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Shared Mental Models and Intra-Team Psychophysiological Patterns:

A Test of the Juggling Paradigm

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Abstract

We explored implicit coordination mechanisms underlying the conceptual notion of "shared mental models" (SMM) through physiological (i.e., breathing and heart rates) and affective-cognitive (i.e., arousal, pleasantness, attention, self-efficacy, other's efficacy) monitoring of two professional jugglers performing a real-time interactive task of increasing difficulty. There were two experimental conditions: "individual" (i.e., solo task) and "interactive" (i.e., two jugglers established a cooperative interaction by juggling sets of balls with each other). In both conditions, there were two task difficulties: “easy” and “hard”. Descriptive analyses revealed that engaging in a dyadic cooperative motor task (interactive condition) required greater physiological effort (Median Cohen’s $d = 2.13$) than performing a solo motor task (individual condition) of similar difficulty. Our results indicated a strong positive correlation between the jugglers’ heart rate for the easy ($r = .87$) and hard tasks ($r = .77$). The relationship between the jugglers’ breathing rate was significant for the easy task ($r = .73$) but non-significant for the hard task. The findings are interpreted based on research on SMM and Theory of Mind. Practitioners should advance the notion of “shared-regulation” in the context of team coordination through the use of biofeedback training.

Shared Mental Models and Intra-Team Psychophysiological Patterns: A Test of the Juggling Paradigm

Since the first use of the term “social neuroscience” in a paper by Cacioppo and Berntson in 1992, there has been minimal, if any, research on cooperative motor tasks based on an interactive, rather than passive, research paradigm (Goldman, 2012; Schilbach et al., 2013). In this context, recent efforts in social cognition have been directed at understanding team coordination, particularly through dynamic research approaches (De Jaegher & Di Paolo, 2013). Scholars have argued that it is important to study interactive tasks, where information flows bidirectionally between two or more individuals, rather than passive tasks in which information flows unidirectionally from an active to a disengaged subject or system (e.g., avatar; see Schilbach et al., 2013). The study of interactive motor tasks allows one to examine whether and how bio-psycho-social networks, such as autonomic and cognitive-affective-behavioral mimicry, might influence team processes in naturalistic settings (De Jaegher, Di Paolo, & Gallagher, 2010; Filho, Bertollo, Robazza, & Comani, 2015a). The present study is an initial attempt to explore team coordination during a real-time interactive task of increasing difficulty.

We subscribed to Eccles and Tenenbaum’s (2004) conceptual framework of team coordination in sports to study coordination *during* (“in-process”) dyadic juggling. This framework is based on the notion that optimal performance is influenced by the development of shared coordination among teammates. Coordination refers to spatio-temporal synchronized action and effort among teammates and includes (a) explicit coordination, manifested through verbal communication and (b) implicit coordination, exhibited through non-verbal behavior and body responses (Filho & Tenenbaum, 2012). In bio-neuro-cognitive terms, team coordination is made possible through the development of “shared mental models” (SMM), which consist of common schemas “about team tasks, task context and strategies, team interaction patterns, and teammates’ traits” (Xinwen, Erping, Ying, Dafei, & Jing, 2006, p. 598).

Although extant research on explicit team coordination exists, few, if any, studies have been conducted on the physiological markers of implicit coordination underlying the conceptual notion of SMM in real-time interactive tasks (Reed et al., 2006; Schilbach et al., 2013). In the present study, we monitored the breathing and heart rate of two professional jugglers participating in an interactive juggling task. Breathing and heart rate patterns have been found to change as a function of increased workload in motor and cognitive tasks (Veltman & Gaillard, 1998). In particular, breathing rate is an indicator of motor coordination in various tasks (e.g., swallowing; see Martin-Harris, 2006; swimming; see Seifert, Chollet, & Sanders, 2010). Similarly, heart rate has been associated with cognitive demands, including attentional control and psychophysiological self-regulation, and the probability of experiencing optimal performance in complex motor tasks (Bertollo et al., 2013).

The study of implicit coordination has its roots in the theory of mind, particularly in its mimicry mechanisms (Goldman, 2012). Mimicry pertains to the synchronization of behavioral and physiological responses. From a behavioral standpoint, there is evidence that individuals are able to “mind-read,” empathize, and ultimately mimic facial expressions reflecting a variety of feelings, including physical or emotional pain (Singer et al., 2004). From a physiological standpoint, there is evidence that individuals unconsciously synchronize their somatic responses, such as breathing and heart rates, while cooperating in a task or sharing a social context (Müller & Lindenberger, 2011). However, there remains a need for studies addressing motor tasks, particularly real-time interactive exchanges, such as dyadic juggling (De Jaegher & Di Paolo, 2013; Konvalinka & Roepstorff, 2012; Schilbach et al., 2013).

Extant research in applied psychology has shown that myriad affective and cognitive states influence team coordination and performance (Eccles & Tenenbaum, 2004). Accordingly, we also assessed the influence of arousal and pleasantness, attentional strategies, self-efficacy, and other's efficacy beliefs on juggling performance. In this regard, there is empirical evidence suggesting that individuals' affective social behaviors are primarily dependent on their arousal and pleasantness levels (Russell, Weiss, & Mendelsohn, 1989). For instance, Carney and Colvin (2010) have shown that arousal and pleasantness levels influence myriad social behaviors (e.g., sympathy towards partner; enjoyment during social interaction) among dyads engaged in an interactive task. Furthermore, attentional measures have been used to study joint attention during social interaction as well as performance in motor tasks (Razon, Hutchinson, & Tenenbaum, 2011). Self-efficacy and other's efficacy are major sources of collective efficacy, which in turn have been found to predict team performance in interactive tasks (Filho, Tenenbaum, & Yang, 2015b; Magyar, Feltz, & Simpson, 2004). Finally, we collected the participants' perceptions of task motivation and task difficulty, given that motivation and difficulty influence the probability of peak performance experiences (i.e., *flow-feeling theory*; see Kimiecik & Jackson, 2002).

In summary, the study of real-time interactive tasks is important to understand how team coordination occurs and can be enhanced in naturalistic settings (De Jaegher et al., 2010; Filho et al., 2015a). However, scant research exists on implicit coordination dynamics during highly interactive motor tasks (De Jaegher & Di Paolo, 2013; Schilbach et al., 2013). Accordingly, we sought to advance research in team coordination through physiological monitoring and affective-cognitive assessment of two professional jugglers performing an interactive juggling task of increasing difficulty. Specifically, we aimed to explore whether the jugglers': (a) physiological and affective-cognitive responses would differ in the individual and interactive conditions, and

(b) breathing and heart rate patterns would be significantly correlated throughout the juggling tasks, in agreement with the conceptual notion of SMM in general, and implicit coordination in particular. Congruent with previous research in socio-cognition, we expected that: (H1) the jugglers' psychophysiological and affective-cognitive patterns would increase in the interactive condition due to the coordination effort needed for cooperative work in team settings, and (H2) the jugglers' breathing and heart rate patterns would correlate throughout the interactive juggling task.

Methods

Design

We conducted a case study based on a multimodal assessment through the acquisition of objective psychophysiological and subjective self-report data. Our study was based on the recently proposed "juggling paradigm", which purports that single studies in dyadic juggling offer an epistemologically and methodologically valid platform to advance knowledge on the coupling of peripheral (e.g., breathing and heart rate) and central mechanisms (e.g., hyperbrain analysis) during interactive tasks (for a review see Filho et al., 2015a). Specifically, Filho et al. (2015a) noted that dyadic juggling makes clear that the locus of interest is the "team" rather than the individual. Furthermore, social loafing is unlikely to occur in dyadic juggling as mistakes and lack of effort can be easily and reliably identified.

