INTER-LIMB COORDINATION DYNAMICS: EFFECTS OF VISUAL CONSTRAINTS AND AGE

Cristina Cortis[1], Caterina Pesce[2], and Laura Capranica[2]

[1]*Department of Human Sciences, Society and Health, University of Cassino and Lazio Meridionale, Cassino, Italy*
[2]*Department of Movement, Human and Health Sciences, University of Rome "Foro Italico", Rome, Italy*

Original scientific paper
UDC: 61.84:796.012.2

Abstract:

This study aimed to verify the effect of visual afference (eyes open – EO vs. eyes closed – EC) on in-phase (IP) and anti-phase (AP) homolateral inter-limb coordination performance in relation to age. Forty individuals (12 youths, age=12±1 years; 16 young adults, age=24±3 years; 12 older adults, age=59±11 years) performed IP and AP synchronized (80, 120, and 180 bpm) hand and foot flexions and extensions. Variability of IP and AP movements was obtained by calculating the within-subject standard deviation of each condition. Significant interactions between coordination mode × age and coordination mode × age × visual afference showed joint effects on IP and AP variability, while no main effects emerged. In the IP-EO condition, *post-hoc* analysis showed higher (p=.0003) variability in older adults (24.8±6.6 s) with respect to young adults (10.5±10.9 s), whereas in the IP-EC condition, older adults showed higher (p=.03) variability (23.4±10.7 s) with respect to both youths (13.7±8.6 s) and young adults (24.1±12.2 s). In both AP conditions, older adults showed lower (p<.002) variability values (EO=9.5±12.1 s; EC=4.6±7.5 s) with respect to the other age groups, with only the youth group showing differences between EO (16.6±12.1 s) and EC (23.6±8.4 s) conditions. Findings show that the age-related worsening of inter-limb coordination is independent of the use of visual afferences. In contrast, at developmental age, visual perception seems to play a differential role depending on the coordinative task complexity (IP/AP). It becomes crucial only in the AP condition, with a lower variability in the EO than in the EC condition indicating youths' tendency to rely more on visual information for stabilizing complex inter-limb coordination performance.

Key words: *vision, hand-foot coordination, motor control*

Introduction

Inter-limb coordination is an important aspect of motor function and represents a complex self-organizing system subject to individual (e.g., biopsychological), task-related and contextual constraints (Swinnen & Carson, 2002). According to the "isodirectionality principle" (Bogaerts, Buekers, Zaal, & Swinnen, 2003; Swinnen, 2002), cyclic flexion-extensions of the hand and its ipsilateral foot are easily and stably associated when the two segments oscillate with the same direction (e.g., in-phase, IP). Conversely, great control and attentional efforts are required when ipsilateral limbs move in opposite directions (e.g., anti-phase, AP; Baldissera, Borroni, & Cavallari, 2000; Serrien, Li, Steyvers, Debaere, & Swinnen, 2001; Serrien & Swinnen, 1998; Swinnen, Jardin, Meulenbroek, Dounskaia, & Hofkens-Van Den Brandt, 1997). In general, the stability of inter-limb performances is governed by a variety of constraints acting at different levels of the motor system (Carson & Kelso, 2004). Such constraints come into play in relation to frequency of execution (Capranica, Tessitore, Olivieri, Minganti, & Pesce, 2004; Capranica, Tessitore, Olivieri, & Pesce, 2005; Jeka & Kelso, 1995; Kelso, 1984; Serrien & Swinnen, 1998), amplitude (Peper & Beek, 1998), loading (Baldissera & Cavallari, 2001), direction (Capranica, et al., 2004, 2005; Meesen, Wenderoth, Temprado, Summers, & Swinnen, 2006), mechanical perturbations (Kay, Saltzman, & Kelso, 1991), mobility impairments (James, et al., 2017), and sensory feedback (Kelso, Fink, DeLaplain, & Carson, 2001; Salesse & Temprado, 2005; Salesse, Temprado, & Swinnen, 2005). Furthermore, an inter-limb coordination pattern emerged during lifespan, with performance development in youths, maintenance in adults, and decrement in older individuals (Capranica, et al., 2004, 2005; Cortis, et al., 2009; Serrien, Swinnen, & Stelmach, 2000). Finally, in relation to athletic expertise evaluations of IP and AP coupling of the ipsilateral limbs proved that acute and chronic exercise elicit beneficial effects on the efficiency of complex motor behaviors of individuals (Capranica, et al., 2004, 2005; Cavallari, Cerri, & Baldissera, 2001; Cortis, et al., 2009, 2011, 2013; Moscatelli, et al., 2016; Tessitore, et al., 2011).

