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The integration of temporally shifted visual feedback in a synchronization task: the role of perceptual stability in a visuo-proprioceptive conflict situation

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Abstract

The present study examined whether the beneficial role of coherently grouped visual motion structures for performing complex (interlimb) coordination patterns can be generalized to synchronization behavior in a visuo-proprioceptive conflict situation. To achieve this goal, seventeen participants had to synchronize a self-moved circle, representing the arm movement, with a visual target signal corresponding to five temporally shifted visual feedback conditions (0%, 25%, 50%, 75% and 100% of the target cycle duration) in three synchronization modes (in-phase, anti-phase and intermediate). The results showed that the perception of a newly generated perceptual Gestalt between the visual feedback of the arm and the target signal facilitated the synchronization performance in the preferred in-phase synchronization mode in contrast to the less stable anti-phase and intermediate mode. Our findings suggest that the complexity of the synchronization mode defines to what extent the visual and/or proprioceptive information source affects the synchronization performance in the present unimanual synchronization task.

PsycINFO classification code: 2330

Keywords: *Synchronization; Visual feedback; Temporal shift; Perceptual Gestalt; Proprioception*

1. Introduction

Bimanual coordination studies have been very straightforward in showing that the in-phase coordination pattern (0° relative phase) is intrinsically more stable than the anti-phase movement pattern (180° relative phase) (e.g., Swinnen, Jardin, Verschueren, Meulenbroek, Franz, Dounskaia et al., 1998; Zanone & Kelso, 1992). These phase effects were corroborated when the coordinated behavior is a product of the interaction between perception and action. Specifically, lower degrees of accuracy and stability were found for anti-phase movements when these movements were visually coordinated between two people (Schmidt, Carello, & Turvey, 1990) or in unimanual synchronization studies in which an arm had to be moved in correspondence with an external visual signal (Buekers, Bogaerts, Swinnen, & Helsen, 2000; Ceux, Buekers, & Montagne, 2003; Ceux, Wagemans, Rosas, Montagne, & Buekers, 2005; Wimmers, Beek, & van Wieringen 1992). These studies highlighted the role of perception in the rhythmic movement coordination since the coupling was visually mediated by the ability to detect the information used to couple and coordinate the oscillating limbs (Wilson, Collins, & Bingham, 2005a, 2005b). Moreover, the stability of the perception of two oscillating visual signals was found to vary as an asymmetric U-function of mean relative phase (i.e., dependent on the directional compatibility between the oscillating signals) (Bingham, Schmidt, & Zaal, 1999; Bingham, Zaal, Shull, & Collins, 2001; Zaal, Bingham, & Schmidt, 2000). In fact, non- 0° phase relations between the two oscillating visual signal were judged to be intrinsically more variable than 0° , maximally so at 90° , with 180° phase relation judged to be intermediate between these performance extremes at 0° and

90°. These findings clearly suggest a close relationship between perceptually judging and producing different relative phase patterns. As a result, manipulations of the visual display of relative phase patterns should possibly facilitate the actual coordinated production of phase relations. Bogaerts, Buekers, Zaal, & Swinnen (2003) addressed whether bimanual coordination patterns with varying degrees of stability were differentially affected by correct and transformed visual feedback conditions. In a bimanual cyclical line drawing task, visuo-motor transformations that dissociated the perceived movement direction from the actually generated direction were applied to one or both limbs, resulting in varying degrees of perceptual grouping power. Specifically, the effect of perceiving motion structures with different degrees of perceptual power was based on the well-known perceptual Gestalt notion of “common fate” (Wertheimer, 1976). This perceptual grouping principle states that stimuli moving coherently in the same direction and at the same speed have a strong tendency to be perceptually grouped together. These iso-directional moving elements are perceptually more salient resulting in easier recognition and more rapid detection than other motion structures (Palmer, 1999; Uttal, Spillmann, Sturzel, & Sekuler, 2000). Bogaerts et al. (2003) showed that the transformed feedback failed to influence the most stable in-phase coordination patterns (0°) whereas the accuracy and/or stability of the more variable anti-phase (180°) and orthogonal coordination patterns (90°) benefited from specific visual feedback manipulations. Particularly, when the provision of transformed feedback resulted in coherently grouped visual motion structures, the quality of the coordination improved significantly in the less stable coordination patterns. Roerdink, Peper, & Beek (2005) extended the research of Bogaerts et al. (2003) to the context of rhythmic unimanual

visuo-motor tracking. The effects of correct (i.e., actual hand movement) and mirrored visual feedback (i.e., hand movement represented in the opposite direction of the actual hand movement) were investigated on in-phase (i.e., visual stimulus and hand moving in the same direction) and anti-phase (i.e., visual stimulus and hand moving in the opposite direction) tracking performance. The results confirmed previous work as the quality of the in-phase tracking was hardly affected by the two forms of visual feedback while anti-phase tracking clearly benefited from the coherently grouped visual motion structures in the mirrored feedback conditions. Actually, these studies emphasized the importance of the coupling between perception and action in the attempt to refine human coordination.

Based on the findings of the facilitating role of basic principles of perceptual grouping for the production of (more complex) coordination patterns, we want to take this issue a step further and explore the effect of temporally shifted visual feedback on the synchronization performance in three synchronization modes (in-phase, anti-phase and intermediate) at the perception-action level. Note that Bogaerts et al. (2003) and Roerdink et al. (2005) studied the effect of transformed feedback as function of directional compatibility since only the direction of the actual hand position was manipulated. In the present rhythmic unimanual synchronization task, we will make use of temporally shifted visual feedback which implies an additional temporal delay between the generated arm movement and the visual representation of the arm movement. Previous studies (Frank, Beek, & Friedrich, 2003; Gauthier, Vercher, Mussa Ivaldi, & Marchetti, 1988; Langenberg, Hefter, Kessler, & Cooke, 1998; Miall, Weir, & Stein, 1985; Tass, Kurths, Rosenblum, Guasti, & Hefter, 1996; Vercher & Gauthier, 1992) already used the technique of delayed visual feedback to explore coordination control in eye and hand

tracking of a visual signal and to examine the role of sensory feedback by altering the match between the internal proprioceptive and external visual feedback. The major research question of this study focused on the interaction between the five temporally shifted visual feedback conditions (0%, 25%, 50%, 75% and 100%) and three synchronization modes (in-phase, anti-phase and intermediate). Specifically, we intended to find out whether the salience of the visual motion structure may also determine the synchronization performance when a severe spatial and temporal conflict was created between the visual and proprioceptive information. The mismatch between visual and proprioceptive feedback involved that the participants had to adapt the calibration of the visuo-motor system in response to the changing relationship between vision and proprioception. The experimental design is presented in Table 1 to further elucidate this research question.

(Insert Table 1 about here)

Given the use of five visual feedback conditions in the three synchronization modes, different feedback conditions could result in the same perceptual pattern between the temporally shifted visual feedback of the arm and the visual target signal across the three synchronization modes. As illustrated in Table 1, in the anti-phase synchronization mode (i.e., arm had to be moved in the opposite direction as the visual target signal) the 50% visual feedback condition involved that the movement of the arm is temporally shifted by a half-cycle duration which could result in an in-phase visual motion pattern of the preprogrammed target signal and the temporally shifted representation of the arm

movement. In the intermediate synchronization mode (i.e., arm had to be moved with a quarter-cycle lag with respect to the visual target signal), coherently grouped in-phase relation between the two visual signals (target signal and visual feedback of the arm movement) could appear in the 75% visual feedback condition. In addition, anti-phase and intermediate (lag and lead) phase relations between the two perceptual signals were achieved in a similar way. In general, the participants will possibly be able to adequately perform this synchronization task when the discordance was detected and followed by the recalibration of the visuo-proprioceptive system. Importantly, performing well the appropriate and instructed synchronization mode was a necessary condition for generating the correct perceptual pattern in the five visual feedback conditions. It is hypothesized that the perception of the most stable in-phase motion pattern (i.e., in the in-phase 100%, anti-phase 50% and intermediate 75%) between the temporally shifted visual feedback of the arm movement and the target signal acts as an attractor resulting in performance increase as compared to the conditions in which a perceptual anti-phase and intermediate (lag and lead) pattern can be achieved. In fact, the performance amelioration in the perceptual in-phase motion pattern needs to be interpreted in terms of a “new perceptual Gestalt” (i.e., between the visual representation of the arm and the target signal) that arises as result of the visual feedback manipulation. In this rationale, we also predict that the perceptual anti-phase pattern conditions (i.e., in-phase 50%, anti-phase 100% and intermediate 25%) are better performed than the perceptual intermediate pattern conditions (i.e., in-phase 25%, in-phase 75%, anti-phase 25%, anti-phase 75%, intermediate 50% and intermediate 100%). Consequently, the degree of perceptual coherence between the temporally shifted visual feedback of the arm and the

preprogrammed target signal is expected to influence the present synchronization performance.