Noteworthy, exploratory research in medicine and social science has relied on case studies to infer functional relationships between two or more conditions (Parker & Hagan-Burke, 2007). Case studies are considered essential in addressing understudied topics in applied psychology (Gage & Lewis, 2013; Kinugasa, 2013), particularly in the testing of novel conceptual frameworks and research paradigms (see Yin, 2011). Case studies are recommended in the study of complex real-life tasks (see Noor, 2008), especially when data collection is complex, costly and time intensive, such as in psychophysiology research (Editorial Nature Neuroscience, 2004; Lane & Gast, 2014). Case study research is also recommended when participants are highly unique and hard to recruit, such as in the case of highly skilled jugglers. To this extent, it has long been noted that a well-designed nomothetic study targeting socio-cognitive processes should be based on an a priori power analysis based on a nested analysis of variance in its compound structure at the individual and group-level of analysis (Cacioppo & Berntson, 1992; Raudenbush & Bryk, 2002). For the present study, this would require a large and unrealistic number of skilled juggling dyads.

Participants

Prior to taking part in the study, the participants signed an informed consent sheet approved by the authors institutional review board. We purposefully recruited two high-skilled male members of a professional circus school in northeast Canada renowned for preparing world-class performance artists. This sampling approach is consistent with the importance of studying “information rich cases” in order to advance knowledge in expertise development across human domains, including performing arts and sports (Williams & Ericsson, 2005). Juggler 1 (J1) was 21 years old with 13 years of juggling experience. Juggler 2 (J2) was 21 years old with 12 years of juggling experience. Their juggling schedule involved 10 hours of supervised deliberate practice (effortful, improvement oriented, feedback-based practice) per week. J1 and J2 had never juggled together prior to this study and had no systematic experience in dyadic juggling, congruent with the importance of controlling for historicity effects in socio-cognitive research (see De Jaegher & Di Paolo, 2013).

Juggling Tasks

J1 was a specialist in juggling clubs, whereas J2 was a specialist in diabolo. For the present study, both jugglers were asked to juggle balls in the “cascade juggling pattern,” which represents the most commonly used instrument (balls) and first-learned symmetric pattern (cascade) in juggling (Dancey, 2003). Both jugglers were experts in their respective specialties but J1 had more experience than J2 in juggling with balls. Thus, it is important to note that the juggling tasks were designed taking into account the jugglers’ abilities. Specifically, the juggling tasks were established after three peer debriefing meetings involving the jugglers and their coaches, as well as two pilot tests, including one independent pilot test with two other jugglers.

The peer debriefing meetings, based on the notion of *cognitive team task analysis* (see Klein, 2000), were used to design a reliable and challenging task able to capture skilled performance in an ecologically valid and realistic environment. The peer debriefing meetings involved round table discussions with the jugglers’ head coach in order to elicit information about the core components of action proper to cooperative juggling. During the pilot tests, the jugglers were asked to juggle with an increasing number of balls until an “easy” (i.e., minimum number of balls needed for the individual and interactive juggling) and “hard” juggling task (i.e., the maximum number of balls each juggler was able to juggle with) had been identified. Of note, tasks of increased difficulty have been used to identify factors linked to socio-cognitive functioning (i.e., perturbation paradigm; see Massimini, Boly, Casali, Rosanova, & Tononi, 2009), as well as to identify the mechanisms underlying skilled motor performance (i.e., expert performance approach; see Williams & Ericsson, 2005). The ideal distance to be kept between the jugglers during the interactive condition was also identified during the pilot trials.

Experimental Conditions

We implemented two experimental conditions: “individual” and “interactive” (see Figure 1). In the “individual” condition, which served as control (see Gage & Lewis, 2013; Schilbach et al., 2013), each juggler performed a solo juggling task. The jugglers performed individually but alongside each other in an effort to control for the presence of another person, thus making it possible to draw comparisons with the interactive condition (Filho et al., 2015a). In the “interactive” condition, the two jugglers established a cooperative interaction by juggling balls with each other. In both conditions, there were two task difficulties: “easy” and “hard”.

The jugglers were given five minutes per condition (i.e., individual, interactive) for both the easy and hard task. Based on the pilot trials, and in agreement with their practice habits and performance demands (i.e., juggling acts in circus usually do not exceed five minutes), a five minute trial was deemed appropriate to prevent feelings of fatigue. Therefore, for both conditions and difficulty tasks, the participants were asked to juggle for 10 trials of 30s or for as many trials as needed to complete the five minute time limit.

Individual condition. In the individual condition, the easy task consisted of juggling three balls for both jugglers. The increase in the number of juggling balls from the easy to hard task depended on each juggler’s ability. Given differences in their ability to juggle with balls, J1 and J2 did not juggle the same number of balls in the hard task. Rather, J1 juggled with seven balls and J2 juggled with four balls. Although different in absolute terms, the hard task was comparable between subjects in relative terms (as verified during the pilot trials and pre-task peer-debriefing meetings). To this extent, psychophysiology research on cognitive and physical tasks has relied on relative workload indices to compare subjects (see American College of Sports Medicine Guidelines for Exercise Testing and Prescription, 2013).

Interactive condition. It was established that a distance of 2.40 m between the jugglers allowed for optimal amplitude of movement and reliable data collection. The easy task consisted of dyadic juggling with six balls. The hard task consisted of dyadic juggling with eight balls. For J1, the individual/hard task allowed for five degrees of freedom (7 balls for 2 hands), whereas the interactive/hard task allowed for two degrees of freedom (8 balls for 4 hands). For J2, both the individual/hard and interactive/hard tasks allowed for two degrees of freedom (4 balls for 2 hands; 8 balls for 4 hands).

Measures

Task motivation, task difficulty, and number of trials per juggling task served as manipulation checks, assessed through inferential statistical tests, to compare the two experimental conditions. Objective physiological data consisted of the participants' breathing and heart rate patterns. Subjective affective-cognitive measures included data on participants reported levels of arousal, pleasantness, attention, self-efficacy, and other's efficacy. All self-report data were collected for both conditions, following the completion of the easy and hard task. The participants' self-reports were collected through single-item measures, which are considered reliable and less intrusive than multi-item measures while collecting data during real-time interactions (Kamata, Tenenbaum, & Hanin, 2002).

Manipulation checks: Task motivation, task difficulty, and number of trials/time per trial. A single-item scale, ranging from 0 (*not at all*) to 10 (*very much*), was used to measure perceived motivation to complete the juggling tasks. The participants were instructed to report on the following item: "To what degree did you feel motivated to complete this juggling task?" To measure task difficulty, the participants were asked to respond to the following statement: "How difficult was it for you to complete this juggling task?" Participants rated the item on a scale ranging from 0 (*not at all difficult*) to 10 (*very difficult*). Finally, we recorded how many trials the jugglers needed to complete the 5min task in both conditions and the two levels of difficulty. The chronometers were stopped every time a ball was dropped to determine the duration of each trial.