Since the seminal work of Woodworth (1899), a role of vision in all aspects of movement has been proposed of having an impact on motor planning, control, and evaluation. According to the isodirectionality principle (Bogaerts, et al., 2003), visual perception of the motions of hand and foot might improve stability of their coordination. However, the effect of vision differed as a function of both neuro-muscular coupling and coordination mode (Salesse, et al., 2005), with the presence of visual feedback able to stabilize IP and destabilize AP performances under dissimilar neuro-muscular coupling (e.g., prone vs. supine movements), while not effecting conditions of similar neuro-muscular coupling. Also, bimanual coordination seemed to be influenced by perceptual information, with increased stability of movements when visual feedback was present (Byblow, Chua, Bysouth-Young, & Summers, 1999) and integration of the senses from different sources (e.g., vision, audition, and proprioception) being more important during AP than IP (Abedanzadeh, Abdoli, & Farsi, 2005). These results shed light on complex interactions between motor and perceptual constraints during execution of coordination patterns (Salesse, et al., 2005).

Despite the findings on hand-foot coordination suggest that perceptual afferences play a role in directional constraints of healthy adults (Salesse & Temprado, 2005; Salesse, et al., 2005; Serrien, et al., 2000) and stroke patients (Debaere, Van Assche, Kiekens, Verschueren, & Swinnen, 2001), no information is available on healthy youths and old individuals. This may be relevant not only to further our understanding of the control and regulation of different complex motor coordination patterns, but also to optimize perceptual-motor training in phases of life, in which motor coordination has still not reached or is already descending from the level of optimal functioning.

Therefore, the purpose of this study was to verify the role of visual afferences in IP and AP inter-limb coordination performances in relation to age. It has been hypothesized that: 1) availability of vision could have a stabilizing effect on both IP and AP inter-limb coordination patterns when compared to no vision conditions; and 2) the destabilizing effect of visual information removal would differ between age groups.

Methods

Participants

The local Institutional Research Committee approved this study designed to evaluate the effect of visual afference on inter-limb coordination performances in young, adult and older individuals. Prior to the evaluation, 40 male participants (12 youths: 12±1 years; 16 young adults: 24±3 years; 12 older adults: 59±11 years) were fully informed about the procedures and the goal of the evaluation and provided their informed consent to participation. For the participants under 18 years of age, consent was obtained from their parents. Criteria for inclusion in the study was the absence of the following conditions: evidence or known history of neuromuscular disorder, cognitive impairment, wrist or ankle arthritis, use of medications able to affect the test performance, or injury to the wrist or ankle during the previous six months. Older adults lived a fully independent and noninstitutionalized lifestyle.

Procedures

After determining the leg preference (i.e., the foot the individual placed first while attempting to climb a flight of stairs beginning from a standing position with feet together), participants were administered inter-limb coordination test (Capranica, et al., 2004). Participants seated shoeless on a table with elbows and knees flexed at 90°. The position allowed independent motion of the hands and lower limbs in the sagittal plane. Participants were instructed to make cyclic homolateral hand and foot movements in a continuous fashion for the total duration of a trial (60 s) and to preserve spatial and temporal requirements of the movement patterns. The experimental condition was tested in two coordination modes: IP (i.e., associations of hand extension with foot dorsal flexion and hand flexion with foot plantar flexion) and AP (i.e., association of hand flexion with foot dorsal flexion and hand extension with foot plantar flexion). Each test condition was performed at three frequencies (80, 120, and 180 bpm), as dictated by a metronome. A 2-minute rest was given between test conditions, during which participants were allowed to stand. After 15 s of the required metronome pace, a "ready-go" command led to the start of a trial. All hand-foot coordination patterns were performed with both normal vision (eyes open – EO) and while being blindfolded (eyes closed – EC), in a randomized order. During the EO condition, participants were instructed to fix their gaze on a target positioned on the wall, while in the EC condition they were required to maintain their eyes closed while wearing a black mask.