In addition, we were also interested in the impact of the different visual feedback conditions on the synchronization performance when a conflict between the visual and proprioceptive information was generated. Five visual feedback conditions (0%, 25%, 50%, 75% and 100%) were applied based on the results of a preliminary experiment in which the use of nine feedback conditions with a relative delay between 0% and 120% was validated (Langenberg et al., 1998). The results clearly showed that the most synchronization problems can be expected in the 75% feedback condition while performance increase will be hypothesized in the 50% and 100% feedback conditions as compared to the respectively the 25% and 75% conditions. Obviously, the no-shift or 0% feedback condition will obtain the best synchronization behavior. Furthermore, the use of the in-phase (i.e., arm and visual target signal in the same direction), the anti-phase (i.e., arm and visual target signal in the opposite direction) and the intermediate (i.e., arm had a quarter-cycle lag with respect to the visual target signal) synchronization modes involved the possibility to test stable and less stable coordination patterns in the present unimanual synchronization task. Based on the findings of numerous studies, it can be hypothesized that the best synchronization performance will be obtained in the preferred in-phase synchronization mode (0° relative phase) whereas the intermediate mode (90° relative phase) will produce the worst performance. The performance in the anti-phase synchronization mode (180° relative phase) will be situated in between these extremes.

To summarize, the overall goal of the current study was to investigate the actual impact of perceptual stability on the unimanual synchronization performance when the visual and proprioceptive information source provide conflicting information. More specific, the participants' ability to adapt their synchronization performance to the changing relationship between vision and proprioception was tested through the integration of different temporally shifted visual feedback conditions in three synchronization modes.

2. Methods

2.1. Participants

Seventeen right-handed participants volunteered to participate in the study (mean age 22.70 years, age range from 21 to 26 years). All participants had normal or corrected-to-normal vision and had no previous experience with the task. Before starting the experimental trials, the volunteers gave their informed consent.

2.2. Apparatus

In a darkened room, the participants were seated on a chair behind a table with the right forearm placed on a lever, gripping a handle fixed to the distal end. The lever could freely rotate in the horizontal plane and the participants' elbow was positioned just above the lever's axis of rotation. A shaft encoder (Tamagawa TS5116) was connected to the axis of the lever and recorded its position (accuracy of 0.05°) at a rate of 200 Hz. The

visual display (see Fig. 1) was projected on the white wall in front of the participants at a viewing distance of 1.45 m by means of a LCD-projector with a spatial resolution of 800 x 600 pixels and a refresh rate up to 75 Hz (Proxima Desktop Projector, 5600). Three stationary targets were displayed consisting of two black squares (3.5 cm x 3.5 cm or $1.38^\circ \times 1.38^\circ$ of visual angle), indicating the left and right reversal positions with an intervening distance of 118 cm (peak-to-peak amplitude of 44° or 44.28° of visual angle), and a vertical black line (3.5 cm x 51 cm or $1.38^\circ \times 19.95^\circ$ of visual angle), located in the centre of the display. The visual target signal, displayed as a red square (5 cm x 5 cm or $1.98^\circ \times 1.98^\circ$ of visual angle), was positioned 11.25 cm (or 4.44° of visual angle) above the centre of the two reversal points and moved sinusoidally at a frequency of 0.5 Hz across 118 cm. The arm movement was displayed by an unfilled self-moved circle (6 cm diameter or 2.37° of visual angle) at the same height as the stationary black squares.

(Insert Fig. 1 about here)

2.3. Task and procedure

Participants had to complete five visual feedback conditions (0%, 25%, 50%, 75% and 100% temporally shifted feedback) in three different synchronization modes (in-phase, anti-phase and intermediate) in which the representation of the generated arm movement by the self-moved circle was temporally shifted. Note that the temporal shift of the visual feedback was calculated as a fraction of the target cycle duration and therefore in literature termed as “relative delays” and expressed as a percentage (Langenberg et al., 1998). In the present task, temporal shifts or delays of 25%, 50%,

75% and 100% were introduced, transforming and displaying the actual performed arm movement with an absolute time delay of respectively 500 ms (25%), 1000 ms (50%), 1500 ms (75%) and 2000 ms (100%) besides an instant visualization of the arm movement (0%). Since in this latter 0% feedback condition no effective temporal shift was present, it could serve as a reference condition to define the mere impact of temporally shifted visual feedback on the synchronization performance. In addition to these five visual feedback conditions, the participants had to complete three synchronization modes (in-phase, anti-phase and intermediate). Whereas the in-phase mode (0° relative phase) required the volunteers to represent the target signal with the lever in the same direction, spatial reversed coupling between the arm and visual target signal was expected in the anti-phase mode (180° relative phase). In the intermediate synchronization mode (90° relative phase), participants had to move the arm with a quarter-cycle lag with respect to the target signal. Nevertheless, the participants were demanded to focus on the visual feedback of the (temporally shifted) arm movement since we instructed them to synchronize the (temporally shifted) self-moved circle in a specific way (i.e., in-phase, anti-phase, intermediate lag or intermediate lead depending on the visual feedback condition) with respect to the visual target signal. The specific instruction given with each experimental condition was shown in Table 1. In fact, subjects were never informed about the specific synchronization mode (in-phase, anti-phase or intermediate) they had to perform with the lever with respect to the target signal to solve the task.

Each experimental condition consisted of 75 reversal arm movements, divided in three successive trials of 25 cycles each. Every movement cycle lasted 2 s, resulting in

total trial duration of 50 s for each experimental condition. The order of the fifteen experimental conditions (feedback condition x synchronization mode) was randomized between the participants. The participants were instructed to start to move the lever with the arm after the target signal had completed 1 cycle (in-phase), 1.5 cycles (anti-phase) or 1.25 cycles (intermediate) according to the correct synchronization mode to solve the synchronization task.

Before starting the experiment, three practice trials (without temporally shifted visual feedback) of 25 cycles were performed in each of the three synchronization modes (in-phase, anti-phase and intermediate) to prevent misunderstandings about the task requirements. During the practice trials subjects focussed on the right starting point after 1, 1.25 or 1.5 cycles since this was of crucial importance to cope with the task constraints. In addition to these 0% visual feedback conditions, the participants became familiar with all feedback conditions in the three synchronization modes and one trial of 25 cycles in the 75% feedback condition was completed to experience the effect of the temporally shifted visual feedback of the generated arm movement for a longer period.

2.4. Data analysis

The movement amplitude ($^{\circ}$) was calculated to examine the spatial accuracy of the arm movement with respect to the fixed criterion amplitude of the target signal (44°). The spatial consistency of the arm movement was represented by the within-participants variability of amplitude ($^{\circ}$). Additionally, the temporal variability at the two reversal positions was expressed by the mean variable error (ms) representing the standard deviation of the constant error (i.e., indicating to what extent participants arrived early or

late at a reversal position). Since no difference was observed between the variable error at the left and right reversal position, the mean variable error was computed for the temporal performance of the arm movement at both reversal positions. Furthermore, the mean absolute error ($^{\circ}$) and the within-participants variability of the (continuous) relative phase ($^{\circ}$) expressed respectively, the spatio-temporal accuracy and consistency between the target and the arm movement throughout the entire trajectory. Both spatio-temporal variables were computed using a formula adapted from Kelso, Scholtz, & Schoner (1986), see also Bueckers et al. (2000). In particular, the absolute error of the (continuous) relative phase was used to indicate the absolute difference in phase angle between the arm movement and the visual target signal at each point of the trajectory while the within-participants variability of the (continuous) relative phase was calculated as the within-participant standard deviation of the (continuous) phase angle difference between target and arm movement.

The results of these dependent measurements were computed as the average of the three trials of 25 cycles each in the different experimental conditions for each participant. Statistical analyses were conducted on all variables using a 5 x 3 (feedback condition x synchronization mode) analysis of variance (ANOVA) with repeated measures. The alpha-level was set at $p < 0.05$ and all significant results involving more than two means were explored using Tukey's HSD procedures.

3. Results

An overview of the mean values for the spatial, temporal and spatio-temporal variables for the five visual feedback conditions in the three synchronization modes can be found in Table 2.