Physiological recordings: Breathing and heart rate. We used two synchronized FlexComp Infiniti biofeedback systems (Thought Technology Ltd., CA) to continuously record the participants' breathing and heart rates. Specifically, electrocardiogram (ECG) and respiration data were recorded continuously. The ECG sampling rate was 2048 Hz and the movement associated with respiration was recorded at 256 Hz. Breathing rates (breaths per minute) were recorded using a respiration sensor belt placed around the jugglers' abdomen at the level of the lower ribs. Heart rate data (beats per minute) were captured using three gelled self-adhesive electrodes placed below the right clavicle, left clavicle, and left pectoral muscle below the xiphoid process (lower part of the sternum). Physiological data for the two jugglers in the interactive condition were collected using two Thought Technology hardware and software systems. The two systems were connected by a series of Bayonet Neil-Concelman (to time-lock the data of both jugglers) and synchronized with a JVC - Everio Digital Camcorder via a TT-AV Sync Sensor with a visual trigger delay time <200µs.

Arousal and pleasantness levels. A modified version of the Affect Grid (Russell et al., 1989) was used to measure affect throughout the juggling tasks. There is extensive psychometrical evidence suggesting that core affect is a byproduct of pleasure-displeasure and degree of arousal (for a review see Russell et al., 1989). The participants were asked to rate their arousal levels ranging from 1 (*sleepiness*) to 9 (*high arousal*) and perceptions of pleasure ranging from 1 (*unpleasant*) to 9 (*pleasant*).

Attention. Dissociation (e.g., external thoughts about the environment; daydreaming) and association (e.g., internal thoughts; juggling technique) attentional focus were measured throughout the juggling tasks. Attention was measured on a 10-point scale ranging from 0 (*pure dissociation*) to 10 (*pure association*) akin to extant research in sport and exercise psychology (for a review see Razon et al., 2011).

Efficacy beliefs: Self-efficacy and other's efficacy. The participants were asked to rate their efficacy beliefs in themselves and their partner using a Likert-type scale ranging from 0 to 100, with increments of 10 and three verbal anchors for 0 (*cannot do at all*), 50 (*moderately can do*), and 100 (*highly certainly can do*). These single-item measurements were designed in agreement with Bandura's (2006) guidelines for constructing efficacy scales. The probe for self-efficacy was: "How confident are you in your ability to successfully juggle with three/four/seven balls?" The probe for other's efficacy collected for the interactive condition only was: "How confident are you that your juggling partner is able to successfully juggle with six/eight balls?"

Procedures

Data collection took place in a spacious athletic gymnasium and consisted of (a) baseline assessment, (b) familiarization trials, and (c) experimental protocol for individual and interactive conditions. The first part of the baseline assessment involved the jugglers standing quietly until their physiological signals showed a stable pattern within normal ranges. The second part of the baseline assessment involved recording breathing rate and heart rate for five minutes. After the baseline assessment, the jugglers were given a series of familiarization trials until they reported feeling comfortable with the biofeedback apparatus.

The experimental protocol commenced with the individual condition. For the easy task, both J1 and J2 juggled with three balls. For the hard task, J1 juggled with seven balls and J2 juggled with four balls, in agreement with their individual maximum ability. The interactive condition followed and involved J1 and J2 juggling together sets of balls at a distance of 1.20m from each other. The jugglers started a dyadic juggling combination with six balls (easy task), and then progressed to eight balls (hard task).

In both the individual and interactive conditions, the jugglers were given a minimum rest period of five minutes between the easy and hard tasks to minimize fatigue. There was not a pre-established time limit for the rest intervals. Rather, the jugglers were able to decide when to restart the task. This rationale was based on the contemporary notion that fatigue is ultimately voluntarily regulated (see Marcora & Staiano, 2010).

The researchers monitored data collection and kept the time for each condition throughout the experimental protocol to assess how long, on average, the jugglers were able to juggle without dropping any balls. Specifically, two researchers monitored the physiological apparatus to ensure reliable data collection. Two other researchers collected the participants' subjective self-report data for the easy and hard juggling tasks for both experimental conditions. Specifically, arousal, pleasantness and attention data were collected prior to and after the easy and hard tasks for both experimental conditions to assess how these variables differ from resting states (baseline) and according to different factors (easy and hard tasks; individual and interactive conditions), akin to previous research in sport psychology (Basevitch et al., 2011; Bertollo et al., 2015; Razon, Mandler, Arsal, Tokac, & Tenenbaum, 2014). Efficacy data were not collected during baseline as efficacy information should be related to a specific performance task (Bandura, 2006). It took approximately two hours to complete the experimental protocol.

Data Analysis

The first step in our data analysis consisted of identifying the total number of trials needed to complete the juggling tasks, as well as the jugglers' breathing and heart rate patterns associated with each trial. We then averaged the data with respect to our factors of interest, which consisted of the two conditions and two task difficulties.

Trial identification. The first and second author viewed the video recording of the study to identify the total number of trials in each 5min task (easy and hard) for both conditions. A trial started when the jugglers threw the first ball in the air and ended when a ball was dropped. We only included trials longer than 10s in our final analysis to allow for reliable signal processing of the physiological data. With psychophysiological data, the signal-to-noise-ratio is less reliable in short epochs (see Weishaupt, Kochli, & Marincek, 2006). Furthermore, it is unlikely that someone can juggle three or more balls by chance for a period of 10 or more seconds (Dancey, 2003). The jugglers breathing and heart rate recordings were visually inspected for each valid trial. Any segments containing artifacts caused by movements or electrical interference from muscle contraction were eliminated from subsequent analysis. Finally, the jugglers' breathing and heart rate mean and standard deviation values were calculated from the artifact-free recordings using the Biograph Infinity software.

Variables of interest. Physiological data for each trial were identified, using the analysis feature of the Thought Technology Biograph Infiniti Software, and averaged for each condition and task difficulty. The affective-cognitive data were also analyzed in regards to each condition and task difficulty. Noteworthy, we adhered to current guidelines on single-case research by using both visual (i.e., line graphs) and descriptive (i.e., effect size computations) methods of analysis (see Gage & Lewis, 2013; Kinugasa, 2013; Lane & Gast, 2014; Tate, Perdices, McDonald, Togher, & Rosenkoetter, 2014). Wide-ranging line graphs are the primary form of displaying results in case studies (Gage & Lewis, 2013; Lane & Gast, 2014; Tate et al., 2014). Accordingly, we prepared our graphs to display information on level (means), variability (point-to-point series) and trend (i.e., changes over time) for both conditions.

We also computed effect sizes (ES), which are considered more appropriate than hypothesis testing in single-case research (Kinugasa, 2013). Specifically, we computed Cohen's *d* effect size to assess whether jugglers' physiological response (i.e., breathing and heart rates) changed from the individual to interactive condition (i.e., H1). We computed *r family ES* to assess the degree of association between the jugglers' heart rate and breathing responses in the interactive condition (i.e., H2). Further, we computed Cohen's Percent of Nonoverlapping Data (CPND), a widely supported technique in comparative case-study analysis, which expresses the percentage of underlap between two data sets (see Parker & Hagan-Burke, 2007). Inferential statistics (T-tests and ANOVAs) were used to test our experimental manipulation, with respect to number of trials/time per trial, and time on trial, and physiological data.

Results

First, we present information supporting our experimental manipulation. We then provide visual and descriptive data exploring H1 and H2. In Tables 1 and 2, we present descriptive statistics for the individual and interactive conditions. In Figures 2, 3 and 4 we visually compare J1 and J2 for both physiological and affective-cognitive data across conditions and task difficulties.

Manipulation Checks

Task motivation. On a 10-point Likert-type scale, motivation scores for both conditions and task difficulties were above 8 (J1, $M = 9$, $SD = 1.41$; J2, $M = 9.5$, $SD = .71$). Therefore, the jugglers were motivated to complete the juggling tasks.