Variables

Using a stopwatch, an observer measured the time of correct execution (in seconds) of the homolateral hand and foot coordination (the time from the beginning of the movement up to when the individual failed to meet either the spatial or the temporal task requirements). To avoid disagreement among observers, a single competent observer scored the performances. The literature (Capranica, et al., 2004) showed significant high test-retest stability coefficients for both IP (range: 0.95-0.96) and AP (range: 0.72-0.98) data and this measurement of gross time and phase transitions proved to be effective in discriminating for age (Capranica, et al., 2004; Cortis, et al., 2009) and expertise (Capranica, et al., 2005; Cortis, et al., 2009).

The variability of IP and AP movements was calculated according to previous studies (Bogaerts, et al., 2003; Salesse, et al., 2005), in which the standard deviation (SD) was used as a measure of (in) consistency of the inter-limb performance. Therefore, variability (in seconds) was obtained by calculating subject's SD for the three execution frequencies, thus obtaining a single value for IP and AP, respectively. Low SD represents similar values across the three frequencies of execution (low variability), while high SD represents higher differences across frequencies (high variability).

Statistical analysis

Preliminary analyses. To verify quality of data, preliminary analyses were run to replicate the effects of age, coordination mode and execution frequency on the time of correct performance that are reported in the literature (Capranica, et al., 2004, 2005; Cortis, et al., 2009, 2011, 2013; Moscatelli, et al., 2016; Tessitore, et al., 2011). Therefore, means and SD of the time (s) of correct execution of IP and AP modes at the three frequencies of execution (80, 120, and 180 bpm) during EO and EC conditions in youths, young and older adults were calculated and submitted to a 3 (Age: youths, young and older adults) × 2 (Coordination Mode: IP and AP) × 3 (Execution Frequency: 80, 120, and 180 bpm) ANOVA with repeated measures.

Main analyses. Variability of IP and AP was then submitted to a 2 (Visual Afference: EO and EC) × 3 (Age: youths, young and older adults) × 2 (Coordination Mode: IP and AP) ANOVA with repeated measures for two of the three factors. Alpha level of .05 was selected for significance throughout the study. If the overall F test was significant, *post-hoc* Fisher's protected least significant difference comparisons with Bonferroni corrections were used. To provide meaningful analysis for significant comparisons from small groups, Cohen's effect sizes (ES) were also calculated, considering trivial ES<0.2, small ES=0.3–0.6, moderate ES=0.7-1.2, and large ES>1.2.

Results

Preliminary analyses. In both EO and EC conditions, inter-limb coordination showed main effects for Age (p<.0001), Coordination Mode (p<.0001), Execution Frequency (p<.0001), and the interactions Coordination Mode × Age (p<.005), and Coordination Mode × Execution Frequency × Age (p<.0001). Better performances (i.e., longer time of correct execution) were found in the IP condition and at slower execution frequencies, with youth and young adult subgroups showing a ceiling effect at 80 bpm. In general, performances were best in young adults, intermediate in youths, and poorest in older adults, with age-related performance decrements more pronounced during AP and fastest movements, which tended to floor effects (Figure 1).

