Effects of Proprioceptive and Visual Disturbance on In-phase and Anti-phase Hand Performance

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ABSTRACT

Purpose: The present study aimed to investigate the effect of sensory and movement speed manipulations on bimanual coordination dynamics. Here we compared to what extent the absence and or bias of different sensory modalities affect performance of coordination of movements.

Methods: Fifteen physical education students of Shahid Beheshti University (aged 18-25 years) were participated in the study. Participants performed bimanual in-phase and anti-phase movements with their wrists at 3 levels of speed ranging from slow to fast and 4 different sensory conditions, including 1) Normal sensory input; 2) Masked vision; 3) Masked proprioception; and 4) Full sensory deprivation. Separate analyses of variance (ANOVA) with repeated measures on speed and sensory conditions were conducted for the in-phase and anti-phase movement patterns, followed by post hoc analyses using the Bonferroni correction. The dependent variable was error of relative phase.

Results: In line with observations from previous studies, results of our study showed that increasing movement speed influenced performance of the anti-phase (P=0.001) but not the in-phase (P=0.9) coordination patterns. Specifically, as speed increased from slow to fast, the performance of 1800 anti-phase patterns destabilized, with participants showing higher error scores of relative phase. Sensory manipulation showed that proprioception and vision did influence the accuracy and consistency of the coordination tasks in both the in-phase and anti-phase movement patterns (P=0.001).

Conclusion: The performance of a bimanual linear coordination task depends mainly on the availability of proprioceptive input.

1. Introduction

Sensory inputs for feedback control include proprioception, vision, and audition. Vision is often regarded as the most important perceptive modality during interaction with the environment in daily life. At least for perceiving spatial information, vision dominates other senses [11, 20]. Many motor tasks are impossible or, at least, are much harder to perform without vision; for example, walking on an uneven terrain, hitting a tennis ball, or skiing [20]. Studies using both discrete [5, 21] and cyclical bimanual movements [19] confirm that vision plays a critical role in coupling of limb movements. In particular, these studies show that bimanual movements are performed with higher levels of accuracy and stability when visual information on the position of the moving effectors is available compared to conditions where visual feedback is absent. Vision, which provides information about target and hand

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positions, is generally considered to be the main cue leading to sensory motor adaptation, whereas proprioception is thought to be secondary [1, 3, 16, 17].

Besides vision, proprioception is also an important source of feedback, which is essential for maintaining the required coordination patterns during bimanual movements [10]. Proprioceptive input from the muscle spindles and tendons is crucial for movement control. It allows the central nervous system to monitor the position and speed of the moving limbs and adjust the motor command if necessary. Coordination of ongoing movements uses proprioception in healthy participants [6], while deafferentiated patients exhibit coordination deficits [4, 2]. Proprioception, however, cannot fully account for successful performance of a coordination task. For example, coordination deficits in deafferentiated patients become apparent only if vision is absent [14, 2,7,10].

The relative contribution of vision and proprioception to the control of coordinate movements may depend, nonetheless, on the nature of the task. For example, a bimanual circle-drawing task, where movements always continue in the same direction with no reversal movements, is controlled by proprioceptive feedback [22]. On the other hand, control of bimanual coordination tasks in which the effectors must stop and reverse direction entails reliance on the use of both vision and proprioception [15].

In the present study, we used a bimanual coordination task that consisted of flexion and extension movements with both wrists in either in-phase or anti-phase mode. The continuous nature of the bimanual actions requires participants to control the limb extensively in an online manner through visual and proprioception or audition feedback loops. Assessing the relative contribution of each aforementioned sensory source on the strength of coupling between wrists was our primary goal. It is also of our interest to have further insight into the dynamics of bimanual coordination by examining how deprivation of the 3 sensory sources would affect performance.