(Insert Table 2 about here)

3.1. Spatial parameters

Statistical analyses showed a significant main effect of feedback condition, $F(4, 64) = 16.78$, $p < .0001$. Arm movements approximated the criterion amplitude of the target signal (44°) most accurately in the 0% (45.57°) and 100% (46.52°) feedback conditions whereas significantly less accurate arm movements were performed in the 25% (51.10°) and 50% (50.09°) feedback conditions. Furthermore, the spatial accuracy of the arm movements with respect to the fixed target amplitude significantly differed between the three synchronization modes, $F(2, 32) = 5.05$, $p = .0124$. The best performance for this spatial variable were observed in the in-phase (47.93°) and intermediate (47.06°) mode while the amplitude of the anti-phase synchronization mode deviated the most from the criterion amplitude (49.01°). Interestingly, the ANOVA on the movement amplitude showed a significant interaction effect between the five feedback conditions (0%, 25%, 50%, 75% and 100%) and the three synchronization modes (in-phase, anti-phase and intermediate), $F(8, 128) = 3.44$, $p = .0013$ (see Fig. 2). Actually, the spatial accuracy of the arm movements of the 25% and 50% visual feedback

conditions was significantly worse in the in-phase and anti-phase synchronization as compared to the performance in the 0% and 100% feedback conditions. In the intermediate synchronization mode, spatial accuracy degraded in the 25% feedback condition and ameliorated again in the 50% feedback condition. This latter performance increase was not observed in the 50% feedback condition of the in-phase and anti-phase synchronization mode. With respect to the perceptual coordination pattern that had to be performed during the several experimental conditions, the perceived anti-phase coordination mode (in-phase 50% and intermediate 25%) resulted in the lowest spatial accuracy of the arm movement.

The ANOVA on the within-participant variability of amplitude varied significantly in function of the feedback condition, $F(4, 64) = 33.47, p < .0001$. Post-hoc analyses demonstrated that performance in the 0% feedback condition was substantially better than in the remaining four visual feedback conditions (i.e., 25%, 50%, 75% and 100%). The highest variability was observed in the 75% feedback condition in which the spatial consistency of the arm movement decreased significantly as compared to the 0%, 25% and 50% temporally shifted feedback conditions. Additionally, the results revealed a significant main effect for the synchronization mode, $F(2, 32) = 21.82, p < .0001$. In fact, the spatial variability of the arm movements became significantly larger when the participants had to synchronize the self-moved circle in the intermediate mode (6.83°) as compared to both the in-phase (4.53°) and anti-phase (5.24°) synchronization mode. The spatial variability of the arm movements did not differ between the in-phase and anti-phase synchronization mode. Furthermore, the results failed to show an interaction effect between the five visual feedback conditions and the three synchronization modes, $F(8,$

128) = 1.27, $p = .27$. Actually, the participants were able to perform consistent arm movements with respect to the fixed criterion amplitude of 44° despite the temporally shifted visual representation of the arm movement.

(Insert Fig. 2 about here)

3.2. Temporal parameter

The variable error scores at the left and right reversal positions illustrated a significant visual feedback condition main effect, $F(4, 64) = 50.75$, $p < .0001$. The temporal consistency of the arm movements diminished significantly in the 25%, 50%, 75% and 100% feedback condition as compared to the 0% visual feedback. A temporal shift of 75% of the target cycle duration provoked the largest performance deterioration, but also the 25% feedback condition was characterized by higher variable error scores as compared to 0%, 50% and 100% feedback conditions. In addition, the results for the variable error scores varied significantly in function of the synchronization mode, $F(2, 32) = 42.12$, $p < .0001$. Post-hoc analyses indicated that the temporal variability of the arm movement at both reversal positions was more consistent in the in-phase synchronization mode (156 ms) than the anti-phase mode (300 ms). Moreover, the temporal synchronization performance in this latter condition was significantly better than in the intermediate (382 ms) mode. Furthermore, the results of the temporal variability of the arm movements at the left and right reversal position showed a significant interaction between the visual feedback condition and the synchronization mode, $F(8, 128) = 2.21$, $p < .05$. Specifically, the temporal variability of the arm

movements at both reversal positions in the 0% feedback condition of the three synchronization modes was significantly better than the performance in the 25% and 75% feedback condition, but the performance amelioration obtained in the 50% feedback condition in the in-phase mode did not occur in the anti-phase and intermediate mode. Actually, the participants' arm movements were temporally more variable at the reversal positions when they had to accomplish the intermediate lag (in-phase 25%) and lead (in-phase 75%) visual pattern between the self-moved circle and the visual target signal in the in-phase synchronization mode. In the anti-phase mode, the most variable arm movements at both reversal positions were performed when a visual intermediate lead (anti-phase 25%), in-phase (anti-phase 50%) and intermediate lag (anti-phase 75%) pattern had to be executed between both the temporally shifted visual feedback of the arm movement and the fixed target signal. Finally, the intermediate synchronization mode was characterized with the worst performance when the volunteers had to perform the anti-phase (intermediate 25%), intermediate lead (intermediate 50%) and in-phase (intermediate 75%) visual pattern between both signals.

3.3. Spatio-temporal parameters

Statistical analyses of the absolute error of the (continuous) relative phase indicated a significant visual feedback condition main effect, $F(4, 64) = 21.51, p < .0001$. The spatio-temporal accuracy of the arm movements appeared to decrease in function of the increasing temporal shift between the target signal and the visual representation of the arm movements from the 0% till the 75% feedback condition. The synchronization performance in this 75% feedback condition was significantly less accurate than in the

four other feedback conditions (i.e., 0%, 25%, 50% and 100%). Synchronization performance of the 100% feedback condition approximated the level of the 50% feedback condition. The data also revealed a main effect for the synchronization mode, $F(2, 32) = 51.87$, $p < .0001$. A significant deterioration was observed between the in-phase and the anti-phase mode. This performance decrease was even aggravated in the intermediate synchronization mode. Furthermore, the results of the absolute error of the (continuous) relative phase demonstrated an interaction effect between feedback condition and synchronization mode, $F(8, 128) = 4.27$, $p < .001$ (see Fig. 3). In the in-phase synchronization mode, the participants' arm movements deviated the most from the preprogrammed target signal in the 75% temporally shifted feedback condition as compared to the other feedback conditions (0%, 25%, 50% and 100%) (see Fig. 4a and 4b). In other words, the absolute error of the (continuous) relative phase attained the largest error scores when the participants had to realize an intermediate lead visual pattern. Yet, in the anti-phase synchronization mode both the 75% feedback condition and the 100% feedback condition provoked significant less accurate arm movements at each point of the trajectory than the 0% feedback condition. These results were confirmed in the intermediate synchronization mode since the performance in the 0% feedback condition differed significantly from synchronization performance in the 75% and 100% visual feedback conditions. Note that in this intermediate mode the 25% feedback condition was significantly better than the remaining feedback conditions (50%, 75% and 100%). Based on these data of the feedback condition x synchronization mode interaction effect, we may conclude that the impact of temporally shifted visual feedback on the synchronization performance was strongly dependent on the synchronization mode in

which the participants had to perform the five feedback conditions. As can be seen in Fig. 5a, 5b, 6a and 6b, the displacement curves of the arm with respect to the visual target signal failed to ameliorate in the anti-phase and intermediate synchronization mode when a perceptual in-phase pattern between the self-moved circle and the target signal could be achieved in respectively the anti-phase 50% and intermediate 75% condition. In fact, the results seemed to indicate that the absolute error of the (continuous) relative phase mainly increased in function of the increasing temporal shift in the more complex synchronization modes as anti-phase and intermediate mode. Specifically, in all synchronization modes the worst synchronization performance was achieved in the 75% feedback condition. Nevertheless, in the in-phase synchronization mode the performance in the 100% feedback condition ameliorated and reached the level of the 0% no-shift feedback condition in contrast to the anti-phase and intermediate mode. Actually, the performance in the 100% feedback condition differed significantly from the performance in the 0% feedback condition in the anti-phase and intermediate mode. In this latter synchronization mode the synchronization behavior in the 50%, 75% and 100% feedback conditions showed similar large performance deficits.

(Insert Figs. 3, 4a, 4b, 5a, 5b, 6a and 6b about here)

The ANOVA of the within-participant variability of the (continuous) relative phase clearly demonstrated a significant visual feedback condition main effect, $F(4, 64) = 38.71$, $p < .0001$. As in the previous analyses, the performance in the 0% feedback condition differed significantly from the remaining four feedback conditions (i.e., 25%,

50%, 75% and 100%) and the highest variability scores were obtained in the 75% feedback condition. Furthermore, the results showed a main effect for the three synchronization modes, $F(2, 32) = 24.92$, $p < .0001$. In particular, the spatio-temporal consistency of the synchronization performance at each point in the trajectory confirmed the data of all previous described variables as the performance decreased significantly from the in-phase (10°) to the anti-phase mode (13°) and from the anti-phase (13°) to the intermediate (16°) synchronization mode. However, the within-participant variability of the (continuous) relative phase failed to reach the level of significance for the interaction between the visual feedback condition and synchronization mode, $F(8, 128) = 1.35$, $p = .23$.