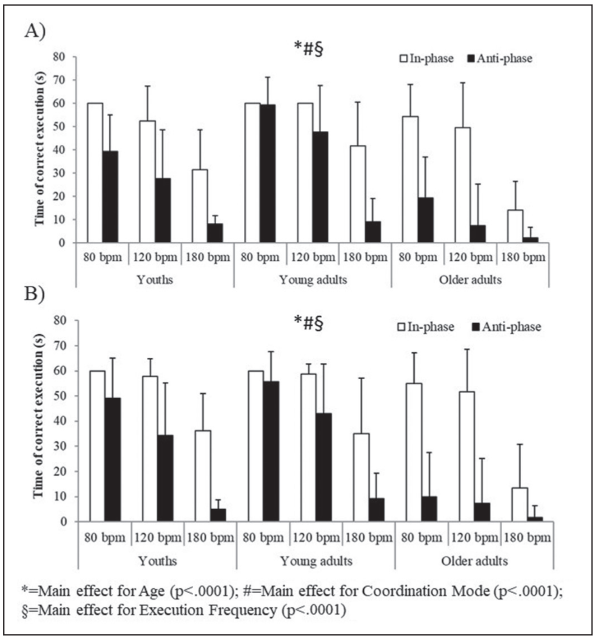

Figure 1. Means and standard deviations of in-phase and anti-phase inter-limb coordination performances in the eyes open (A) and eyes closed (B) conditions for youths, young and older adults.

Main analyses. No main effects for coordination mode, age category, or visual afference emerged for IP and AP variability (Figures 2 and 3). Interactions showed the differences for Coordination Mode × Age Category (F(2, 37)=35.6; p<.0001) and Coordination Mode × Age × Visual Afference (F(2, 37)=5.8; p=.007). Only the three-way interaction was analysed further because it included the two-way interaction. In the IP-EO condition, *post-hoc* analysis showed a higher (p=.0003; ES=1.59) variability in older adults (24.8±6.6 s) with respect to young adults (10.5±10.9 s), whereas in the IP-EC condition, older adults showed a higher variability (23.4±10.7 s) with respect to both youths (p=.03; ES=1.00) and young adults (p=.03; ES=0.81). In both AP conditions, older adults showed lower (p<.002; ES range: 1.64-2.94) variability values (EO=9.5±12.1 s; EC=4.6±7.5 s) with respect to the other two age groups, with only the youth group showing the differences (p=.02; ES=0.85) between EO (16.6±12.1 s) and EC (23.6±8.4 s) conditions.

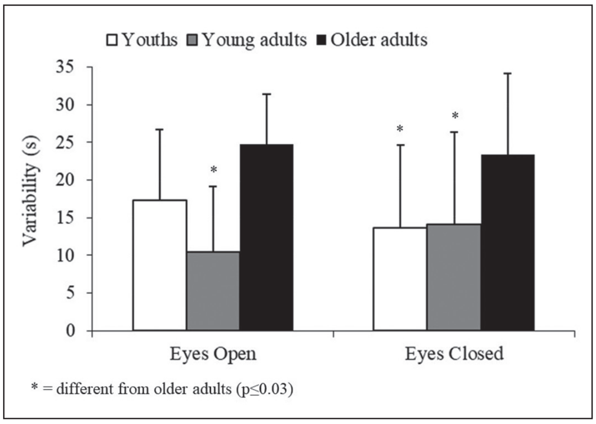

Figure 2. Means and standard deviations of the variability of in-phase inter-limb coordination performances in the eyes open and eyes closed conditions for youths, young and older adults.

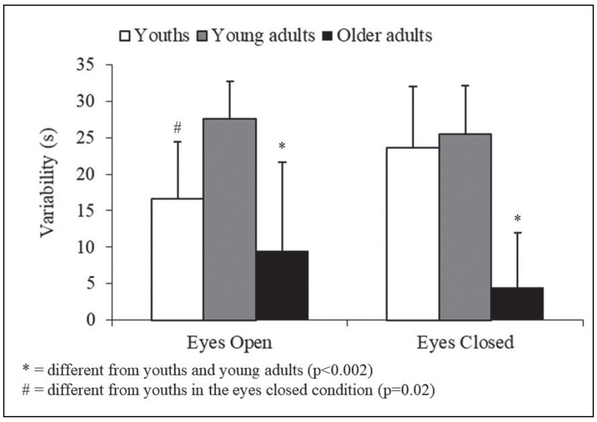

Figure 3. Means and standard deviations of the variability of anti-phase inter-limb coordination performances in the eyes open and eyes closed conditions for youths, young and older adults.