In general, one requires proprioceptive and visual information to fine tune motor patterns. Exploring the coordinated behavior in the absence of all sensory sources received less attention. However, to our knowledge, the technique of visual feedback transformations has been used mainly in unilateral tasks, whereas bimanual tasks have received much less attention. The present experimental design also addressed the question of whether in-phase and anti-phase bimanual coordination patterns (which vary with respect to their performance stability in different speeds) are differentially affected by the absence or presence of visual and proprioceptive feedbacks.

2. Materials & Methods

Participants and procedure

First, the participants read and signed informed consent forms, which have been approved by the local Ethics Committee of Shahid Beheshti University. Then, they were asked to complete the questionnaires about their health condition. Participants were 15 males with no history of neuromuscular disease. All were right-handed (assessed by the Edinburgh Handedness Inventory; Oldfield, 1971), healthy, aged between 18 and 26 years with a mean age of 21 years. Inclusion criteria were having normal vision based on the Snellen chart test, self-reported normal audition, and absence of any neuromuscular, motor and or sensory disorders. Next, the participants received a general orientation to the task. The task required them to grasp 2 handles attached to moving slides and displace them horizontally in the left-right dimension (wrist extension and flexion). While grasping the 2 handles, the participants should produce 00 relative phase (in-phase) and 1800 relative phase (anti-phase) patterns.

They 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, 58 beat/minute for 20 seconds. After completion of the 20-second trial at slow speed, the same required coordination task was paced at a medium metronome frequency (90 beat/min), and subsequently at a fast metronome frequency (152 beat/min).

We obtained consent (and assent, when appropriate) from the participants after their entering the laboratory. Afterwards, we conducted a handedness inventory when the participants were seated. Also, we encouraged participants to perform in-phase and anti-phase patterns during experiment. There were 4 counterbalanced conditions: 1) Normal sensory condition (normal vision, normal proprioception, normal audition); 2) Masked vision (normal proprioception and normal audition); 3) Masked proprioception by tendon vibration (normal vision, and normal audition); and 4) Full sensory deprivation (no vision, masked proprioception and masked audition).

Equipment and software

The participants sat on an adjustable chair at a table covered by a white laminated poster board (50 cm deep and 86cm wide). Wrist movements were permitted in only the extension and flexion orientation from midline. Linear potentiometers were attached parallel to the slides (Bourns Instruments, Riverside, CA), and encoded the displacement of the handled over a 20-second trial. Data were sampled using a microprocessor (80486DX2) with a sampling rate of 150 Hz (i.e. one sample each 5 ms). Lab Windows software (National Instrument Corporation, version 2.2.1) initiated and terminated 20-second 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 bimanual task [8].

We also used a self-build tendon vibrator consisting of pager motors and small vibration motors, which rotated an unbalanced mass attached to the shaft of a small magnet DC motor. This apparatus constitutes very low-cost actuators for inducing tendon vibration. We used a Panasonic vibration motor (micro-motor with dimensions 0.59×1.15) with an operating range up to approximately 150 Hz. Natio et al. (1999) reported that although some qualitative aspects of the illusion were affected by the amplitude of vibration [13], illusion strength was mainly determined by vibration frequency (70 and 80Hz). The surface area of the head of the vibrator was adjusted to allow an optimal contact with the skin by adding bars with different profiles. The vibrator was positioned over the wrist tendon near the radiocarpal joint as shown in Figure 1B.

Experimental design and data reduction

The position signals were smoothed with a symmetrical Bartlett (triangular) filter. Its time series were derived from the position signal using a 2-point central difference algorithm and then smoothed with a Bartlett window. Then, the smoothed position and velocity time series were used to calculate each component of the near-continuous phase state for each trial according to the formula:

$$ØR=tan\text{-}1\{(DXR/dt0/XR\}$$

where is the phase of the right wrist at each sample, XR is the position of the right wrist rescaled to the interval, {-1,1} for each cycle of oscillation and (dXR/dt) is its normalized instantaneous velocity. The same formula was used to calculate from the position and velocity signals of the left wrist. The relative phase between the two wrists, was then expressed as:

$$\varphi= ØR\text{-}ØL$$

Two-way (4 Sensory condition×3 Speed) analyses of variance for repeated measures (ANOVA) were performed using STATISTICA software (version 8.0). Significant results of interest were examined post hoc by using pairwise comparisons with Bonferroni correction. The α level of significance was set at 0.05.