4. Discussion

Since previous studies (Bogaerts et al., 2003; Roerdink et al., 2005) indicated that the perception of coherently grouped motion structures facilitated the performance of visuo-motor coordination tasks, the current synchronization study was designed to explore the strength of perceptual stability on the synchronization performance when a conflict between visual and proprioceptive information was established. The primary goal of this study was to investigate how synchronization performance evolves at the interaction level between five temporally shifted visual feedback conditions (i.e., 0%, 25%, 50%, 75% and 100%) and three synchronization modes (i.e., in-phase, anti-phase and intermediate) in an unimanual perception-action coupling task. In particular, the

participants were instructed to synchronize the temporally shifted self-moved circle in a specific coordination mode with respect to the visual target signal (as illustrated in Table 1). Yet, this perceived coordination mode was different than the synchronization mode (between the arm and the visual target signal) they had to accomplish to solve the task (with exception of the 0% and 100% feedback conditions). By doing so, we were able to explore the role of coherently grouped visual motion structures on the synchronization performance in a visuo-proprioceptive conflict situation. Specifically, the interaction between five temporally shifted feedback conditions and three synchronization modes implies the possibility to test the same perceptual coordination patterns in different conditions. Note that it was stipulated that the participants had to perform the correct synchronization mode to achieve appropriately the instructed perceptual pattern. For this reason, we instructed the participants to start the arm movements after the visual target signal completed 1 cycle (i.e., in-phase), 1.5 cycles (i.e., anti-phase) or 1.25 cycles (i.e., intermediate) to provide them the ability to begin each experimental condition according to the correct synchronization mode.

The current results showed that the impact of the visual distortion of motion structures (i.e., between temporally shifted visual representation of the arm and the target signal) on synchronization performance differed in the three synchronization modes as indicated by the visual feedback condition x synchronization mode interaction effect for the spatial, temporal and spatio-temporal parameters respectively expressed by movement amplitude ($^{\circ}$), variable error (ms) and absolute error of the (continuous) relative phase ($^{\circ}$).

The performance in the *in-phase synchronization mode* corroborated the findings in the literature (Bingham et al., 1999; Bogaerts et al., 2003; Buekers et al., 2000; Langenberg et al., 1998; Roerdink, Peper, & Beek, 2005; Ryu & Buchanan, 2009; Swinnen, et al., 1998; Wilson, Collins, & Bingham, 2005a, 2005b). The spatial accuracy of the arm movements was significantly lower in the 50% feedback condition in which the spatial incompatibility (i.e., perception of the arm in a position that is incompatible with the proprioceptive information of the muscle afferents) between the target signal and the temporally shifted visual feedback of the actual arm movement was maximal (Langenberg et al., 1998; Poulton, 1974). Since performance amelioration was found in the temporally larger visual feedback conditions (75% and 100%) spatial rather than temporal (i.e., perception of an arm movement with a temporal delay) incompatibility between the performed arm movements and the visual display seemed to dominate the results of the movement amplitude in the in-phase synchronization mode. This finding confirmed the notion that relative delays (i.e., delay in function of the total cycle duration) rather than absolute temporal delays influenced the spatial accuracy in this rhythmical synchronization task.

In addition, the temporal and spatio-temporal variables demonstrated that the best synchronization was attained in the most stable 0%, 100% (0° relative phase) and 50% (180° relative phase) feedback conditions whereas the worst performance level was found in the less preferred and intrinsically unstable 25% and 75% feedback conditions (90° relative phase). Interestingly, the good performance in the 100% feedback condition provided evidence of the attracting and facilitating impact of the new perceptual Gestalt between the temporally shifted visual feedback of the arm and the preprogrammed visual

target signal. Moreover, the participants also better synchronized with the target signal in the 50% feedback condition in which the perceptual anti-phase pattern could be achieved as compared to the intermediate 25% and 75% feedback conditions in the in-phase synchronization mode.

In the *anti-phase synchronization mode*, the impact of the temporally shifted visual feedback conditions on the synchronization performance seemed to enlarge as compared to the in-phase synchronization mode. The spatial accuracy of the 25% and 50% visual feedback conditions deviated the most from the criterion amplitude of 44° . The perceptual in-phase pattern between the temporally shifted self-moved circle and the target signal failed to positively affect the accuracy of the arm movements with respect to the fixed amplitude in this feedback condition. Furthermore, the temporal variability and spatio-temporal accuracy of the arm movement deviated the most from the target signal in the 75% feedback condition. The participants attained their best synchronization level in the 0% feedback condition representing a perceptual anti-phase pattern. Interestingly, the variability and accuracy of the synchronization performance improved again in the 100% feedback condition with the largest absolute delay of 2000 ms between the actual performed and the displayed arm movement. Note that the perceptual anti-phase coordination pattern had to be executed in this 100% feedback condition. In addition to the good performance in the perceptual anti-phase conditions (0% and 100%), the results of the absolute error of the (continuous) relative phase at each point of the trajectory revealed better arm movements in the 50% feedback condition inducing a perceptual in-phase coordination pattern as compared to the 75% and 100% feedback conditions. Since the best synchronization behavior was produced in the perceptual in-phase and anti-phase

pattern conditions (anti-phase 0%, 50% and 100%) these results partially confirmed the hypothesis that coherently grouped visual motion structures has the potential to aid the synchronization performance when a conflict between the visual and proprioceptive information was created.

In the *intermediate synchronization mode*, the spatial accuracy of the movement amplitude corroborated the findings of the previous described in-phase synchronization mode. Specifically, the participants arm movements became significantly larger in the perceptual anti-phase pattern in which the spatial incompatibility between the target signal and the temporally shifted feedback of the performed arm movement was the largest (Langenberg et al., 1998; Poulton, 1974). In contrast to this spatial parameter, the temporal shift between the visual feedback and the actual executed arm movement seemed to primarily dominate one's synchronization performance in the intermediate synchronization mode. Specifically, significant performance loss was observed for the temporal and spatio-temporal parameters in the 50%, 75% and 100% feedback conditions as a result of the larger amount of absolute delay between the visualized and generated arm movement. As such, these findings failed to confirm the facilitating role of the coherently grouped visual motion structures on the synchronization performance in the most complex intermediate synchronization mode. In fact, the large impact of the temporally shifted visual feedback showed that the participants were not able to correctly perform the required synchronization mode. Since performing the correct synchronization mode (in-phase, anti-phase and intermediate) was the necessary condition to generate the different perceptual patterns (in-phase, anti-phase and intermediate lag or lead), the stable perceptual in-phase pattern could not fulfill the previously mentioned attractor role.

Considering the effect of temporally shifted visual feedback on synchronization behavior, we may conclude the importance of the proprioceptive information source in the less preferred synchronization modes. Actually, the contribution of vision and proprioception seemed to progressively differ between the in-phase, anti-phase and intermediate synchronization mode. In the in-phase synchronization mode, the accuracy and consistency of the performance was not influenced by the conflict between visual and proprioceptive information. As a result, the perceptual Gestalt laws in visual motion perception seemed to overrule the impact of proprioception since performance amelioration was observed in the most stable perceptual patterns (i.e., in-phase and anti-phase) (Bogaerts et al., 2003; Ryu & Buchanan, 2009). In the less stable anti-phase and intermediate synchronization modes the synchronization performance tended to vary in function of the increasing absolute amount of delay duration. In these latter synchronization modes, the proprioceptive information source seemed to gain importance against the role of vision since no performance benefit was observed in case of perceptual in-phase coordination patterns. Recent work of Ryu & Buchanan (2009) showed the impact of creating a coherently grouped visual motion structure that can influence the performance stability of less stable coordination patterns in dynamic perception-action tasks. The inability of our participants to adapt properly to the mismatch between the visual and proprioceptive information in the anti-phase and intermediate synchronization modes prevented the creation of global coherent visual motion structures that could stabilize the synchronization performance. Other studies (Rossetti, Desmurget, & Prablanc, 1995; van Beers, Wolpert, & Haggard, 2002) also reduced the classical dominance of vision on proprioception in the control of hand position when the

information of both senses is available (Welch & Warren, 1986). Obviously, the weighting between vision and proprioception was flexible and the weights were optimized for the precision in a given situation. Recent work of Sarlenga, Gauthier, & Blouin (2007) clearly stated that visuomotor adaptation is a multisensory and highly flexible process.

