were right hand dominant, based on self-report. Third, participants received a general orientation to the task. The task required them to grasp two handles attached to the moving slides and displace them horizontally in the left-right dimension. While grasping the two handles, participants produced 0º relative phase (in-phase) and 180º relative phase (anti-phase) patterns. In the in-phase pattern, the limbs move toward and then away from each other symmetrically and continuously using homologous muscle group contractions. In the anti-phase pattern, the limbs move together in an isodirectional fashion with homologous muscle groups contracting in an alternating fashion [12, 13].

Participants received instructions to keep pace with a metronome by performing a complete cycle of in-out-in handle displacement in time with the beat. The metronome paced the required speed or frequency of limb movement beginning at a slow speed equivalent to a frequency of 1 Hz for 20-seconds. After completion of the 20-second trial at 1 Hz, the same required coordination task was paced at a medium metronome frequency (2 Hz), and subsequently at a fast metronome frequency (3 Hz). Participants were encouraged to maintain the required coordination timing pattern as best as possible throughout all trials; therefore, emphasis on timing coordination was foremost. Also, participants were instructed to attempt to recapture the required temporal coordination pattern if it was destabilized even in mid-trial [14]. All three metronome frequencies for one relative phase pattern were completed before switching to a new relative phase pattern.

Participants produced the relative phase patterns at increasing speed under four different sensory conditions. For the normal sensory condition (i.e., normal vision + normal audition), participants had a clear view of their arms and hands during the production of the relative phase patterns, and they could hear the noise produced by the linear slides as they were displaced. In the no vision condition (i.e., no vision + normal audition), total visual deprivation was achieved by extinguishing all lights so that visual access to the limbs was completely blocked. In the masked audition condition (i.e., normal vision + masked audition by white noise), participants received white noise presented to their ears *via* supra-aural headphones at an intensity level that was adequate to mask the sound produced by the bimanual slides without causing discomfort to the subject. In the complete deprivation condition (i.e., no vision + masked audition by white noise), participants experienced total visual and auditory deprivation by total darkness in the room to block all visual access to the limbs and by white noise presented to the ears to block all sounds produced by the bimanual linear slide. Auditory pacing from the metronome, however, could be perceived above the white noise through the headphones during the masked audition condition and the complete deprivation condition. The intent was to alter the audition of the movement goal itself not the speed of movement production.

Equipment and Software

The bimanual coordination apparatus involved two plastic handles (i.e., 12.5 cm in height x 3 cm diameter) independently attached to linear sliding devices that glided horizontally over ball bearings encapsulated in metal casings (see Fig. **1**). Limb movements were permitted in only the left-right orientation from midline. Attached in parallel to the slides were linear potentiometers (Duncan Electronics, DEL Elec 612R12KL.08), which encoded the displacement of the slides over a 20-sec trial. Data were sampled using a microprocessor (80486) with a sampling rate of 200 Hz (i.e., one sample each 5 msec). LabWindows software (National Instruments Corporation, version 2.2.1) initiated and terminated 20-sec trials and also provided data capture and recording of limb position over time.

An auditory metronome (NCH Swift Sound Tone Generator, version 2.01) provided pacing information for the bimanual tasks. Under visual deprivation conditions, lights were extinguished and computer monitors were covered to achieve total darkness in the room, so that participants' view of their arms was completely eliminated. In auditory deprivation conditions, a white-noise masking stimulus (NCH Swift Sound Tone Generator, version 2.01) was delivered to the subject's ears *via* supra-aural headphones (Optimum Pro-155 stereo headphones) so that audition about performance from the linear slides was masked.

Fig. (1). Bimanual Linear Slide.

Experimental Design and Data Reduction

The design of the experiment involved three independent variables, all being within-participants. The three factors were: (1) required relative phase coordination pattern (i.e., in-phase and anti-phase), (2) metronome pacing frequency (i.e., 1 Hz, 2 Hz, and 3 Hz), and (3) sensory condition (i.e., normal vision and normal audition, no vision and normal audition, normal vision and masked audition by white noise, and no vision and masked audition by white noise). The entire experimental design was replicated three times per subject. Order of the relative phase patterns and sensory conditions were randomized within and across participants. The dependent variables were mean error of relative phase and standard deviation of relative phase. A three-way, repeated measures analysis of variance (ANOVA) was conducted on each of the dependent variables. Significance level was set at $\alpha = .05$ and post hoc simple main effects were analyzed using the Bonferroni correction.