3. Results

Coordination accuracy (in phase)

The results of the 4×3 ANOVA for the AE scores (Figure 2) revealed no significant main effects for speed (F_2=0.106, P=0.9) but the main effects for sensory condition was significant (F_4=866.9, P=0.001). The interaction effect of speed and sensory condition was not significant (F_8=0.722, P=0.55). Pairwise comparisons between conditions showed that participants produced the in-phase movements with similar levels of accuracy during 1) Normal sensory conditions; and 2) Masked vision (all, P>0.9). Significant deterioration of the coordination accuracy (i.e. higher AE scores) were observed during the sensory conditions involving masked pro-

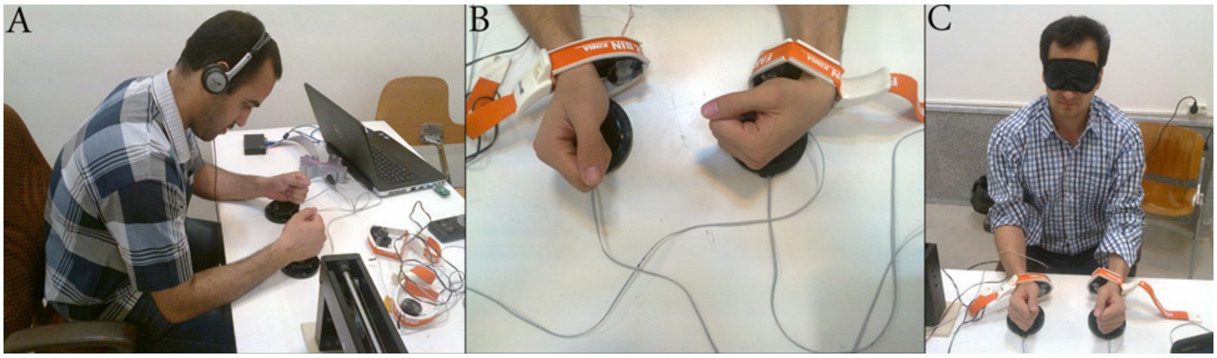

Figure 1. The bimanual wrist coordination task under:

A) Visual interference condition.

B) Proprioception interference condition.