The findings of the present study were interpreted along the lines of the perceptual Gestalt laws, referring to the tendency of iso-directional moving elements to be perceived as coherently grouped visual motion structures (Wertheimer, 1976). Actually, we unilaterally focused on the facilitating role of salient visual motion patterns in an important visuo-proprioceptive conflict situation. It must be noted however that our results could only partially confirm the beneficial impact of perceptual grouping principles on task performance. A probable explanation for this limited impact might be found in the potential disrupting influence of transformed visual feedback on motor behavior. Actually, several studies (Carnahan, Hall, & Lee, 1996; Cunningham, 1989; Hefter & Langenberg, 1998; Langenberg et al., 1998; Miall et al., 1985; Morikiyo & Matsushima, 1990; Reed, Liu, & Miall, 2003) reported the existence of these detrimental effects. An alternative explanation for the present findings could be found in the disturbing effect of the integration of temporally delayed visual feedback. In particular, the results of the less stable anti-phase synchronization mode revealed the disadvantageous effect of transforming and displaying the actual performed arm movement with an absolute time delay up to 500 ms (25%). Note that Miall et al. (1985) and Vercher & Gauthier (1992) set 200 - 250 ms as upper limit of absolute delay that can be compensated by the prediction mechanism of the arm motor system. Morikiyo &

Matsushima (1990) examined delays up to 1000 ms and found that the performance for the 1000 ms delay condition (one cycle duration) was significantly better than for the 767 ms delay condition (75% of cycle duration), but the no-delay condition evoked the best tapping performance. In line with this finding and as illustrated in Figure 5a and 5b, the synchronization performance seemed to be affected primarily by the temporally delayed visual feedback manipulation since performance in the anti-phase trial without delay (0%) was significantly better than the 50% delay condition despite the perceptual in-phase visual motion structure. In addition, performance in the intermediate synchronization mode showed an even stronger deterioration resulting from the temporally disrupted visual target-feedback relationship as the performance deficit already materialized in the 50% feedback condition (see Figs. 3, 6a and 6b). The participants were clearly unable to benefit from the perceptual Gestalt laws because of the complexity of the anti-phase and intermediate synchronization modes when temporally transformed feedback was provided. At present we cannot rule out the former explanation. Further experiments are needed to take a firm position on this issue.

Another point of interest was examining the main effects of temporally shifted visual feedback on the synchronization performance. As mentioned before, the movement amplitude was largely affected by the spatial incompatibility as could be seen in the 50% feedback condition (Langenberg et al., 1998). For the temporal and spatio-temporal variables we hypothesized that temporally transformed feedback will negatively influence the synchronization performance as compared to the no-shift or 0% feedback condition. The data clearly underpin this hypothesis and revealed the largest synchronization problems when a temporal shift of 75% of the total cycle duration (= absolute time delay

of 1500 ms) was applied. Interestingly, the participants' performance increase in the 100% feedback condition confirmed that the temporal incompatibility between the visual feedback of the arm movement and the target signal (increasing monotonically with the absolute amount of the delay duration) failed to determine the overall synchronization performance in this synchronization task (Langenberg et al., 1998).

The last research question in this study addressed how action constraints influence synchronization performance in three synchronization modes. As hypothesized, the results generally confirmed the findings of previous research that clearly showed that accuracy and variability evolve monotonically between the different coordination modes (Buekers et al., 2000; Swinnen, Jardin, Meulenbroek, Dounskaia, & Hofkens-Van Den Brandt, 1997; Zaal et al., 2000). Specifically, the best synchronization performance was observed in the in-phase synchronization mode while the anti-phase mode involved significant performance loss. Furthermore, the participants showed even more severe synchronization problems for all parameters when they had to move the lever with a quarter-cycle lag with respect to the target signal in the intermediate synchronization mode. A possible explanation of this performance decrease could be found in the fact that it was not appropriate in the intermediate synchronization mode to rely on the reversal positions in the participants' attempt to comply with the task constraints. As a matter of fact, previous research (Ceux et al., 2003) had demonstrated the importance of the reversal positions as anchor points for efficient movement production in a similar synchronization task, containing in-phase and anti-phase synchronization modes. Since in the intermediate synchronization mode the self-moved circle and the visual target signal had to change direction at different points in time to solve the task, an alternative anchor

point had to be found as compared to the left and right reversal positions in both the in-phase and anti-phase mode.

To summarize, the synchronization performance in the stable in-phase synchronization mode is aided by visual feedback transformations resulting in coherently grouped visual motion structures. Conversely, the participants' behavior deteriorated in function of the absolute amount of delay duration in a visuo-proprioceptive conflict situation in the less preferred anti-phase and intermediate synchronization modes. The stability of the synchronization mode seems to determine the ability to benefit from the perceptual Gestalt laws of motion processing in the present perception-action task.

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Table 1

The Experimental Design with the Perceptual Pattern (i.e., participants' specific instruction involving the synchronization of the self-moved circle with the visual target signal) for each Visual Feedback Condition in the three Synchronization Modes

<i>Synchronization mode</i>	<i>Visual feedback condition</i>				
	0%	25%	50%	75%	100%
In-phase (0°)	<i>In-phase</i>	<i>Intermediate lag</i>	<i>Anti-phase</i>	<i>Intermediate lead</i>	<i>In-phase</i>
Anti-phase (180°)	<i>Anti-phase</i>	<i>Intermediate lead</i>	<i>In-phase</i>	<i>Intermediate lag</i>	<i>Anti-phase</i>
Intermediate (90°)	<i>Intermediate lag</i>	<i>Anti-phase</i>	<i>Intermediate lead</i>	<i>In-phase</i>	<i>Intermediate lag</i>

Table 2

Mean of the Dependent Synchronization Measurements for the five Visual Feedback

Conditions in the three Synchronization Modes

			0 %	25 %	50 %	75 %	100 %
			45,57	51,10	50,09	46,74	46,52
Amplitude (°)	<i>In-phase</i>	47,93	45,47	49,78	51,22	47,24	45,96
	<i>Anti-phase</i>	49,01	46,33	51,29	51,10	48,18	48,16
	<i>intermediate</i>	47,06	44,90	52,22	47,94	44,80	45,43
Within-participant variability of amplitude (°)			0 %	25 %	50 %	75 %	100 %
			2,15	6,00	5,68	7,56	6,27
	<i>In-phase</i>	4,53	1,61	5,88	4,18	6,37	4,61
	<i>Anti-phase</i>	5,24	2,12	5,16	5,71	7,14	6,10
	<i>intermediate</i>	6,83	2,73	6,98	7,18	9,18	8,10
Variable error (ms)			0 %	25 %	50 %	75 %	100 %
			108,14	356,79	273,80	460,27	197,92
	<i>In-phase</i>	155,74	40,25	203,86	97,43	358,10	79,05
	<i>Anti-phase</i>	299,97	123,76	358,55	313,86	474,34	229,34
	<i>intermediate</i>	382,44	160,40	507,95	410,10	548,37	285,38
Absolute error of (continuous) relative phase (°)			0 %	25 %	50 %	75 %	100 %
			55,19	60,07	65,12	82,75	70,65
	<i>In-phase</i>	51,34	38,28	52,98	49,09	70,97	45,40
	<i>Anti-phase</i>	66,65	55,01	60,53	60,79	83,75	73,19
	<i>intermediate</i>	82,27	72,27	66,71	85,48	93,53	93,35
Within-participants variability of (continuous) relative phase (°)			0 %	25 %	50 %	75 %	100 %
			7,12	12,78	12,37	20,99	12,53
	<i>In-phase</i>	10,31	4,93	11,38	7,07	19,16	9,03
	<i>Anti-phase</i>	13,01	7,58	12,19	13,02	19,95	12,31
	<i>intermediate</i>	16,15	8,85	14,76	17,03	23,85	16,25

Figure Captions

- Fig. 1.* The visual display projected in front of the participants.
- Fig. 2.* The movement amplitude in the five feedback conditions for the three synchronization modes. The feedback condition x synchronization mode interaction effect indicated the lowest spatial accuracy of the arm movements in both the 25% and 50% feedback conditions in the in-phase and anti-phase synchronization modes. In the intermediate mode, performance increase was observed in the 50% visual feedback condition in contrast to the in-phase and anti-phase synchronization mode.
- Fig. 3.* The absolute error of the (continuous) relative phase in the five feedback conditions, separate for the three synchronization modes. The feedback condition x synchronization mode interaction effect indicated a performance increase in the 50% and the 100% feedback conditions in the in-phase synchronization mode in contrast to the anti-phase and intermediate mode. The synchronization performance in the more complex anti-phase and intermediate seemed to evolve in function of the increasing temporal shift between the visual feedback of the arm movement and the target signal.
- Fig. 4a./4b.* The displacement curves of the arm and the target signal in the third trial in the in-phase synchronization mode for a representative participant. The

performance in the 0% feedback condition (4a) was significantly better than the synchronization behavior in the 75% feedback condition (4b).