Data collection involved a continuous estimate methodology in which limb position was sampled at a rate of 200 Hz (every 5 ms). This method allowed for finer-grained information about movement accuracy as compared with point estimates, which typically focus on two time-points per cycle [28]. Relative phase difference for each time point was determined in the following way. For each time point sampled, the relative phase of the right limb in space was captured, relative to the left limb, where a reference of 0º indicated that both limbs were at the midline position. Each trial resulted in an average mean error (i.e., an average of the mean relative phase error data points) and a within-trial standard of these data points. Three replications of the experiment were run. Therefore, statistical analyses were performed on the mean error and standard deviations averaged over the 3 trials.

Mean error of relative phase was calculated for the in-phase pattern and for the anti-phase pattern. Specifically, the final mean error term for the in-phase pattern was simply the mean of relative phase because the mean of relative phase error subtracted from zero is equal to the mean of relative phase. To compute the final error term for the anti-phase pattern, the performed mean of relative phase from each trial was subtracted from 180, so that values could be compared to those for the in-phase trials. In addition to mean error of relative phase, the standard deviation of relative phase was computed for each experimental condition.

RESULTS

Mean Error of Relative Phase

The ANOVA for mean error of relative phase revealed significant main effects for *phase* [F(1,14)=73.36, *p*<.001] and *frequency* [F(1.36,19)=48.95, *p*<.001]. The main effect of *sensory condition* [F(2.24,31.39)=1.13, *p*=.342], however, was not significant. A significant two-way interaction was shown for *phase x frequency* [F(1.49,21)=41.69, *p*<.001, see Fig. **2**]. The three-way interaction for *phase x frequency x sensory condition* [F(3.43,48)=.363, *p*=.806] was not significant. Eta squared, an indicator of effect size, was .840 and .778 for the significant main effects of phase and frequency, respectively and .749 for the significant two-way interaction.

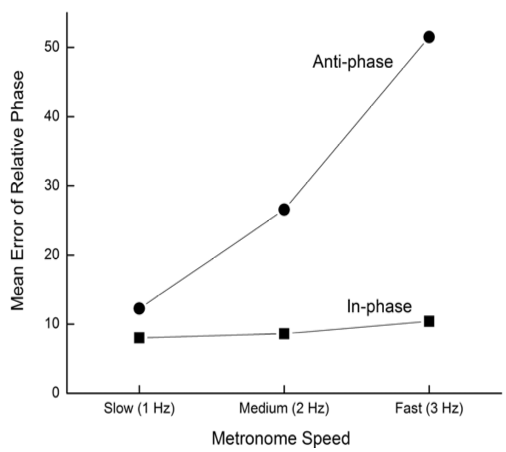

Fig. (2). Significant two-way interaction for *phase x frequency* (F(1.49, 21)=41.69, *p*<.001). Mean error of relative phase as a function of frequency or metronome speed (i.e., slow (1Hz), medium (2Hz), and fast (3 Hz)) for the in-phase pattern and the anti-phase pattern.

The significant two-way interaction for *phase x frequency* was further analyzed using the Bonferroni correction. For the in-phase pattern, the slow versus medium [t(32)=.171, *p*=.865], slow versus fast [t(32)=.685, *p*=.498], and medium versus fast [t(32)=.514, *p*=.611] pairwise comparisons were not significant suggesting that the in-phase pattern was produced with the same amount of error across the slow, medium, and fast speeds (see Fig. **2**). For the anti-phase pattern, the slow versus medium [t(32)=4.09, *p*<.001], slow versus fast [t(32)=11.20, *p*<.001], and medium versus fast [t(32)=7.11, *p*<.001] pairwise comparisons were all significant indicating that the performance of the pattern was influenced by the increasing frequency or speed. Specifically, the anti-phase pattern was produced with more error as speed increased (see Fig. **2**).