Discussion and conclusions

The present results substantiate that inter-limb coordination highly depends on mode and frequency of execution, with isodirectional tasks and slower execution frequencies resulting in better performances, probably due to a lower request of attentional monitoring (Capranica, et al., 2004, 2005; Cortis, et al., 2009; Kelso, 1994; Serrien, et al., 2000). Findings also support the development over lifespan and deterioration of the coordinative capability (Capranica, et al., 2004; Cortis, et al., 2009; Meinel & Schnabel, 1998; Spirduso, Francis, & Macrae, 2005), with peak performances reached during young adulthood and the poorest performances occurring after the fifth decade of life. In particular, age-related decrements were more pronounced during the AP movements performed at the faster velocities, during which older individuals showed a tendency towards a floor effect probably due to their difficulty to allocate attentional resources in inhibiting the natural IP mode (Wuyts, Byblow, Summers, Carson, & Semjen, 1998).

Regardless of visual afference, inter-limb coordination performances of the youth, young adult and older adult subgroups are comparable to those reported for co-aged individuals (Cortis, et al., 2009). Furthermore, youths and young adults showed IP values in line with those reported for open skills sport athletes (Moscatelli, et al., 2016; Tessitore, et al., 2011). In the present study, young adults showed better performances with respect to older adults regardless of visual afference (EO/EC). The apparently diverging pattern of age having effects on variability of performance in the less and more complex coordinative task conditions (IP/AP) (Figures 2 and 3) is attributable to a consistently worsened performance at old ages. In fact, the lowest intra-individual variability at the advanced age under complex task conditions, being coupled with the lowest times of correct execution (Figure 1), probably reflects a floor effect. In the life phase of optimal functioning, overall best IP and AP performances have been reported in young and élite team sport players (Cortis, et al., 2011; Tessitore, et al., 2011), who must cope with situation uncertainty and with the need to adapt their motor coordination to variable conditions. The inter-limb coordination advantage of athletes practicing sports that imply variable conditions is paralleled and probably intertwined with high skills in attentional control (Pesce & Bösel, 2001) and executive inhibitory function (Di Russo, Taddei, Aprile, & Spinelli, 2006).

Findings from the present study show that visual perception did not affect IP and AP variability in young and older adults. Although the early study by Flowers (1975) suggested that the hemisphere governing the dominant arm might be specialized in processing visual feedback, a few years later Annett, Annett, Hudson, and Turner (1979) hypothesized that the dominant hand was superior not in the feedback processing, but rather in executing an initial plan that did not need many corrections. This suggests that difference in accuracy is not a result of differences in processing visual information, but of a dominant hemisphere advantage in generating more consistent and accurate movement features (Roy & Elliot, 1986). Because no significant differences between body sides have been reported while evaluating inter-limb coordination performances (Capranica, et al., 2004, 2005), in this study only data regarding the preferred body side were collected. Therefore, it is possible that no difference with respect to visual afference emerged because the non-dominant hemisphere relies more on proprioceptive information than the dominant one (Goble & Brown, 2008).