Task difficulty. In the individual condition, J1 and J2 reported low scores of difficulty for the easy task (scores ≤ 2) and high scores for the hard task (scores ≥ 8). In the interactive condition, both jugglers reported low scores of difficulty for the easy task (scores = 1). The hard task was perceived as slightly more difficult than the easy task by J1 (score = 2). J2 perceived the hard task as more difficult than the easy task (score = 5). Thus, for both conditions, J1 and J2's perceived assessment of task difficulty was higher for the hard task, with respect to the easy task. J2 perceived the interactive hard task as more difficulty than J1 did, adding to the notion that J1 was the more skilled juggler. To verify the task difficulty levels and thus our experimental manipulation from an objective standpoint, we contrasted the number of trials/time per trial for the two different tasks according to the individual and interactive conditions.

Number of trials/time per trial. In the individual easy task, both jugglers were able to complete 10 trials of 30s without any mistakes. In the individual hard task, J1 used 21 trials (9 valid) and J2 used 15 trials (10 valid). In the interactive condition, the jugglers used 10 trials in the easy condition (9 valid) and 26 trials in the hard condition (7 valid). Overall, from the easy to the hard tasks, there was an increase in the number of trials associated with a decrease in time per trial. In the individual condition, time per trial differed between the easy (*M* = 30 sec) and hard tasks (*M* = 13.56 sec, *SD* = 2.61) for J1, *t*(7) = 17.81, *p* = .001. Furthermore, time per trial also differed for J2 between the easy (*M* = 30 sec) and hard tasks (*M* = 14.05 sec, *SD* = 6.08), *t*(9) = 8.29, *p* = .01. In the interactive condition, time per trial also differed, *t*(6) = 6.46, *p* = .001, between the easy (*M* = 28.17 sec, *SD* = 2.98) and hard tasks (*M* = 13.43 sec, *SD* = 3.46).

A repeated measures (RM) ANOVA was used to compare the jugglers' time per trial (i.e., how long they were able to keep the balls in the air) for the easy and hard tasks across the two experimental conditions. The results revealed a non-significant effect for the three easy tasks (easy task for J1, J2, and interactive condition), *F*(2, 8) = 2.70, *p* = .14, and for the three hard tasks (hard task for J1, J2, and interactive condition), *F*(2, 5) = .71, *p* = .54. Thus, there was reliability in comparing difficulty levels for the jugglers in both conditions.

Time on trial and physiological data. J1 and J2's time on trial and physiological data were contrasted for the first half (0 to 2.5 min) and second half (2.5 to 5.0 min) of the 5 min trials by condition and task difficulty. In the individual condition, non-significant effects were revealed for both the easy and hard tasks on time on trial. However, differences were observed in the individual/hard task for J1 on both breathing rate, *F*(1, 3) = 43.61, *p* = .001, and heart rate, *F*(1, 3) = 40.90, *p* = .001. Furthermore, differences were observed for J2 on the individual/hard task for both breathing rate, *F*(1, 4) = 49.85, *p* = .002, and heart rate, *F*(1, 4) = 14.96, *p* = .02. In the interactive condition, no statistically significant differences were found between the first and second halves.

Individual Condition

Physiological recordings: Breathing and heart rate. Breathing and heart rates were higher when performing the hard task for both jugglers (Figure 2), attesting that the hard task required greater physiological activation. J1's breathing rate, *t*(16) = 11.57, *p* = .01, and heart rate, *t*(16) = 7.50, *p* = .01, were significantly higher for the hard task compared with J2 (Figure 4). J1's breathing and heart rates were not significant for the easy task (*r* ES = .56, *p* = .10, *n* = 10) and strongly correlated for the hard task (*r* ES = .87, *p* = .01, *n* = 9). Similar to J1, J2's breathing and heart rates were moderately correlated and not significant for the easy task (*r* ES = .60, *p* = .07, *n* = 10) and strongly correlated for the hard task (*r* ES = .74, *p* = .02, *n* = 10). Thus, there was a higher intra-physiological overlap between breathing rate and heart rate for both jugglers in the hard task.

Easy task. Breathing rate for the easy task was lower for both J1 and J2 in the individual condition than in the interactive easy condition. CPND was 85.20% for J1 and 91.31% for J2, suggesting a minimal combined data overlap across the conditions. Furthermore, the 95% confidence intervals (CI) for the Cohen's *d* ES computations did not include zero, indicating that estimated differences are a robust statistical effect distinguishable from zero. Heart rate for the easy task was lower for J1 and J2 in the individual condition compared to the interactive easy condition. The magnitude of this difference was 83.20% for J1 (*d* = 2.08) and 36.11% for J2 (*d* = .65). The CIs for this comparison did not include zero for J1, whereas the CI for J2 did include zero. Thus, it is not possible to affirm with 95% reliability that J2's heart rate differed in the individual and interactive conditions, in respect to the easy task.

Hard task. Breathing rate for the hard task was noticeably lower for J1 (*d* = -5.04; CPND = 100%) and moderately higher for J2 (*d* = .25, CPND = 13.89%) compared to the interactive hard condition. The CI for this comparison did not include zero for J1. However, the CI for J2 did include zero. Thus, it is not possible to affirm, with 95% reliability, that J2's breathing rate differed between the individual and interactive conditions, in respect to the hard task. Finally, heart rate for the interactive hard task was lower for both J1 (*d* = -4.46) and J2 (*d* = -2.14) compared to the respective values recorded during the individual hard task.

Affective-cognitive data. Both jugglers reported that the easy task was less pleasant and required less activation than the hard task (Figure 2, Panels A and B). Both jugglers reported directing their attention more inwards (associative strategy) in the hard task than the baseline assessment and easy task (Figure 2, Panel C). Self-efficacy was lower for both jugglers in the hard task (Figure 2, Panel D).

Interactive Condition

Physiological recordings: Breathing and heart rate. J2's breathing rate and heart rate were positively correlated for both the easy (*r* ES = .69, *p* = .04) and hard task (*r* ES = .77, *p* = .04). Conversely, J1's breathing and heart rate responses were not related for both the easy (*r* ES = -.17, *p* = .72) and hard tasks (*r* ES = .46, *p* = .30). Hence, J1's heart and breathing responses were not correlated.

Easy task. When correlating J1 and J2's physiological responses for the easy task (see Table 2), we found a strong effect for breathing rate (*r* ES = .73, *p* = .03) and heart rate (*r* ES = .87, *p* = .01). The CIs for breathing rate and heart rate did not include zero or negative values, thereby indicating that the correlation between J1 and J2's physiological responses did not occur by chance, and is positive in nature. The CI for breathing rate was wide and thus a firm conclusion on the "true effect" magnitude of this relationship is not warranted. The CI for heart rate indicates that, when juggling together in an easy task, J1 and J2's heart beats were strongly correlated.

Hard task. When correlating J1 and J2's breathing rates for the hard task, we observed a small negative effect (Table 2). Descriptive statistics indicated that J1 and J2 exhibited similar breathing rate mean values (J1, *M* = 37.43, *SD* = 3.26; J2, *M* = 35.00, *SD* = 3.83), with an overlap ratio of 87.5% (i.e., 12.5% CPND) for the hard task. Although similar in level, J1 and J2's breathing rate did not exhibit the same variability and trend patterns. When correlating J1 and J2's heart rate for the hard task, a strong relationship (*r* ES = 0.77, *p* = .04) was revealed with a positive CI ranging from .04 to .96. Thus, J1 and J2's heart rate overlapped greatly throughout the hard task.