For the slow speed, the pairwise comparison was not significant [t(32)=1.27, *p*=.212]. The in-phase and anti-phase relative phase patterns, therefore, were produced with the same amount of error at the slow speed. At the medium and fast speeds, the pairwise comparisons were significant [t(32)=5.39, *p*<.001] and [t(32)=12.33, *p*<.001], respectively. As the speed increased from medium to fast, the anti-phase pattern was produced with more error as compared to the in-phase pattern (see Fig. **2**).

Standard Deviation of Relative Phase

The ANOVA for standard deviation of relative phase revealed significant main effects for *phase* [F(1,14)=292.69, p<.001] and *frequency* [F(2,28)=135.25, p<.001]. The main effect for *sensory condition* was not significant [F(3,42)=.418, p=.741]. A significant two-way interaction was shown for *phase x frequency* [F(1.85,25.87)=122.79, p<.001, see Fig. **3**]. The three-way interaction for *phase x frequency x sensory condition* [F(4.06,56.88)=.366, p=.835] was not significant. Eta squared, an indicator of effect size, was .954 and .906 for the significant main effects of phase and frequency, respectively and .898 for the significant two-way interaction.

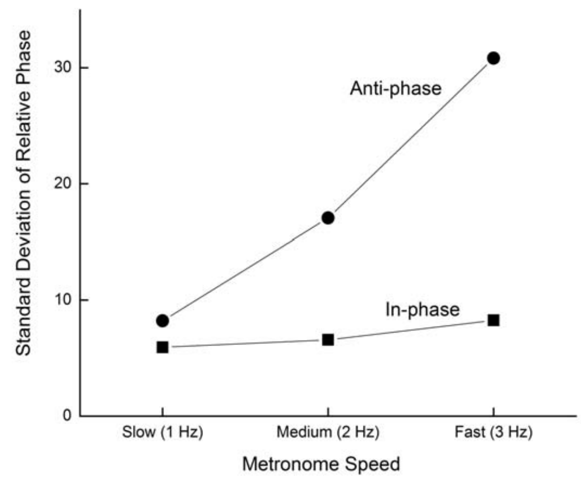

Fig. (3). Significant two-way interaction for *phase x frequency* (F(1.85, 25.87)=122.79, *p*<.001). Standard deviation of relative phase as a function of frequency or metronome speed (i.e., slow (1Hz), medium (2Hz), and fast (3 Hz)) for the in-phase pattern and the anti-phase pattern.

The Bonferroni correction was used to further analyze the significant two-way interaction. For the in-phase pattern, the slow versus medium [t(32)=.635, *p*=.529], slow versus fast [t(32)=2.27, *p*=.030], and medium versus fast [t(32)=1.64, *p*=.111] pairwise comparisons were not significant suggesting that the in-phase pattern was produced with the same amount of variability across the slow, medium, and fast speeds (see Fig. **3**). For the anti-phase pattern, the slow versus medium [t(32)=8.64, *p*<.001], slow versus fast [t(32)=22.12, *p*<.001], and medium versus fast [t(32)=13.48, *p*<.001] pairwise comparisons were significant indicating that the variability in performance of the anti-phase pattern was influenced by the increasing speed. Specifically, the anti-phase pattern was produced with more variability as the speed increased (see Fig. **3**). The pairwise comparison between the in-phase and anti-phase patterns at the slow speed was not significant [t(32)=2.19, *p*=.035]. At the medium and fast speeds, the pairwise comparisons were significant [t(32)=10.04, *p*<.001] and [t(32)=21.66, *p*<.001], respectively. As the speed increased from medium to fast, the anti-phase pattern was produced with more variability as compared to the in-phase pattern (see Fig. **3**).

DISCUSSION

The purpose of the present study was to investigate the influence of vision and audition on bimanual timing coordination for in-phase and anti-phase patterns at increasing frequency of oscillation for a linear slide task. Overall, results failed to indicate any clear evidence that the presence of vision and/or audition influenced the performance of either in-phase or anti-phase movement patterns. Increasing speed of oscillation clearly had a detrimental effect on the performance of the anti-phase pattern, but not the in-phase pattern. Nevertheless, the effects of the increasing pacing frequency were uninfluenced by the presence or absence of audition and/or vision.

