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Coordination Matters: Interpersonal Synchrony Influences Collaborative Problem-Solving

Lynden K. Miles[1], Joanne Lumsden[2], Natasha Flannigan[1], Jamie S. Allsop[1], Dannette Marie[1]

[1]School of Psychology, University of Aberdeen, Aberdeen, UK
[2]Aberdeen and Grampian Chamber of Commerce, Aberdeen, UK
Email: lynden.miles@abdn.ac.uk

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Abstract

Moving in time with others is a central characteristic of social life and has been shown to promote a host of social-cognitive attunements (e.g., person memory, affiliation, prosociality) for those involved. Less attention has been paid, however, to how the effects of coordination can serve higher-order goal-directed social behaviour. Here we explored whether interpersonal synchrony impacts performance on a collaborative problem-solving task. One hundred and ninety two participants completed a short movement exercise in pairs whereby coordination mode was manipulated (in-phase synchrony, asynchrony, control). Each pair then jointly discussed a problem-solving exercise while the degree to which coordination spontaneously emerged was assessed. The results revealed that collaboration was more effective following in-phase coordination. Of theoretical significance, both instructed and spontaneous synchrony were associated with better performance, with the short-term history of each dyad shaping precisely when coordination was functional. Overall, the synchronization of body movements appears to support effective collaboration.

Keywords

Interpersonal Synchrony, Coordination, Problem Solving, Social Interaction, Collaboration

1. Introduction

Daily life involves many goal-directed social interactions—complex activities that present a challenge to even the most sophisticated agent. One key to reducing such complexity is coordination. By coordinating with others, we routinely achieve fundamental social goals (e.g., communication, affiliation, protection) with seemingly only minimal effort. Coordination functions by establishing a unitary common ground, temporarily linking individuals to form a coherent entitative whole (Lang, Bahna, Shaver, Reddish, & Xygalatas, 2017; Marsh, 2013; Schmidt & Richardson, 2008; Semin, 2007). While it can take many guises (e.g., linguistic turn-taking, behavioural mirroring, complexity matching), synchrony, as one form, is arguably primary. Governed by the lawful physical principles of coordination dynamics (Kelso, 1995), components of a system will, over time, tend to synchronize towards one of two attractor states (i.e., in-phase or anti-phase) if they are: 1) coupled, and 2) share relevant qualities (e.g., movement frequency). Empirical observations of synchronized mechanical (e.g., pendula, Huygens, 1673/1986), biological (e.g., fireflies, Buck & Buck, 1976) and social (e.g., dyads, Schmidt & O'Brien, 1997) systems reveal precisely these characteristic dynamical properties.

Given this physical basis for coordination it is perhaps no surprise that, anecdotally at least, we feel the pull to behave like others, to be "in sync" or "on the same wavelength" with our interaction partners. Researchers exploring this phenomenon have consistently demonstrated that people experience a host of social (e.g., affiliation, Hove & Risen, 2009), cognitive (e.g., person memory, Macrae, Duffy, Miles, & Lawrence, 2008), perceptual (e.g., motion sensitivity, Valdesolo, Ouyang, & DeSteno, 2010), neurophysiological (e.g., β-endorphin release, Cohen, Ejsmond-Frey, Knight, & Dunbar, 2010) and behavioural (e.g., cooperation, Wiltermuth & Heath, 2009) effects when their actions are synchronized (see Mogan, Fischer, & Bulbulia, 2017 for an overview). McNeill (1995) has argued that synchronous actions (e.g., marching) serve to provide esprit de corps in military contexts, while large-scale coordination (e.g., singing, dancing, chanting) is at the heart of many collective rituals and is arguably a driving force of cultural evolution (Freeman, 2000; Launay, Tarr, & Dunbar, 2016). However, as pervasive as synchrony may be, less is known about precisely how and when synchronous actions functionally serve higher-order social goals.