Affective-cognitive data. J1 reported low levels of arousal for both the easy and hard tasks. J2 reported low levels of arousal in the easy task, and moderate arousal levels in the hard task (see Figure 2, Panel A). Both jugglers reported relatively low levels of pleasantness for both the easy and hard tasks (see Figure 2, Panel B). J1 reported directing his attention more inwards (associative strategy) in the hard task than in the easy task. J2 reported the same attentional level, primarily dissociative, for both the easy and hard task (see Figure 2, Panel C). J1 reported the highest self-efficacy value possible for both the easy and hard tasks. J2 reported high self-efficacy for the easy task and moderate efficacy for the hard task (see Figure 2, Panel D). J1 and J2's rates for other's efficacy were 100 of 100 for both task difficulties, and therefore we did not include this finding in the Figures.

Discussion

We conducted a single-case experimental study aimed at addressing two hypotheses. First, we explored whether two jugglers' physiological and affective-cognitive responses would differ when comparing solo juggling (individual condition) and dyadic juggling (interactive condition) of increasing difficulty (easy and hard tasks). Secondly, we explored whether the jugglers' breathing and heart rate patterns would be statistically correlated in an easy and hard juggling task, in agreement with the conceptual notion of SMM in general, and implicit coordination in particular. In light of our results, we elaborate on each hypothesis.

Hypothesis 1: Comparison between solo and dyadic juggling

For the easy task in the individual and interactive condition, H1 was confirmed for both jugglers. The interactive/easy task required greater physiological activation for both J1 and J2 than the individual/easy task. Hence, engaging in a dyadic cooperative motor task likely requires greater physiological effort than performing an individual motor task of similar difficulty. This increase in physiological effort is likely due to one of two reasons. First, the jugglers were less efficient in dyadic juggling, as they had less experience in this interactive task, in comparison to solo juggling. More experienced dyadic jugglers would be better able to detect and correct execution mistakes, whereas less experienced dyadic jugglers cannot (for a review see Carter, Braver, Barch, Botvinick, Noll, & Cohen, 1998; Tenenbaum, 2003). Second, the increase in physiological effort may be a result of the additional energy needed to cope with the coordination requirements associated with cooperative work in team tasks. Both J1 and J2 perceived the interactive/easy task as less pleasant than the individual/easy task, and thus coordinating movements with another person in a dyadic task does not appear to be as pleasant as performing an individual mastered motor task. Noteworthy, our findings do not allow for the determination as to whether the increase in physiological expenditure was due to the former or the latter explanation. It is likely that both factors partially explain this finding, akin to the notion of *reciprocal determinism* in socio-cognitive tasks (Bandura, 1997), which purports that team performance is co-determined by multiple variables on a many-to-many basis. Further research comparing experienced juggling dyads with less experienced dyads is needed to clarify this issue.

For the hard task across conditions (individual and interactive), H1 was verified for J2 but not for J1. For J1, the interactive/hard task demanded lower physiological activation than the individual/hard task. For J2, no differences in physiological activation were observed when comparing the hard task in the interactive condition with the hard task in the individual condition. These findings can be explained based on the notion of multiscale complexity, which purports that more degrees of freedom are linked to greater task difficulty (Bar-Yam, 2004). In fact, for J1 the hard task in the individual condition was more challenging (7 balls for 2 hands; 5 degrees of freedom) than the hard task in the interactive condition (8 balls for 4 hands; 2 degrees of freedom). For J2, the hard task in both conditions required the same number of degrees of freedom.

It is important to highlight the fact that J1's physiological responses were associated with J2's breathing and heart rate patterns. This result is in line with Theory of Mind, in which individuals' physiological and affective-cognitive responses tend to overlap in time-locked interactive tasks (Goldman, 2012). This result is also in line with the theoretical notion that there is a "leader" and a "follower" in interactive motor tasks (Konvalinka & Roepstorff, 2012; Schilbach et al., 2013). Thus, the notion that your team is "only as strong as your weakest link" may hold true for interactive motor tasks, such as juggling and other acrobatics (e.g., dyadic hand-to-hand). Perhaps more importantly, these results suggest that the initiator is likely to be the lower skilled performer, with the follower being the more skilled individual. The better juggler did not experience cognitive overload in the interactive/hard task, and thus he was able to adapt to the less skilled juggler. To this extent, extant empirical evidence suggests that cognitive flexibility allows highly skilled performers to anticipate and adapt to their teammates actions during real-time tasks (Tenenbaum, Basevitch, Gershgoren, & Filho, 2013).

Hypothesis 2: Intra-team psychophysiological and affective-cognitive responses

Our results showed a strong positive correlation (i.e., < .70) between the jugglers' heart rate responses for both the interactive/easy and interactive/hard tasks. Breathing rate for J1 and J2 were also strongly correlated for the interactive/easy task but there was no reliable effect between the jugglers' breathing rates for the interactive/hard task. Three theoretical implications stem from these findings. First, these results offer empirical evidence supporting the theoretical notion that the coupling of physiological mechanisms, such as the positive correlation of heart rate and breathing responses, likely reflects team coordination in interactive motor tasks (Filho et al., 2015a). Secondly, the ability to successfully coordinate physiological responses is likely moderated by task difficulty, reinforcing the importance of task analysis in the study of socio-cognition (Klein, 2000; Massimini et al., 2009; Williams & Ericsson, 2005). In other words, individuals may be more likely to have similar frequency of physiological responses under lower task difficulties and effort demands. Third, the fact that the jugglers' breathing rates did not correlate for the hard task suggests that, although related, breathing rate and heart rate may be indicative of different physiological demands under pressure (i.e., varying degrees of task complexity). Specifically, heart rate has been primarily linked to cognitive load (Veltman & Gaillard, 1998), whereas breathing rate has been associated with motor coordination (Martin-Harris, 2006). In the interactive/hard task, J2 faced difficulties coordinating his motor responses (probably due to cognitive overload), forcing J1 to compensate for any potential mistake from J2. Therefore, in addition to establishing SMM, evidenced through the coordination of explicit and implicit mechanisms, teammates may also need to develop complementary mental models to achieve optimal performance (Filho et al., 2015a).

It is noteworthy that J1 and J2 reported the same arousal levels in the interactive/easy task, where a strong correlation of breathing and heart rate responses was observed. However, in the interactive/hard task, J1 reported higher arousal levels than J2, likely because he needed to be more vigilant to adapt to his less skilled partner. Again, these findings corroborate theory of mind assumptions in which social interaction in a naturalistic task is made possible by one's ability to attribute and mimic the mental states of others (see Goldman, 2012; Singer et al., 2004). J1's attentional rates support the notion that harder tasks require greater associative focus (Razon et al., 2011). Conversely, J2 was "frozen" in the same attentional mode, perhaps unable to display attentional flexibility under pressure, as is the case for less skilled individuals under increasing pressure (Bertollo et al., 2013; Tenenbaum et al., 2013).

Furthermore, J1's efficacy belief scores were higher than J2 for both the interactive/easy and interactive/hard tasks, adding to the evidence that J1 was the more skilled ball juggler. Finally, both jugglers reported the maximum possible score for "others' efficacy". Although the jugglers' responses were collected confidentially and in accordance with Bandura's (2006) guidelines for measuring efficacy beliefs, it is likely that they refrained from reporting negatively on their partner's ability. Future studies should consider cooperative partners with no previous interactions, or larger groups for greater data variability, to better gauge the effect of others efficacy in explaining team coordination. Additional limitations, avenues for future research, and applied implications are discussed next.