Fig. 5a./5b. The displacement curves of the arm and the target signal in the third trial in the anti-phase synchronization mode for a representative participant. The performance in the 0% feedback condition (5a) was significantly better than the synchronization behavior in the 50% feedback condition (5b).

Fig. 6a./6b. The displacement curves of the arm and the target signal in the third trial in the intermediate synchronization mode for a representative participant. The performance in the 0% feedback condition (6a) was significantly better than the synchronization behavior in the 75% feedback condition (6b).

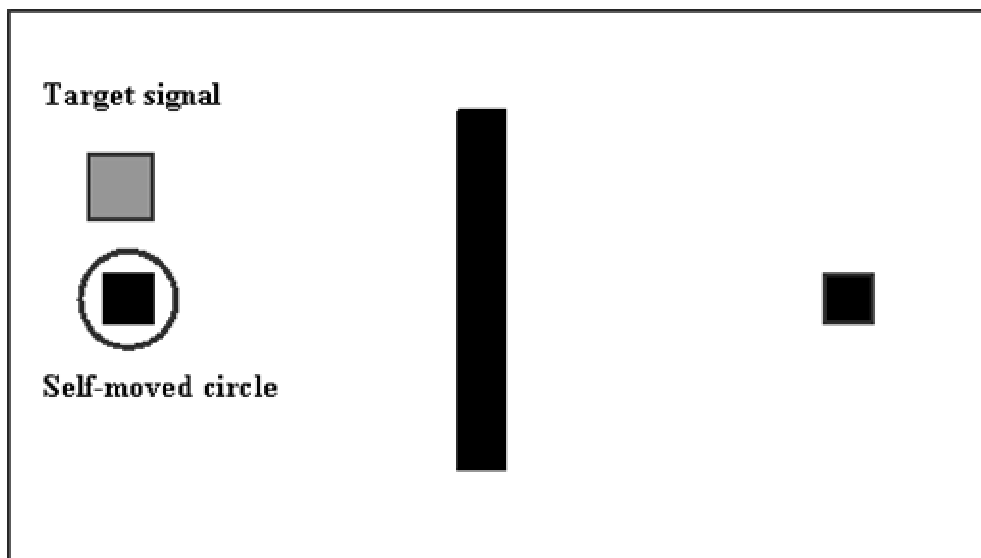


Fig. 1.

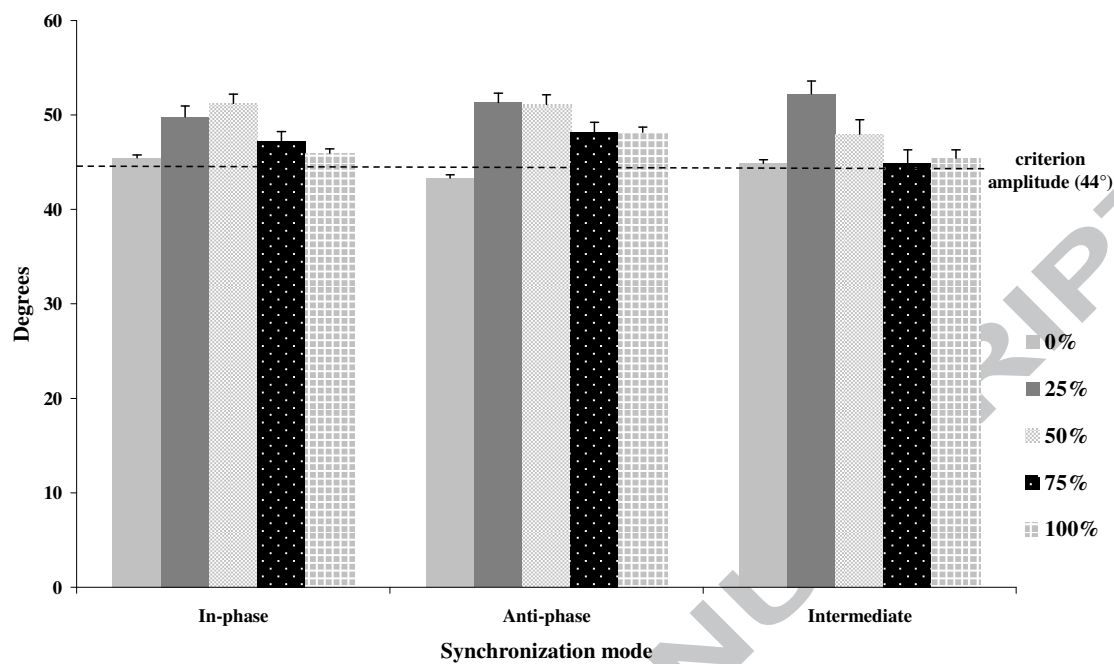


Fig. 2.

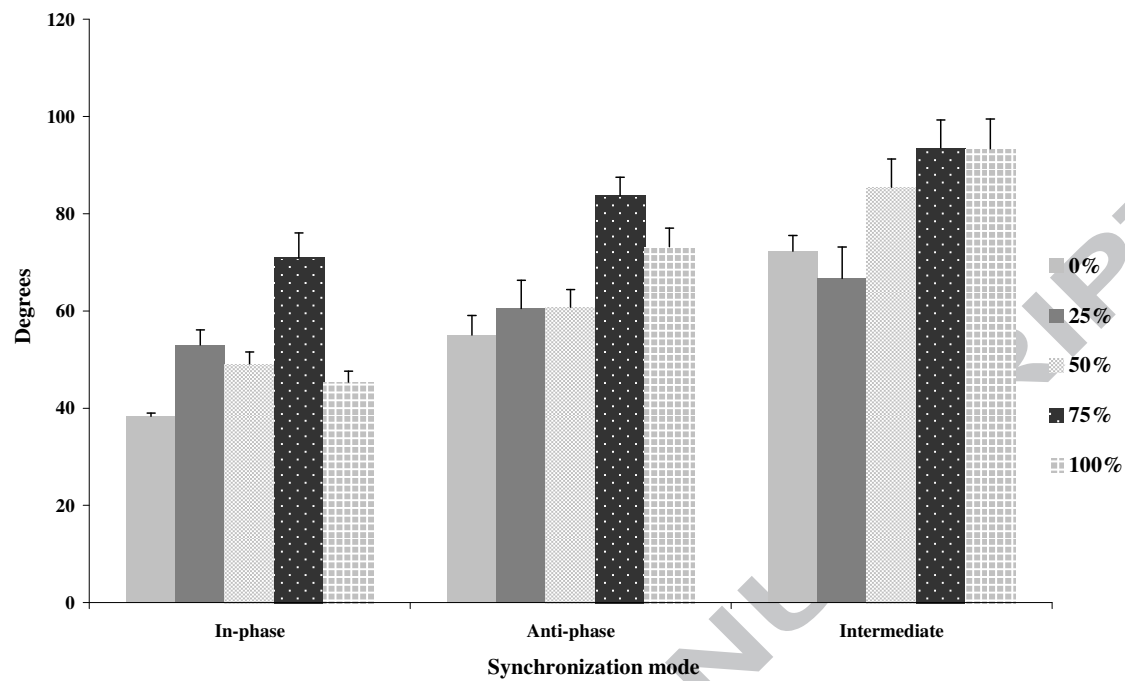


Fig. 3.