2. Coordination and Task Performance

A "holy grail" of social exchange exists in the potential for group-based productivity gains—for teamwork to furnish outcomes that are superior to individual inputs. However, the process of collaboration itself often creates task-specific dependencies (i.e., links) between individuals (e.g., communication requirements, shared goals, environmental and task constraints) which when suboptimal, can thwart outputs. Managing the effectiveness of these dependencies, that is, ensuring members coordinate their efforts appropriately, is therefore a primary factor for enhancing group performance (Allsop, Vaitkus, Marie, & Miles, 2016; Espinosa, Lerch, & Kraut, 2004; Kozlowski & Ilgen, 2006; Steiner, 1972). Although a precise specification of how to coordinate individual contributions to best achieve collaborative goals is dependent on task context and constraints (Fusaroli, Bjørndhal, Roepstorff, & Tylén, 2016), equipping team members with the capacity to realise the benefits of coordination is an important precursor to group success. Contrast, for instance, a tug-of-war team with workers in a fine-dining restaurant kitchen. While the specific coordination requirements are quite distinct[1], common to both examples team members need to be able to mutually adapt their efforts to those of others in a manner consistent with overarching performance goals (e.g., pulling on the rope precisely when others are or ensuring the sous vide filet mignon has rested sufficiently before dressing with the celeriac foam). Here, a real-time understanding of others' behaviour, including their goals, motives, and intentions, is likely to be essential if coordinated actions are to be efficient (von Zimmerman & Richardson, 2016). This then raises the possibility that the socially relevant outcomes of instances of interpersonal synchrony may pave the way for enhancing the effectiveness of coordination links in teams more generally, by shaping how individuals interact.

A key component of this argument rests on the nature of the consequences of synchronous actions. As discussed above, interpersonal synchrony promotes a range of outcomes that in practice can serve to enhance entitativity, communication, and social functioning (Lang et al., 2017; Marsh, 2013; Mogan et al., 2017)—factors that could feasibly serve to support collaborative efforts. Indeed, recent meta-analytical evidence confirms that along with enhanced prosociality, rapport, and affect, bouts of synchronous behaviour (i.e., exact behavioural matching) reliably promote social-cognitive functioning, including enhancing theory of mind, perception, attention, and memory of others (Mogan et al., 2017). For instance, influential work by Valdesolo et al. (2010) demonstrated that a short period of intentional interpersonal synchrony facilitated subsequent performance on a dyadic maze task that demanded effective coordination for success. Joint action was enhanced by the attunements, in this case increased perceptual sensitivity to others' actions, promoted by previous synchronous behaviour. Taken together, this work indicates that the augmentation of social-cognitive functioning seen to accompany interpersonal synchrony could generically serve to help establish, and maintain, the effectiveness of the specific coordination links necessary for teams to fully realise their potential. We set out to explore this possibility in the context of a collaborative problem solving task that relied on effective face-to-face communication—a context wherein the social cognitive attunements resulting from a bout of interpersonal synchrony ought to promote better task performance.

Recently, attention within the coordination literature has also turned to understanding how coordination may function in real-time so as to enhance group outcomes. Here emphasis has been put on the emergence of coordination during a task and how this relates to performance goals. Won, Bailenson, Stathatos, and

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[1] Using Steiner's (1972) taxonomy of group tasks, a tug-of-war team is faced with a unitary, additive, maximising task while the kitchen workers are engaged in a divisible, optimizing, conjunctive task. Put simply, the former are required to act as one to exert the maximum quantity of force possible while the latter have distinct tasks that when combined ought to lead to the highest quality food achievable.

Dai (2014), for example, reported that dyads tasked with idea generation were more creative to the extent that they spontaneously synchronised their movement, again pointing towards behavioural coordination providing a basis on which to form effective collaborations. Importantly however, Abney, Paxton, Dale and Kello (2015) recently established that when assigned specific roles, pairs required to perform a joint construction task were most successful when they showed moderate levels of coordination (i.e., a "loose" coupling). Similarly Fusaroli et al. (2016) showed that behavioural coordination was positively related to competence in a group LEGO building task, while Wallot, Mitkidis, McGraw, and Roepstorff (2016) demonstrated that synchronous actions may actually impair the quality of joint task outcomes (i.e., building model cars), in particular when roles were tightly constrained. Although in its infancy, this work begins to paint a more detailed picture—while the generic effects of synchrony (e.g., social cognitive attunements, entitativity) may confer broad advantages for teamwork, context-specific demands (e.g., role assignment, dyad history, task constraints) could feasibly determine how and when coordination functions to enhance collaboration in real-time. To this end, as an exploratory goal of the present research, we also measured interpersonal synchrony as it arose during dyadic engagement.