Limitations and Future Research Avenues

Our study has limitations that we address to better orient future research in dyadic coordination in sports, particularly studies using interactive research paradigms. First, generalizability power is limited in case studies. Accordingly, future studies should focus on small-n studies (i.e., multi-case studies) to allow for greater inter-subject validation (Noor, 2008). For instance, small-n rather than single-case studies would allow for controlling of potential order and learning effects.

Second, the individual/hard task required maximum effort from both jugglers, especially during the second half of the five minute trial. The interactive/hard task was likely limited by J2's ability and was likely not challenging enough to J1. In other words, the individual/hard task equaled a maximum test for each individual, while the interactive/hard condition was, by definition, a byproduct (not necessarily linear) of each juggler's ability. Notwithstanding, the interactive/hard task was still very challenging for the dyad as a unit and was comparable in difficulty level to the individual hard/task, as verified by the objective data of number of trials/time per trial. The measurement of perceived feelings of exertion and fatigue, through the use of well-established measures such as the Borg Scale of Perceived Exertion (see Borg, 2001), would have strengthened our ability to compare the easy and hard tasks across conditions. Overall, future studies should continue to explore how individual ability influences intra-team psychophysiological dynamics in dyadic teams. In fact, in the "real world" performers' abilities vary greatly within teams, and coaches and practitioners have to find solutions to optimize coordination among teammates with different skill levels and bio-psycho-social profiles (Filho & Tenenbaum, 2012). Furthermore, important developments about group dynamics and team processes (e.g., Kohler effect) have originated from studies examining individuals of varying skills levels.

Despite the aforementioned limitations, our study is one of the very first to address psychophysiological coupling in a cooperative real-time motor task. The "juggling paradigm" tested herein may help to answer many of the questions raised on cooperative motor coordination. There is minimal research on this area, and the few that exist involve constrained environments and simple tasks (e.g., finger coordination on fMRI; see De Jaegher & Di Paolo, 2013; Reed et al., 2006; Schilbach et al., 2013). In particular, scholars can alter juggling tasks (cascade vs. shower paradigms; balls vs. clubs), skill levels (experts vs. novices) and difficulty (number of instruments juggled), while monitoring different variables (breathing rate, heart rate, skin conductance, brain waves) through the use of psychophysiological data collection systems, including electroencephalogram and eye-tracking (Filho et al., 2015a). Multi-brain studies, implemented through hyperscanning methodologies, are particularly warranted to identify the neural markers of implicit coordination (i.e., topology and efficiency of the functional hyperbrain networks) through high-performance neuroimaging analyses (see Babiloni, & Astolfi, 2014; Filho et al., 2015a). Finally, studies advancing the concept of shared and complementary mental models in exercise settings are welcomed. Scholars could examine whether and how physiological and cognitive-affective-behavioral mirroring happens in group exercise (e.g., running partners).

Conclusions and Applied Implications

Our first hypothesis was only partially supported as one of the jugglers exhibited higher psychophysiological activation during the individual hard task, rather than in the interactive hard task, as we had predicted. Therefore, it remains to be determined whether the increase of psychophysiological and affective-cognitive patterns of teammates in interactive motor tasks is due to (1) group-level variability; e.g., the coordination effort needed to complete cooperative tasks, in comparison with individually performed tasks; or (2) individual-level variability; e.g., skill level and personal experience in cooperative tasks. It is likely that both group- and individual-level variability influences team coordination in interactive tasks (i.e., *reciprocal determinism*, see Bandura, 1997). As such, practitioners should focus on developing both individuals' skills and team processes (e.g., cohesion, collective efficacy).

Our second hypothesis was supported as we showed that implicit coordination of physiological and affective-responses occurred, although this coordination is likely moderated by each individual's skill level and by task difficulty. To this extent, we observed that the more skilled juggler was more likely to "follow" the less skilled juggler. While further research, particularly targeting hyperbrains functional connectivity, must be conducted to determine "leader-follower directionality" in interactive motor tasks (Filho et al., 2015a), this initial result has an important applied implication. When proposing cooperative motor tasks, coaches and practitioners should balance challenge and skill of the dyadic team as a whole rather than primarily focusing on the needs of their “star” performer. Instead of having the lower skilled performer adapting to the best player, our results suggests that the best player should be encouraged to adapt to his/her less-skilled teammate.

Finally, our findings have the potential to orient the development of group-level bio-neurofeedback interventions. Practitioners could incorporate group-level psychophysiological analysis to identify high and low instances of implicit coordination among teammates in order to orient group-level biofeedback interventions. Applied researchers should advance the notion of “shared-regulation” in the context of team coordination and through the use of biofeedback training, much like we discuss “self-regulation” in the context of individually performed tasks.

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Table 1

Descriptive Statistics for the Jugglers' Breathing Rate (breaths per minute) and Heart Rate (beats per minute) in the Individual and Interactive Conditions by Task Difficulty

Juggler	Individual				Interactive					
	M	SD	Range	*n* trials[†]	M	SD	Range	*n* trials[†]	Cohen's *d*	CPND
J1										
Breathing Rate										
Easy	23.80	3.19	19-28	10	31.44	4.00	27-40	9	2.13 [1.00, 3.25]	85.20%
Hard	56.38	4.10	51-62	9	37.43	3.26	32-41	7	-5.04 [-7.05, -3.04]	100%
Heart Rate										
Easy	87.70	5.21	76-93	10	96.89	3.33	92-102	9	2.08 [0.96, 3.19]	83.20%
Hard	153.75	14.83	125-170	9	101.86	2.91	96-105	7	-4.46 [-6.24, -2.68]	100%
J2										
Breathing Rate										
Easy	22.30	1.57	20-24	10	29.00	2.91	25-36	9	2.91 [1.62, 4.20]	91.31%
Hard	34.00	4.01	29-40	10	35.00	3.83	32-43	7	0.25 [-0.72, 1.22]	13.89%
Heart Rate										
Easy	97.00	4.24	86-101	10	99.44	3.13	94-104	9	0.65 [-0.27, 1.57]	36.11%
Hard	116.30	5.10	108-126	10	106.29	3.95	100-111	7	-2.14 [-3.35, -.94]	85.60%