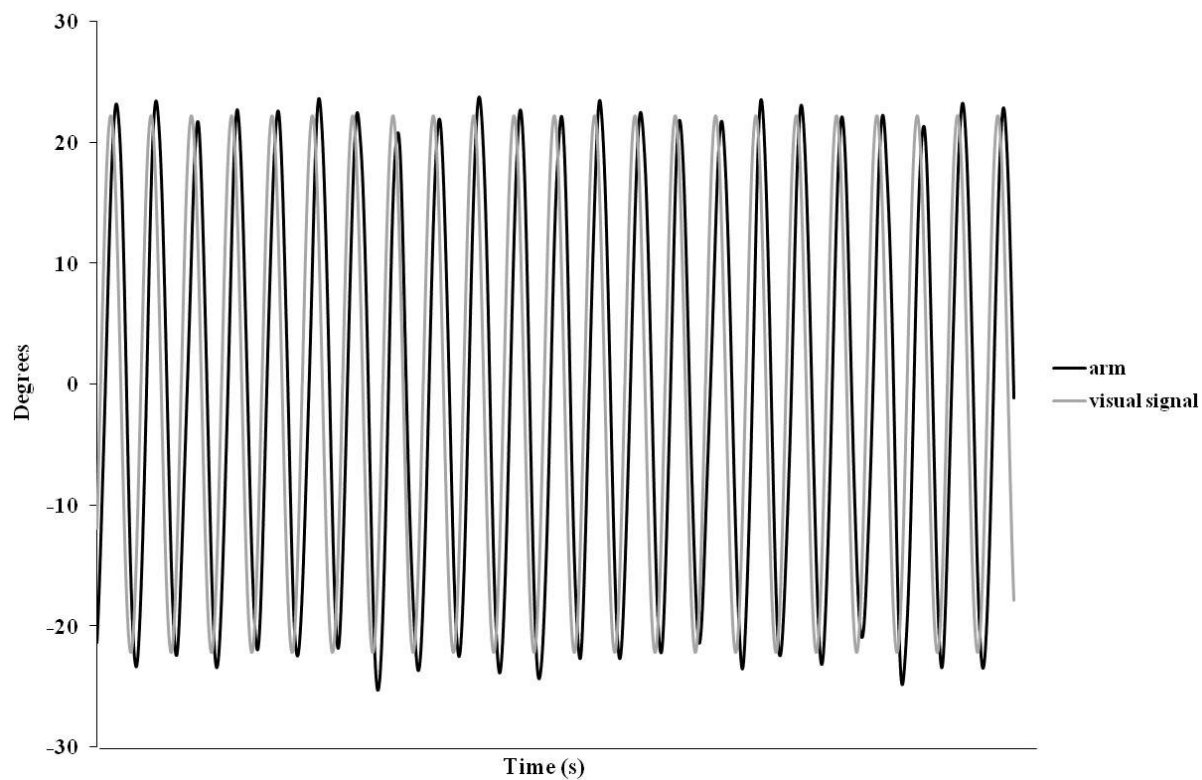


Fig. 4a.

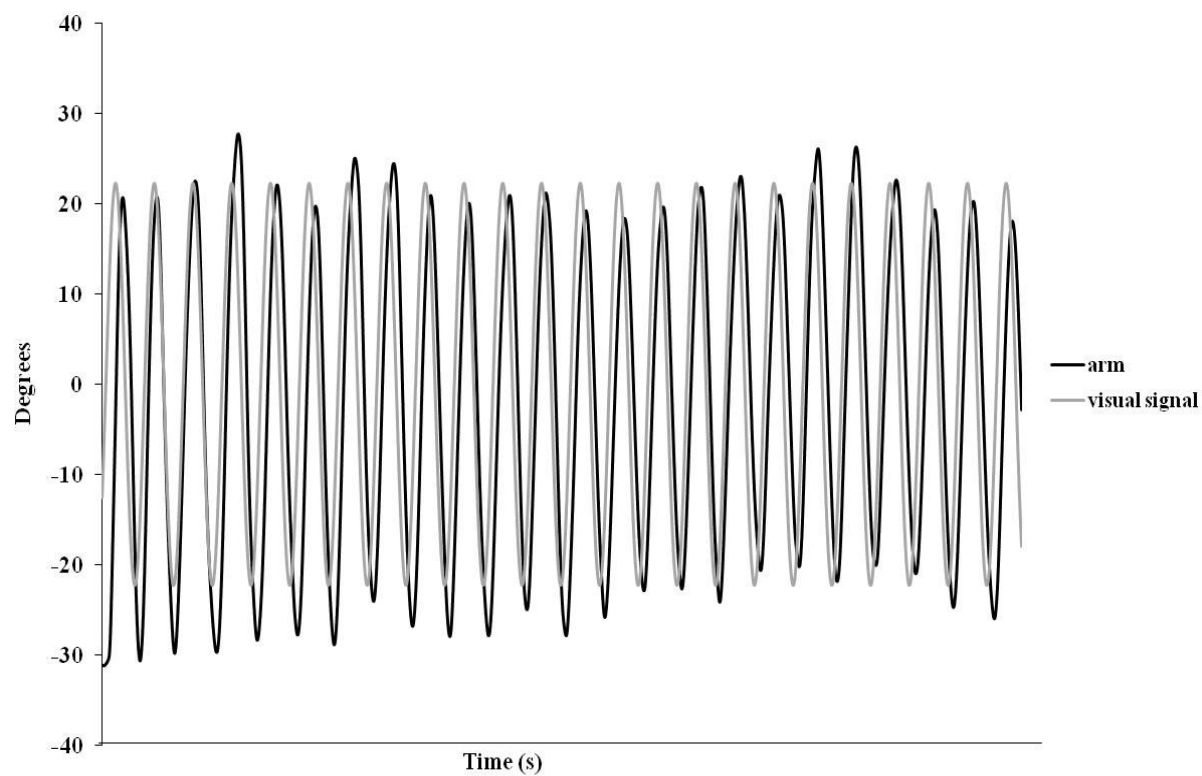


Fig. 4b.

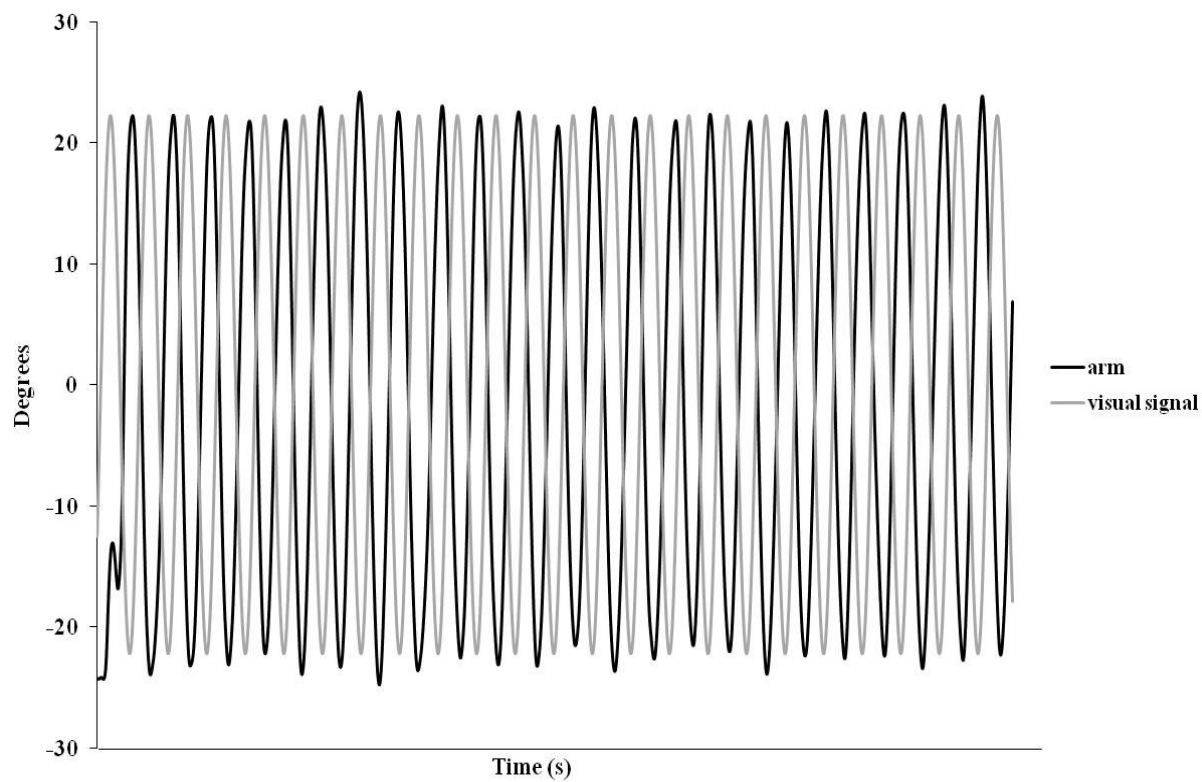


Fig. 5a.