3. Current Research

The present study was designed to evaluate the impact of a prior synchronous interaction (cf. an asynchronous interaction, and a no interaction control) on the effectiveness of dyadic collaboration in the context of a communication-based problem-solving exercise. In addition we also sought to explore the influence of real-time spontaneous coordination during the collaborative exercise on task performance. Pairs of participants took part in an activity designed to manipulate interpersonal synchrony before jointly discussing the 'Lost on the Moon' (LotM) problem-solving task (Hall & Watson 1970). During this collaborative discussion participants' movements were recorded and the degree to which behavioral coordination spontaneously emerged was assessed. To evaluate the impact of coordination on problem-solving efficacy, participants then completed the LotM task individually.

4. Method

4.1. Participants and Design

The study had a single-factor (Coordination condition: Synchrony, Asynchrony or Control) between-participants design. An a priori power analysis (G*Power, version 3.1.9.2) based on an effect size of η_p^2 = 0.05 indicated that a minimum sample of $n = 148$ was required to achieve 80% power (3 groups, 1 covariate). To be conservative, we decided to oversample and set a stopping rule of $n = 200$ (≈33 pairs per condition). However, during testing a number of pairs were excluded and replaced in the sample which meant the available participant pool was exhausted prior to reaching this limit. Most exclusions were the result of participants in the asynchrony condition not adhering to the movement instructions during the coordination manipulation. Because interpersonal synchrony has stable attractor states (i.e., in-phase and anti-phase; see Schmidt & Richardson, 2008), it can be difficult to avoid these modes even when intentionally attempting to do so (Issartel, Marin, & Cadopi, 2007). Therefore we set a cut-off whereby pairs in the asynchrony condition who spent more than 25% of the duration of the task in either an in-phase (i.e., 0° - 20°, $n = 2$ pairs) or an anti-phase (i.e., 160° - 180°; $n = 11$ pairs) mode were excluded and replaced (see Materials and Procedure, and Data Reduction and Analysis sections for details regarding the measurement and calculation of coordination). Movement data from the synchrony condition was also inspected, however all pairs managed to maintain in-phase coordination adequately (i.e., minimum duration in 0° - 20° phase region = 57.8%). In addition, 6 pairs (2 synchrony, 3 asynchrony, 1 control) were excluded due to participants reporting knowing one another prior to the study (see Materials and Procedure for further details). The final sample consisted of 192 participants (96 pairs: 33 synchrony, 32 asynchrony, 31 control; see Appendix for demographic information).

4.2. Materials and Procedure

Participants self-selected time slots and arrived at the laboratory individually (see **Figure 1** for an overview of the procedure). Once both individuals were present they were briefly introduced and informed that the study would involve