Conversely, in youths an effect of visual perception emerged, with a higher variability during EC only in the AP condition and a reverse, but nonsignificant, trend in the IP condition. This result does not support, at this developmental age, the destabilizing effect of vision during non-homologous coordination patterns previously observed in young adults (Temprado, Swinnen, Carson, Tourment, & Laurent, 2003). Instead, our finding suggests that when the inter-limb coordination demands are complex (AP), youths rely on visual afference to ensure performance stability, which is poorer when they perform inter-limb coordination patterns relying on the proprioceptive feedback only (Figure 3). Moreover, a greater visual weighing in stationary and dynamic contexts has been reported in youths with respect to adults, especially when involving hand position (Bremner, Hill, Pratt, Rigato, & Spence, 2013). Finally, although during adulthood people tend to weigh the senses in proportion to their reliabilities within the context of the current task, thus maximizing efficiency, youths tend to rely more on visual perception with respect to the older groups. When vision is no longer the most reliable sense, other modalities, such as proprioception, are given greater importance during the perception of the limb position (Nardini, Bedford, & Mareschal, 2010). It is therefore possible that the optimal weighings of the senses would continue to improve during adolescent (Bremner, et al., 2013), peaking during adulthood and remaining stable during older ages. The present study adds to this issue, suggesting that the developmental trajectories of change in considering visual and proprioceptive perceptions in inter-limb coordination differ in relation to either more or less complex coordination modes. When the coordination is less complex (IP), youths are able to reach stability levels similar to those of young adults based on proprioceptive information (Figure 2, right), but seem to remain still intermediate between young and older adults in the use of visual perception to stabilize coordination performance (Figure 2, left). When the coordination is more complex, youths seem to reach stability levels similar to young adults regardless of the availability of visual information (Figure 3).

When interpreting these results, it must be taken into consideration that, in line with the literature (Bogaerts, et al., 2003; Salesse, et al., 2005), in this study the within-subject SD of the three execution frequencies during IP and AP performances was used as a measure of the variability of interlimb coordination. However, the identification of a unique number representative of a whole performance could not always be the best solution (Gambarelli, 2008). In particular for inter-limb coordination, a low SD could represent similar values across the three frequencies of execution, thus a good stability across measurements, although not indicating good overall performances. In fact, in this study older adults showed the lowest variability values, indicating the best stability, during AP-EC, although their performances were the poorest. This coupling of the poorest performance and lowest intraindividual variability at advanced age under complex task conditions may be interpreted, as mentioned above, as a floor effect.

In conclusion, the present results add new insights to the extant literature, furthering our understanding of the role that the visual afference has in controlling and regulating the stability (or variability) of motor coordination across the lifespan. The finding that vision plays a differentiated role in either more or less complex coordination performances at a certain developmental age, may inform the development of designed perceptual-motor training in youth sport and physical activity contexts.

References

Abedanzadeh, R., Abdoli, B., & Farsi, A. (2015). The effect of sensory information on the transition of the relative phase in bimanual coordination task. *International Journal of Sport Studies*, *5*(3), 287-295.

Annett, J., Annett, M., Hudson, P.T.W., & Turner, A. (1979). The control of movement in the preferred and non-preferred hands. *The Quarterly Journal of Experimental Psychology*, *31*(4), 641-652.

Baldissera, F., Borroni, P., & Cavallari, P. (2000). Neural compensation for mechanical differences between hand and foot during coupled oscillations of the two segments. *Experimental Brain Research, 133*(2), 165-177.

Baldissera, F., & Cavallari, P. (2001). Neural compensation for mechanical loading of the hand during coupled oscillations of the hand and foot. *Experimental Brain Research, 139*(1), 18-29.

Bogaerts, H., Buekers, M.J., Zaal, F.T., & Swinnen, S.P. (2003). When visuomotor incongruence aids motor performance: The effect of perceiving motion structures during transformed visual feedback on bimanual coordination. *Behavioural Brain Research*, *138*(1), 45-57.

Bremner, A.J., Hill, E.L., Pratt, M., Rigato, S., & Spence, C. (2013). Bodily illusions in young children: Developmental change in visual and proprioceptive contributions to perceived hand position. *PloS One*, *8*(1), e51887.

Byblow, W.D., Chua, R., Bysouth-Young, D.F., & Summers, J.J. (1999). Stabilisation of bimanual coordination through visual coupling. *Human Movement Science*, *18*(2), 281-305.

Capranica, L., Tessitore, A., Olivieri, B., Minganti, C., & Pesce, C. (2004). Field evaluation of cycled coupled movements of hand and foot in older individuals. *Gerontology, 50*(6), 399-406.