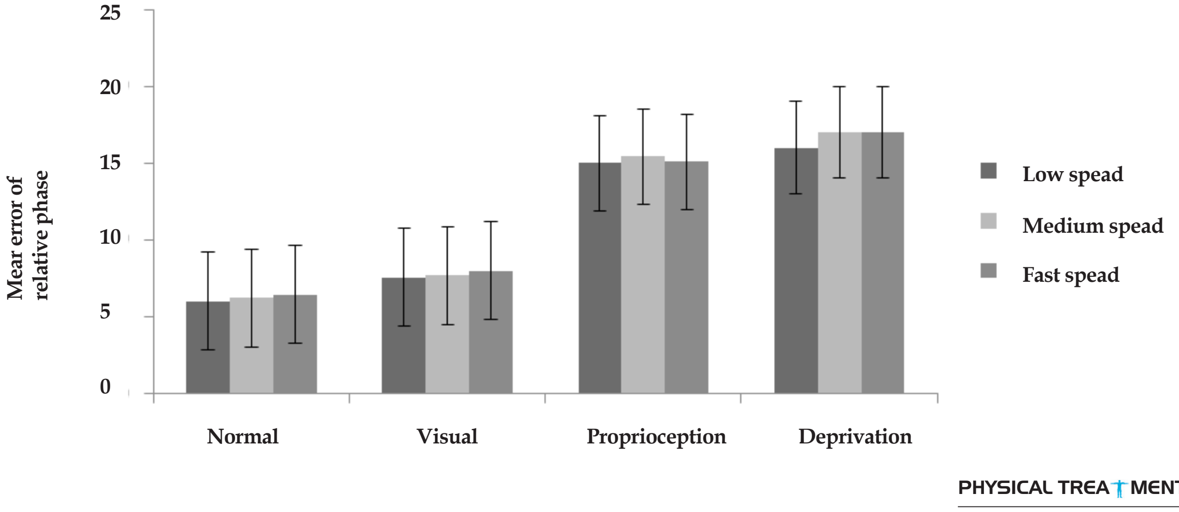

Figure 2. Histograms showing the group means for error of relative phase in the in-phase mode across the 3 speed and 4 sensory conditions. Only the main significant effect sensory condition was found (F4= 866.9, P=0.001). Mean relative phase error scores as a function of the metronome speed in the low (58 beat/min), medium (90 beat/min), and fast (158 beat/min) did not differ significantly from each other.

prioception and full sensory deprivation (all, P<0.001). However, performance scores for masked proprioception and full sensory deprivation did not differ significantly (all, P>0.5).

Coordination accuracy (anti-phase)

The results of the 4×3 ANOVA for the AE scores (Figure 3) revealed significant main effects for speed (F2= 118.03, P=0.001) and sensory condition (F4=68.33, P=0.001). The interaction effect for speed and sensory condition was also significant (F8=4.72, P=0.019). The significant 2-way interaction for speed×sensory condition was further analyzed using the Bonferroni test. Speed factor for all sensory conditions was significant (P=0.001). Pairwise comparisons revealed a significant increase in AE scores between slow versus medium speed (P=0.001), slow versus fast speed (P=0.001), and medium versus fast speed (P=0.001). Overall, these observations indicate that the performance of anti-phase coordination mode is strongly influenced by increasing the movement speed (Figure 4).

To further explore the significant speed×sensory condition interaction, 1-way ANOVA with repeated measure of sensory condition were separately conducted