If the equipment and experimental procedures were not responsible for the lack of evidence supporting an interaction between sensory condition and relative phase, then perhaps an uncontrolled sensory information variable influenced the results. Although vision and audition were controlled in the present study, proprioception was not controlled. The influence of proprioception, therefore, cannot be ruled out. In fact, the bimanual coordination task using the bimanual linear slide may not be governed by auditory and visual information, but rather by proprioceptive information. Salter, Wishart, Lee, and Simon [29] suggested that the friction of the bimanual linear slide and the reversal of movements in the horizontal plane may direct participants' attention towards proprioceptive information from the upper limbs rather than visual and auditory information. In addition, Verschueren, Swinnen, Cordo, and Dounskaia [30] suggested that proprioceptive information plays a role in the online monitoring of interlimb coupling for relative phase patterns during cyclical bimanual movements in the horizontal plane. In contrast, a different bimanual task involving unidirectional circling movements may rely more on vision rather than proprioception [31]. In a study by Pfordresher [27], altered auditory feedback by changes in pitches did influence the performance of a bimanual piano task possibly because the task itself is ultimately a musical goal with inherent auditory requirements. It seems possible that such discrepancies across studies related to specific bimanual tasks may account for the difference in findings.

Stated differently, the reliance on visual, auditory, and/or proprioceptive information in the performance of the in-phase and the anti-phase patterns may be task-specific. Consequently, if the correct sensory information mechanism is identified for a given bimanual coordination task, then its perturbation should affect the performance of the relative phase patterns. Relative to the present study, the question can be asked whether temporal coordination would have been affected if proprioceptive information had been perturbed. In Serrien and colleagues [25], visual and proprioceptive information were varied for a bimanual coordination task involving bimanual cyclical movements. Results indicated that the young and older adult participants' demonstrated decreases in stability for the anti-phase pattern during altered proprioceptive conditions (i.e., vibratory stimuli to one limb). In the absence of visual information, the young adult participants produced less stable in-phase patterns and more stable anti-phase patterns. This finding that visual information influenced bimanual coordination in the study by Serrien and colleagues [25] stands in direct contrast to findings of the current study where visual and auditory information did not influence the performance of the in- and anti-phase bimanual coordination patterns. In addition, the in-phase and the anti-phase patterns were produced with the same stability at the slow speed in the current study, but the Serrien and colleagues [25] study reported that the in-phase and anti-phase patterns were produced with different stability measures at the slow speed. Findings from the present study, however, were more consistent with widely reported effects demonstrating stability of both the in-phase and the anti-phase patterns at the slow speed [12, 13, 28, 32].

The discrepancy in findings across the present study and the one reported by Serrien and colleagues [25] may be related to two factors. First, in the study by Serrien and colleagues [25], the combination of the proprioceptive and the visual information may have influenced the participants' ability to integrate sensory information in a much different way as compared to the auditory and visual combination in the present study. In fact, audition was not controlled in the study by Serrien and colleagues [25]. Second, vision in the study by Serrien and colleagues [25] was controlled by the opacity of glasses worn by the subject, whereas vision in the current study was manipulated by controlling the lights in the room and thus absolute visibility. The opacity of the glasses could have provided an additional distraction that influenced performance rather than visual information.

These discrepancies between the study by Serrien and colleagues [25] and the current study could be pursued with appropriately designed studies considering all relevant sensory information that may be influencing the specific bimanual task. Of equal or greater interest is the pursuit of questions regarding the role of proprioception on the coordination dynamics of a bimanual linear slide task. Future studies should be conducted to further explore such questions. Proprioception could be disrupted by adding vibratory stimulation to one or both limbs, and perhaps healthy participants as well as age-matched participants with disordered proprioception loops could be evaluated for the task. In sum, although the present study did not show any clear role of vision and audition on the bimanual timing coordination of relative phase for a linear slide task, the role of visual, auditory, and proprioceptive information on the performance of coordinative movements, as a function of specific task, remains an important question for continued research.

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