Capranica, L., Tessitore, A., Olivieri, B., & Pesce, C. (2005). Homolateral hand and foot coordination in trained older women. *Gerontology*, *51*(5), 309-315.

Carson, R.G., & Kelso, J.A.S. (2004). Governing coordination: Behavioural principles and neural correlates. *Experimental Brain Research*, *154 51*(3), 267-274.

Cavallari, P., Cerri, G., & Baldissera, F. (2001). Coordination of coupled hand and foot movements during childhood. *Experimental Brain Research, 141*(3), 398-409.

Cortis, C., Tessitore, A., Lupo, C., Perroni, F., Pesce, C., & Capranica, L. (2013). Changes in jump, sprint, and coordinative performances after a senior soccer match. *Journal of Strength and Conditioning Research*, *27*(11), 2989-2996.

Cortis, C., Tessitore, A., Lupo, C., Pesce, C., Fossile, E., Figura, F., & Capranica, L. (2011). Inter-limb coordination, strength, jump, and sprint performances following a youth men's basketball game. *Journal of Strength and Conditioning Research*, *25*(1), 135-142.

Cortis, C., Tessitore, A., Perroni, F., Lupo, C., Pesce, C., Ammendolia, A., & Capranica, L. (2009). Interlimb coordination, strength, and power in soccer players across the lifespan. *Journal of Strength and Conditioning Research*, *23*(9), 2458-2466.

Debaere, F., Van Assche, D., Kiekens, C., Verschueren, S.M., & Swinnen, S.P. (2001). Coordination of upper and lower limb segments: Deficits on the ipsilesional side after unilateral stroke. *Experimental Brain Research*, *141*(4), 519-529.

Di Russo, F., Taddei, F., Aprile, T., & Spinelli, D. (2006). Neural correlates of fast stimulus discrimination and response selection in top-level fencers. *Neuroscience Letters*, *408*(2), 113-118.

Flowers, K. (1975). Handedness and controlled movement. *British Journal of Psychology*, *66*(1), 39-52.

Gambarelli, G. (2008). The "coherent majority average" for juries' evaluation processes. *Journal of Sports Sciences*, *26*(10), 1091-1095.

Goble, D.J., & Brown, S.H. (2008). Upper limb asymmetries in the matching of proprioceptive versus visual targets. *Journal of Neurophysiology*, *99*(6), 3063-3074.

James, E.G., Leveille, S.G., Hausdorff, J.M., Travison, T., Cote, S., Conatser, P., et al. (2017). Rhythmic interlimb coordination impairments are associated with mobility limitations among older adults. *Experimental Aging Research, 43*(4), 337-345.

Jeka, J.J., & Kelso, J.A. (1995). Manipulating symmetry in the coordination dynamics of human movement. *Journal of Experimental Psychology: Human Perception and Performance*, *21*(2), 360-374.

Kay, B.A., Saltzman, E.L., & Kelso, J.A.S. (1991). Steady-state and perturbed rhythmical movements: A dynamical analysis. *Journal of Experimental Psychology: Human Perception and Performance*, *17*(1), 183-197.

Kelso, J.A., Fink, P.W., DeLaplain, C.R., & Carson, R.G. (2001). Haptic information stabilizes and destabilizes coordination dynamics. *Proceedings of the Royal Society B: Biological Sciences*, *268*(1472), 1207-1213.

Kelso, J.A.S. (1984). Phase transitions and critical behaviour in human bimanual coordination. *American Journal of Physiology – Regulatory, Integrative and Comparative Physiology, 246*(6 Pt 2), R1000-1004.

Meesen, R.L., Wenderoth, N., Temprado, J.J., Summers, J.J., & Swinnen, S.P. (2006). The coalition of constraints during coordination of the ipsilateral and heterolateral limbs. *Experimental Brain Research*, *174*(2), 367-375.

Meinel, K., & Schnabel, G. (1998). *Bewegungslehre – Sportmotorik*. Berlin: Sportverlag.