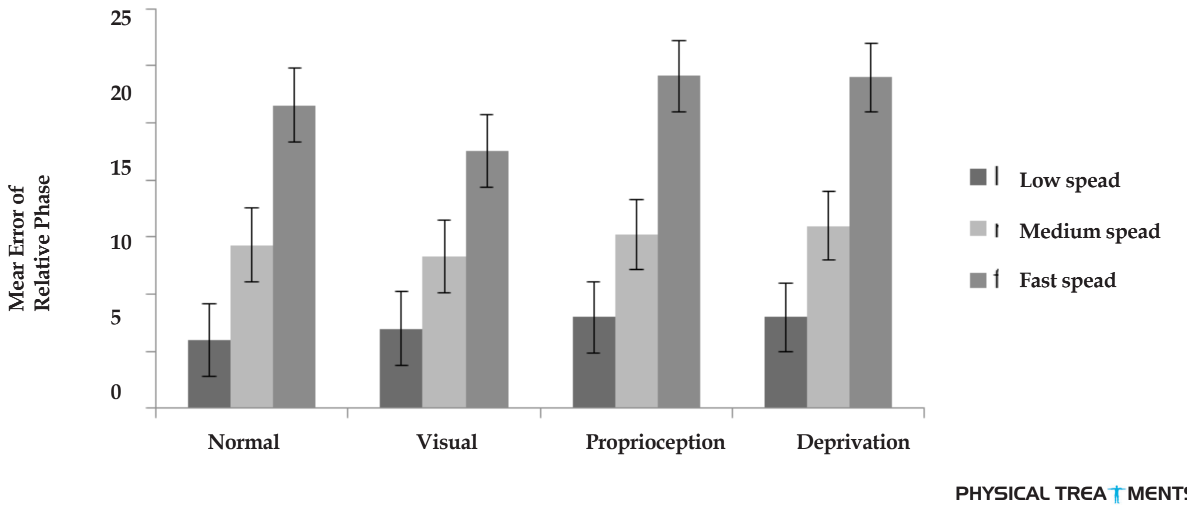

Figure 3. Histograms showing the group means for error of relative phase in the anti-phase conditions across the three speed and five sensory conditions. Significant main effects for speed (F2=118.03, P=0.001), sensory condition (F4=68.33, P=0.001), and speed×sensory (F8=4.72, P=0.019) were found. Mean relative phase error scores increased a function of the metronome speed. Low=58 beat/minute, medium=90 beat/minute, fast=158 beat/minute.

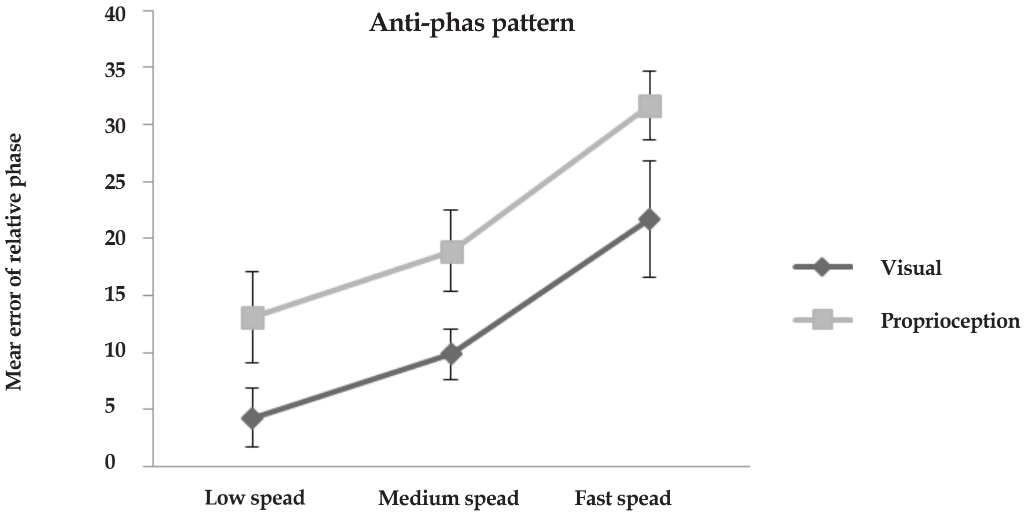

Figure 4. Mean relative phase as a function of metronome speed with slow (58 beat/min), medium (90 beat/min), and fast (158 beat/min). Anti-phase pattern was produced with more error as speed increased with proprioceptive deprivation causing the higher error scores as compared to the conditions where vision or audition was masked.

for each speed. Overall, ANOVA revealed a significant main effect of sensory condition for all 3 speed levels (slow F4=53.29, P=0.001; medium F4=36.6, P=0.001; and fast F4=60.4, P=0.001). However, pairwise comparisons revealed a significant increase of AE scores in the masked proprioception versus normal sensory condition and masked vision (all, P<0.001). Interestingly, AE scores during visual deprivation were significantly lower than those observed during performance with normal sensory condition (P=0.001), whereas AE scores during full sensory deprivation were generally lower than those observed for the performance of the anti-phase mode with masked proprioception (however, differences did not reach significance).

Trends were similar to those observed for the coordination accuracy scores (illustration not shown). Again, results of the 4×3 ANOVA for SD scores revealed significant main effects for speed (F2=142.38, P=0.001) and sensory condition (F4=223.61, P=0.001), and speed×sensory condition (F8=13.96, P=0.001). Pairwise comparisons revealed significant increase of SD scores with speed (all sensory conditions: SD scores at slow<SD, scores at medium<SD, scores at fast speed; P<0.001). Further analyses of the significant speed×sensory condition interaction revealed that full sensory deprivation conditions were performed with the same level of consistency across all three speed levels (all, P>0.9). For all 3 speed levels, SD scores for performance of the anti-phase mode with the masked proprioception were significantly higher than those recorded in the remaining sensory conditions (all, P<0.001). Finally, SD scores during visual deprivation were significantly lower than those observed during performance with normal sensory condition (all speed levels, P<0.025).