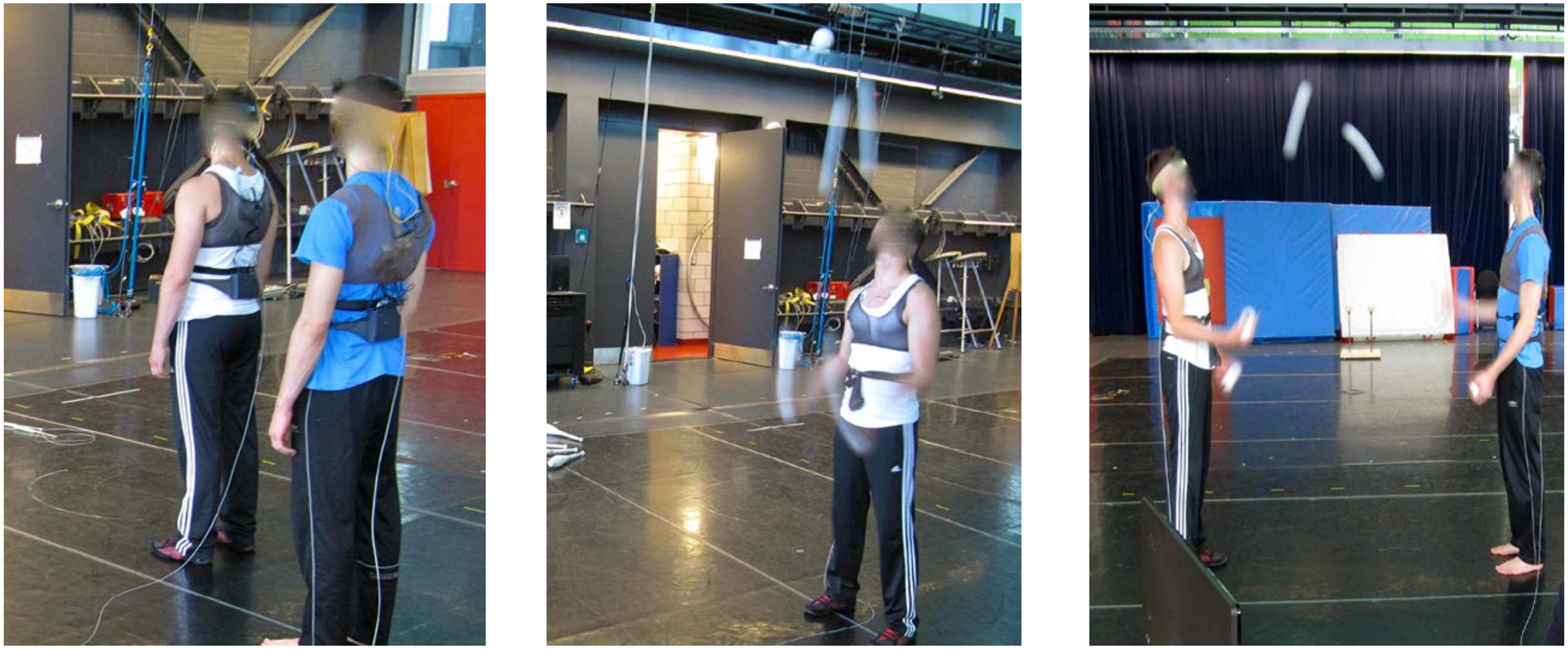
Note. [†]Only valid trials (>10 sec) were considered in the analysis.

Table 2

Correlation between J1 and J2 Physiological Responses in the Interactive Condition

Interactive Condition	*r* ES	CPND
Breathing Rate		
Easy	.73* [.13, .94]	83.4%
Hard	-.10 [-.79, .71]	12.5%
Heart Rate		
Easy	.87** [.49, .97]	99.4%
Hard	.77* [.04, .96]	88.0%

$^{*}p < .05$; $^{**}p < .01$



Panel A

Panel B

Panel C

Figure 1. Baseline assessment (Panel A), individual condition (Panel B), and interactive condition (Panel C).

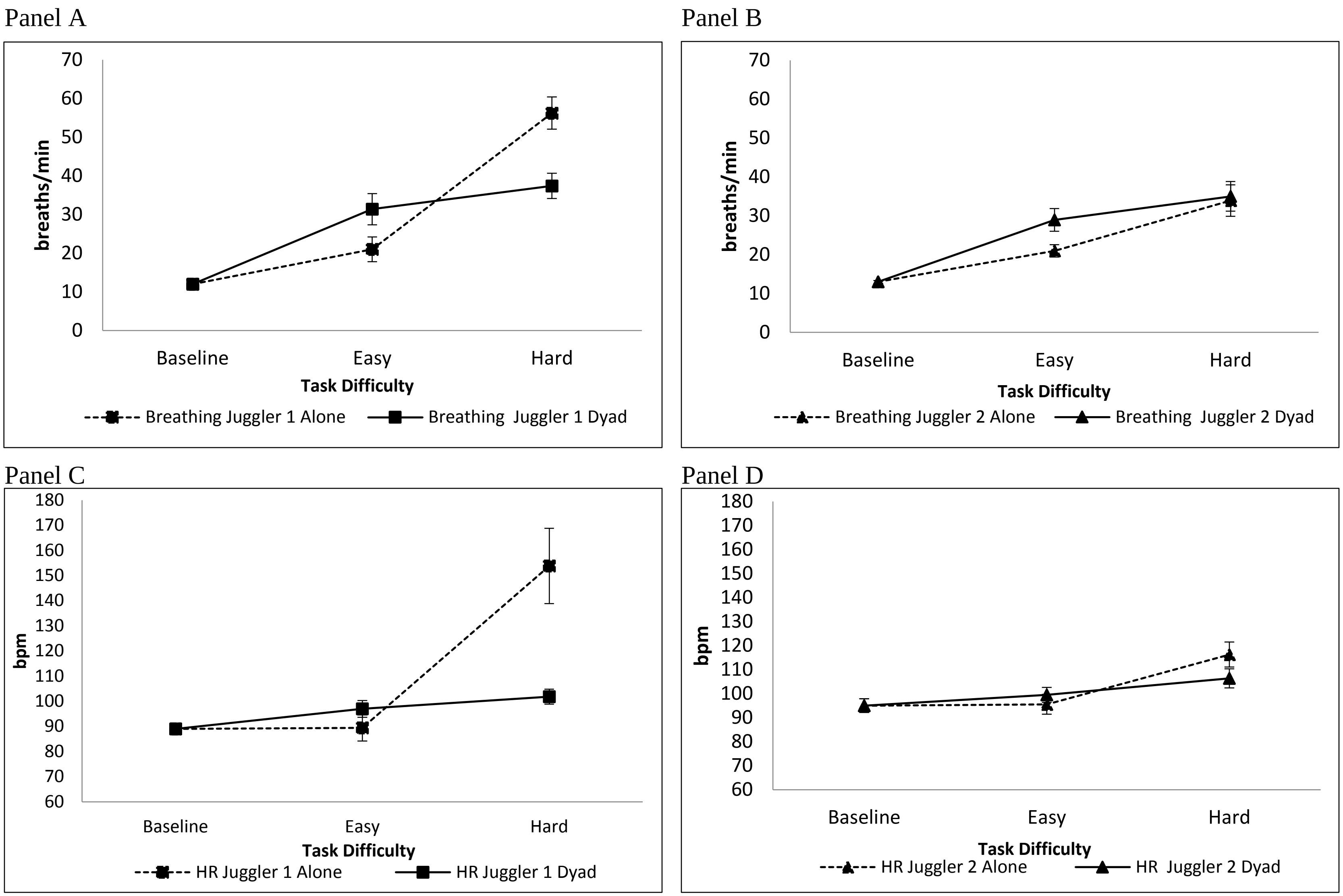


Figure 2. Jugglers’ breathing rate (breaths per minute; Panel A and B) and heart rate (beats per minute; Panel C and D) by juggling conditions and task difficulties.