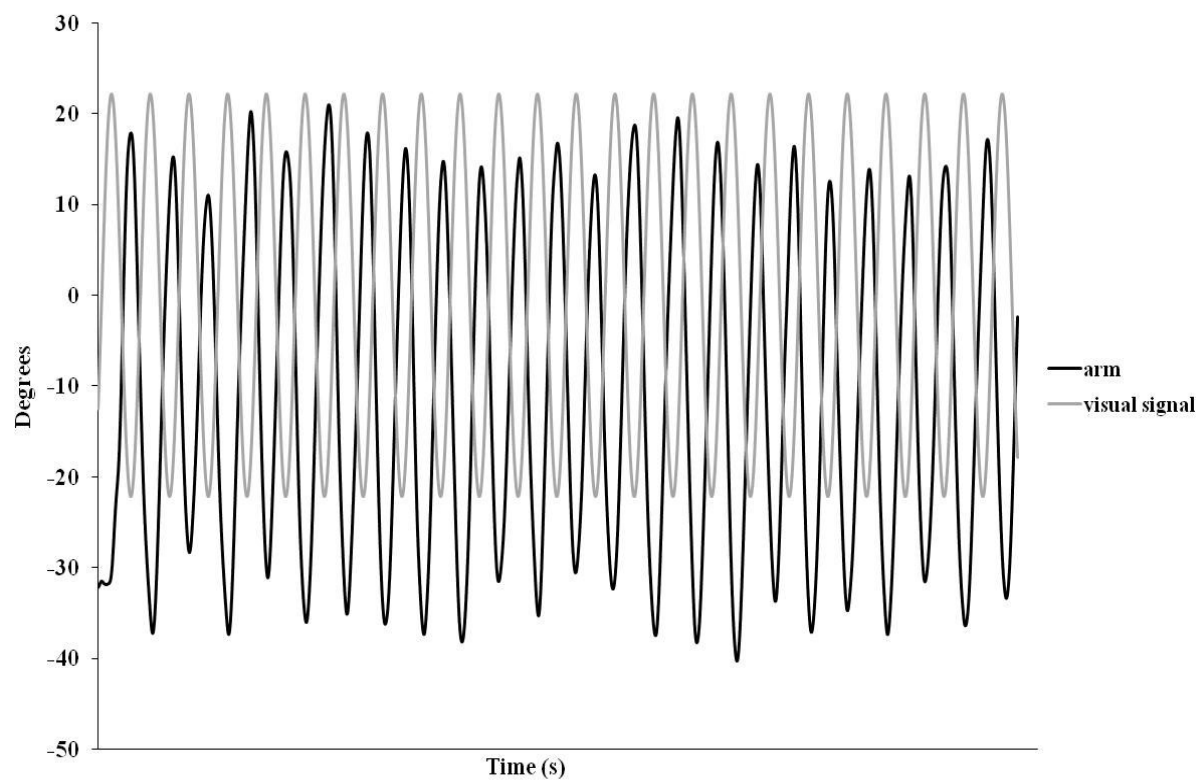


Fig. 5b.

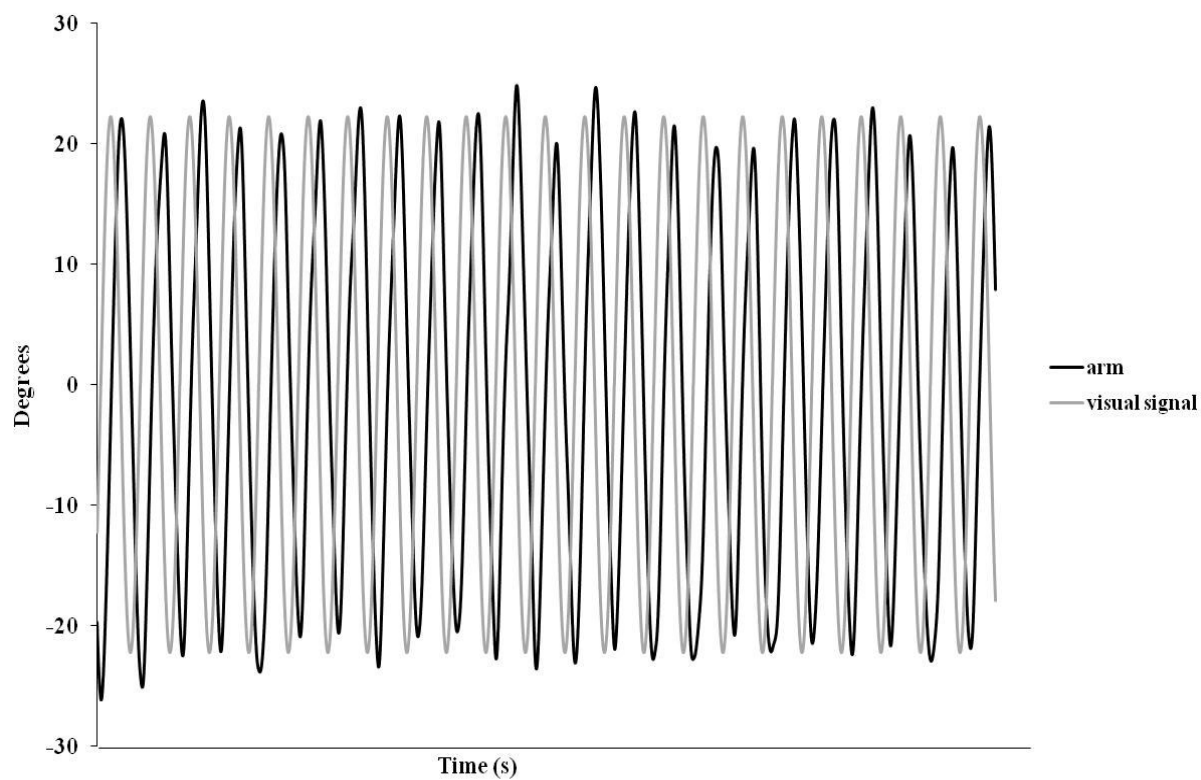


Fig. 6a.

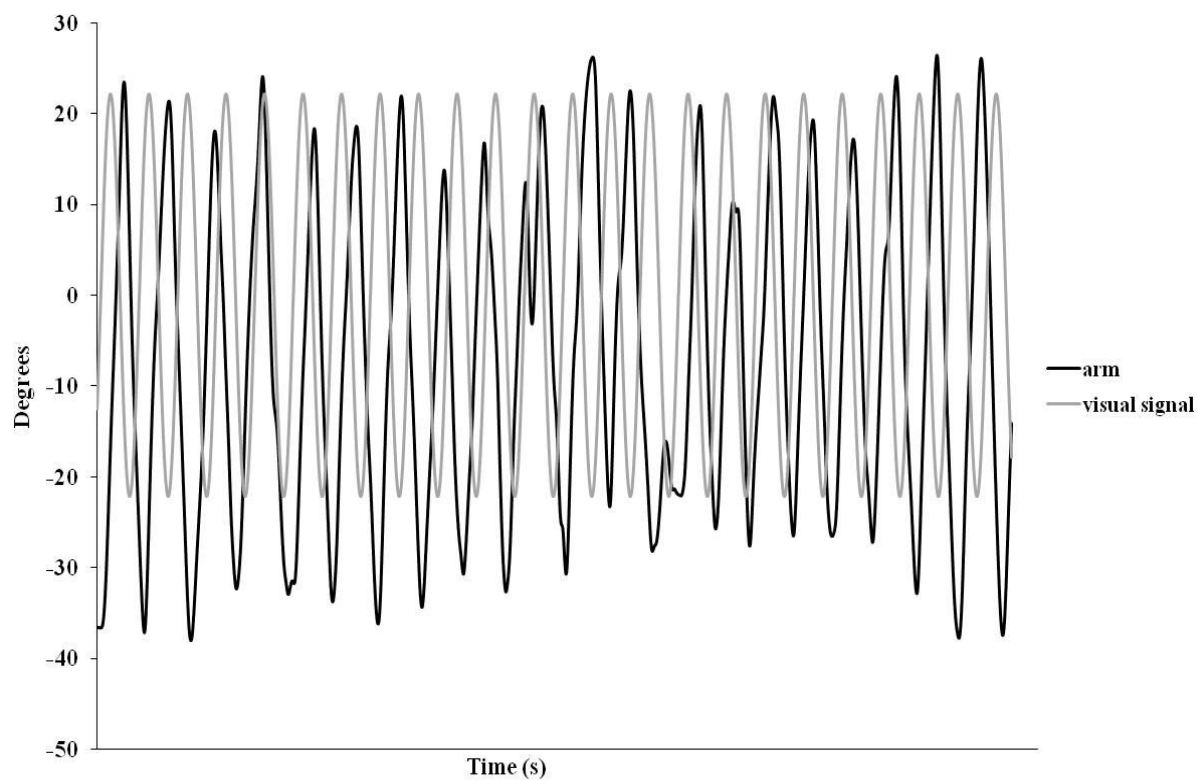


Fig. 6b.