Moscatelli, F., Messina, G., Valenzano, A., Monda, V., Viggiano, A., Messina, A., et al. (2016). Functional assessment of corticospinal system excitability in karate athletes. *PLoS One*, *11*(7), e0159846.

Nardini, M., Bedford, R., & Mareschal, D. (2010). Fusion of visual cues is not mandatory in children. *Proceedings of the National Academy of Sciences*, *107*(39), 17041-17046.

Peper, C.E., & Beek, P.J. (1998). Are frequency-induced transitions in rhythmic coordination mediated by a drop in amplitude? *Biological Cybernetics*, *79*(4), 291-300.

Pesce, C., & Bösel, R. (2001). Focusing of visuospatial attention: Electrophysiological evidence from subjects with and without attentional expertise. *Journal of Psychophysiology*, *15*(4), 256-274.

Roy, E.A., & Elliott, D. (1986). Manual asymmetries in visually directed aiming. *Canadian Journal of Psychology/ Revue Canadienne de Psychologie*, *40*(2), 109-121.

Salesse, R., & Temprado, J.J. (2005). The effect of visuo-motor transformations on hand-foot coordination: Evidence in favor of the incongruency hypothesis. *Acta Psychologica*, *119*(2), 143-157.

Salesse, R., Temprado, J.J., & Swinnen, S.P. (2005). Interaction of neuromuscular, spatial and visual constraints on hand-foot coordination dynamics. *Human Movement Sciences*, *24*(1), 66-80.

Serrien, D.J., Li, Y., Steyvers, M., Debaere, F., & Swinnen, S.P. (2001). Proprioceptive regulation of interlimb behaviour: Interference between passive movement and active coordination dynamics. *Experimental Brain Research*, *140*(4), 411-419.

Serrien, D.J., & Swinnen, S.P. (1998). Load compensation during homologous and nonhomologous coordination. *Experimental Brain Research*, *121*(3), 223-229.

Spirduso, W.W., Francis, K.L., & Macrae, P.G. (2005). *Physical Dimensions of Aging*. Champaign, IL: Human Kinetics.

Swinnen, S.P. (2002). Intermanual coordination: From behavioural principles to neural-network interactions. *Nature Reviews Neuroscience*, *3*(5), 350–361.

Swinnen, S.P., & Carson, R.G. (2002). The control and learning of patterns of interlimb coordination: Past and present issues in normal and disordered control. *Acta Psychologica*, *110*(2), 129-137.

Swinnen, S.P., Jardin, K., Meulenbroek, R., Dounskaia, N., & Hofkens-Van Den Brandt, M. (1997). Egocentric and allocentric constraints in the expression of patterns of interlimb coordination. *Journal of Cognitive Neuroscience, 9*(3), 348-377.

Temprado, J.J., Swinnen, S.P., Carson, R.G., Tourment, A., & Laurent, M. (2003). Interaction of directional, neuromuscular and egocentric constraints on the stability of preferred bimanual coordination patterns. *Human Movement Science*, *22*(3), 339-363.

Tessitore, A., Perroni, F., Cortis, C., Meeusen, R., Lupo, C., & Capranica, L. (2011). Coordination of soccer players during preseason training. *Journal of Strength and Conditioning Research, 25*(11), 3059-3069.

Woodworth, R.S. (1899). *The Psychological Review: Monograph Supplements, 3*(3), 13.

Wuyts, I.J., Byblow, W.D., Summers, J.J., Carson, R.G., & Semjen, A. (1998). Intentional switching between patterns of coordination in bimanual circle drawing. In J.P. Piek (Ed.), *Motor behaviour and human skill* (pp. 191-208). Champaign, IL: Human Kinetics.

Correspondence to:
Cristina Cortis, Ph.D.
Assistant Professor at the Department of Human Sciences, Society and Health
University of Cassino e Lazio Meridionale
Via S. Angelo - Località Folcara
03043 Cassino (FR)
Phone: +39 0776 299 4436
Fax: +39 0776 299 3839
E-mail: c.cortis@unicas.it