4. Discussion

The study was designed to investigate whether sensory information contributed by skin and muscle receptors, vision is parametrically redundant or distinct. Healthy human subjects performing coordination tasks were required to produce in-phase or anti-phase movements with their wrists under different sensory conditions where the availability of visual and proprioceptive feedback was manipulated. Results indicated that proprioception was more important than other sensory feedbacks in this bimanual task. Overall, these finding revealed that when the proprioceptive input was manipulated (or masked) with tendon vibration, participants performed both the in-phase and anti-phase coordination tasks with higher mean relative phase error scores and poorer coordination consistency as compared to other conditions when proprioception was not manipulated. In the study by Serrien and colleagues (1996), visual and proprioceptive information were manipulated when young and old healthy participants performed a coordination task involving bimanual cyclical movements [19].

Results from the aforementioned study indicated that the young and older adult participants demonstrated decreases in stability for the anti-phase pattern during altered proprioceptive conditions. Again, their finding that visual information influences bimanual coordination agrees with our finding where manipulation of proprioception and vision influence the performance of the in- and anti-phase whereas manipulation (masking) of audition does not. This agreement in findings may be related to similarity of the experimental procedures used in both studies. In the study by Serrien et al. (1996), the proprioceptive manipulation was tendon vibration like our study and second, vision in their study was controlled by the opacity of glasses worn by the subjects [19]. This means that their visual deprivation was similar to that used in our study. Our findings were, nonetheless, in contrast to the findings of Grillo and colleagues (2010). This may be attributed to differences in the procedure applied in both studies to deprive vision [8]. First, in the study by Grillo et al. (2010), combination of the vision and audition was not controlled. Therefore, this study lacks the ability to determine how much the participants integrate the 2 sensory modalities (i.e. vision and audition). Second, vision in their study was controlled by switching off the lights in the room which may have allowed participants to use some visual inputs whereas in our study the occultation of vision was complete.

Considering a convergence of the different sources of proprioceptive information, whether arising from an external perturbation (vibration) or from active movement, one can hypothesize that the available afferent inflow is distorted and does not correspond to the actual situation at wrists. Our findings were consistent with the findings reported in a study by Baldissera et al. (1991) where the sensory input from the hand was biased during ipsilateral hand and foot coordination at different levels of speed [4]. Observations from this study suggested that afferent information was elaborated differently during in-phase and anti-phase movements. The availability of visual feedback did influence the performance of subjects in the present study. This finding was in agreement with the observations reported in the studies of Cardoso de Oliveira et al. [4] and Swinnen et al. [21], showing that the presence of visual information enabled stable in-phase movements, whereas it disturbed the stability of the anti-phase movements. The latter finding suggests that visual monitoring influences the production of both coordination modes in a different way. Interpretation is as follows: during in-phase coordination, the extremities of both hands are in central vision when the reversal occurs in a flexed position.

Other main finding in the present study is the role of speed in the coordination movements. Increasing speed clearly influenced the performance of the 1800 anti-phase pattern, but not the 00 in-phase pattern. As speed increased from slow to fast, the previously stable 1800 anti-phase pattern destabilized, and was performed with increased variability and decreased accuracy. The 00 in-phase pattern, however, remained stable across frequency conditions. These findings replicated those from previous research [18, 12]. An explanation of this finding has been derived from ideomotor theories of action control [9]. This approach assumes that motor actions are cognitively represented by their sensory effects, i.e. by codes of the perceptual effects that contingently follow certain motor actions. For further studies, healthy participants engaged in this study as well as age-matched participants with disordered proprioception loop could also be evaluated for this task. Future studies should be conducted to further explore such suggestions.

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