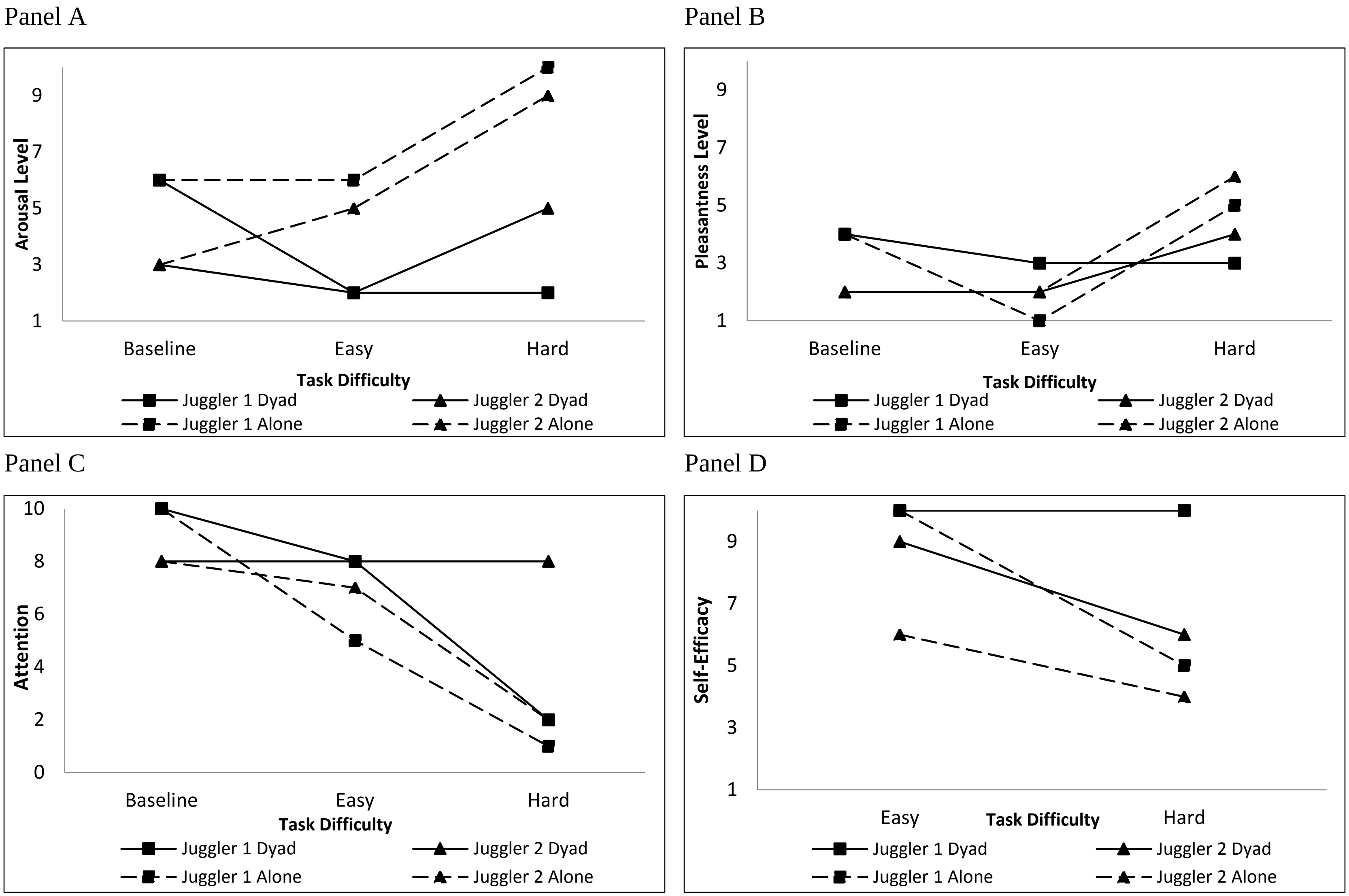


Figure 3. Jugglers' arousal (Panel A), pleasantness (Panel B), attention (Panel C) and self-efficacy levels (Panel D) by juggling conditions and task difficulties.

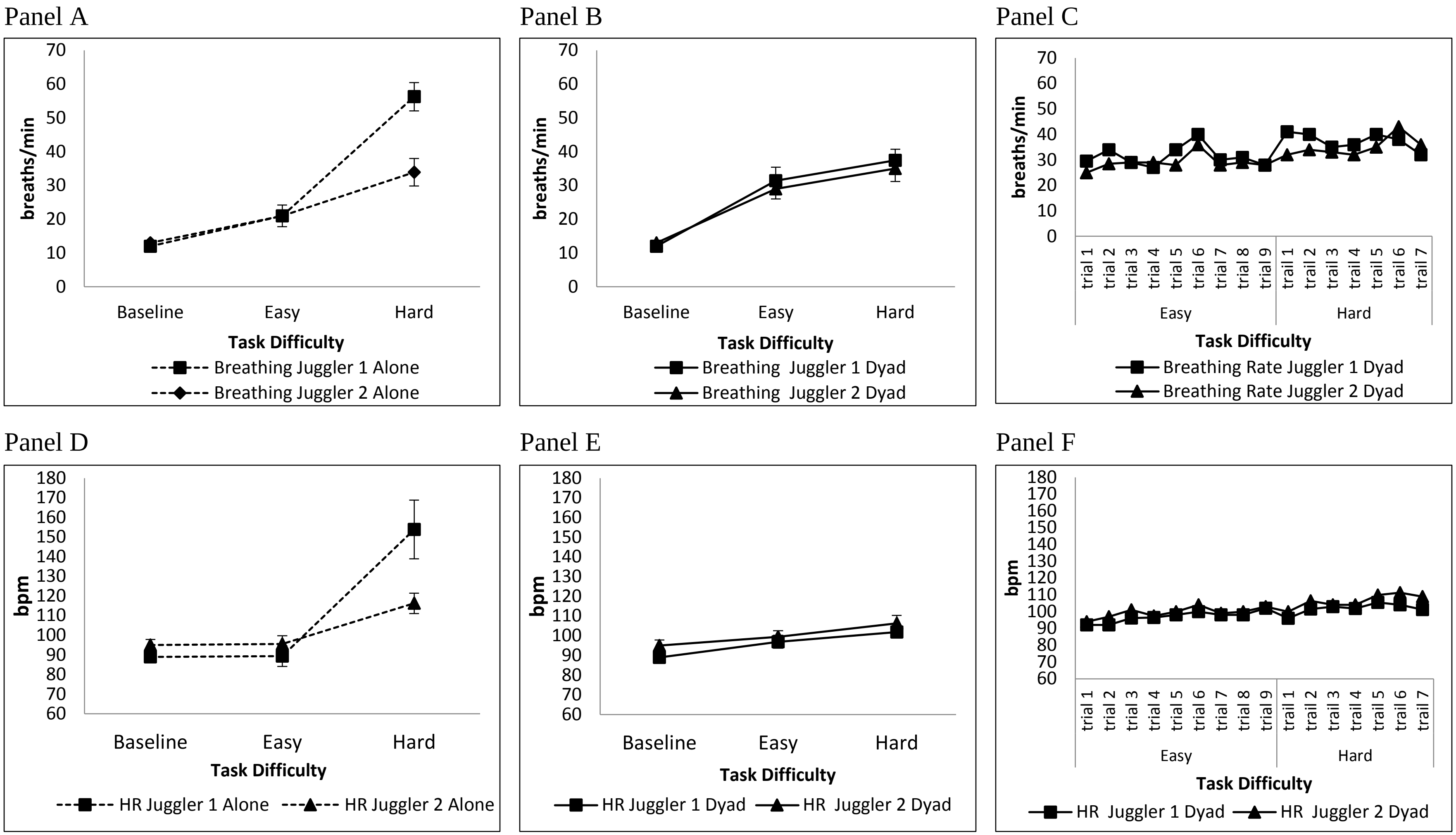


Figure 4. Panel A – J1 and J2 breathing rate (breaths/min) means for individual condition by task difficulty. Panel B – J1 and J2 breathing rate (breaths/min) means for interactive condition by task difficulty. Panel C – Trial per Trial J1 and J2: Breathing rate (breaths/min) means for interactive condition by task difficulty. Panel D – J1 and J2 heart rate (bpm) means for individual condition by task difficulty. Panel E – J1 and J2 heart rate (bpm) means for interactive condition by task difficulty. Panel F – Trial per Trial J1 and J2: heart rate (bpm) means for interactive condition by task difficulty.