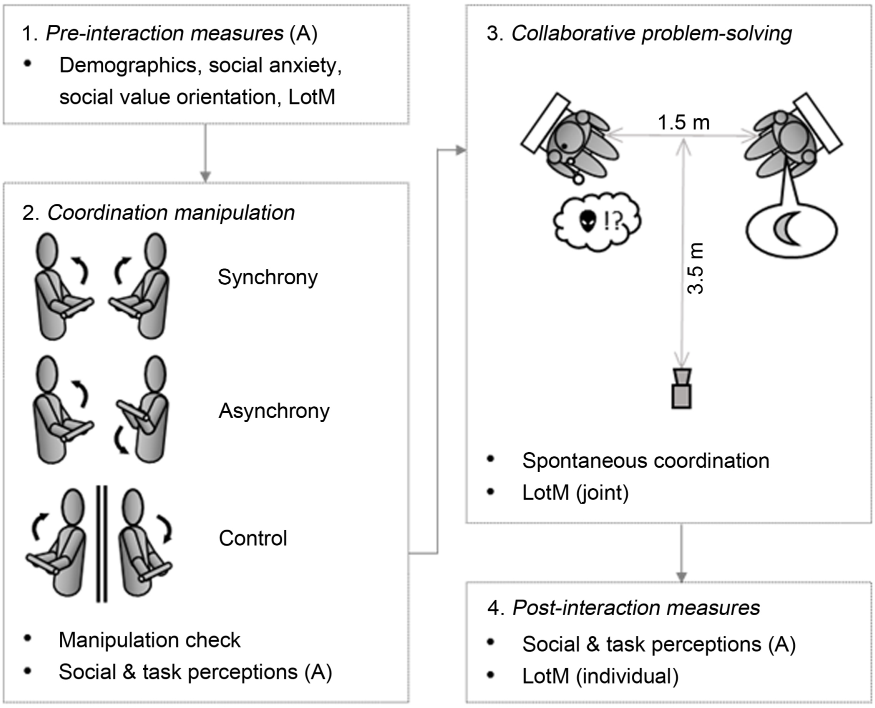

Figure 1. Overview of the experimental procedure and measures. An (A) denotes that results are presented in the **Appendix**.

a number of different tasks and questionnaires, some to be completed alone and others as a pair. After obtaining informed consent, participants completed an initial set of questionnaires in individual cubicles (see Appendix – Pre-interaction measures). Participants were also asked to rate how well they knew their partner on a 150 mm analogue scale (anchored by "not at all" and "extremely well"). Those who indicated any familiarity (i.e., > 10 mm from "not at all") were excluded (see Participants and Design for further information). Participants were then asked to complete the "Lost on the Moon" task individually. This requires participants to imagine they are stranded on the moon and to rank 15 items (e.g., water, matches) based on their importance for survival (Hall & Watson, 1970). This task has been widely used to empirically assess group problem-solving (e.g., Bluedorn, Turban, & Love, 1999; Erffmeyer & Lane, 1984; Meslec & Curşeu, 2013). Performance is scored in comparison to an objective ranking of the 15 items supplied by the National Aeronautics and Space Administration (NASA) in order to calculate an error score whereby lower scores represent better performance. Participants were given 6 minutes to complete the LotM task.

Next, pairs were asked to perform a light movement activity under one of three coordination conditions: synchrony, asynchrony or control (i.e., no coordination). The activity consisted of 190s of repetitive arm curls (i.e., flexion/extension about the elbow) while holding a lightweight wooden rod (5 cm diameter, 60 cm long).

Before receiving any instructions regarding the coordination manipulation, the experimenter modelled the required movement in time with a metronome (84 bpm). Each participant was then asked to demonstrate the movement to ensure they were performing it appropriately (e.g., sufficient range of motion). This check was completed individually to avoid any inadvertent contamination of the coordination manipulation. For this practice stage, participants initially moved in time with the metronome (84 bpm) which was turned off after 5 seconds, whereby participants were asked to maintain the same tempo for another 10 seconds. The coordination manipulation instructions were only given once the experimenter was satisfied that both participants were executing the arm curls correctly.

Participants allocated to the synchrony condition were asked to synchronize with one another (i.e., to ensure they were both at the same point of the movement cycle at the same time). In contrast, participants allocated to the asynchrony condition were instructed to avoid synchronizing with one another (i.e., to ensure they were both at a different point in the movement cycle). Pairs in this condition were also instructed to avoid simply being at the opposite point of the movement cycle (i.e., to avoid anti-phase as well as in-phase coordination). Although avoiding synchronizing can be considered a form of coordination (i.e., coordinating to ensure movements are at a different point of the movement cycle), consistent with previous literature (e.g., Lumsden, Miles, & Macrae, 2014) here we use the term asynchrony to refer specifically to an absence of systematic in-phase or anti-phase synchrony. In the synchrony and asynchrony conditions, participants stood approximately 50 cm apart at a 90˚ angle from one another so as to be able to maintain a visual coupling but avoid potential discomfort arising from a direct face-to-face interaction while in such close proximity. Participants in the control condition performed the activity back-to-back separated by a partition in order to eliminate visual coupling, and were given no instructions regarding coordination, rather they were told to maintain the tempo used during the practice stage. In order to objectively measure coordination, arm movements were recorded at 120 Hz using a magnetic motion tracking system (Polhemus Liberty, Polhemus Corporation, Colchester, VT) with sensors attached to the end of each participant's rod. Immediately following this manipulation, participants made ratings of their social perceptions, anticipated motivation and contribution to the forthcoming dyadic problem-solving task (see **Appendix**).

Next, each pair was given 4 minutes to jointly discuss the LotM problem. They were seated approximately 1.5 m apart on chairs arranged at a 90˚ angle to each other, facing a digital video camera (Sony HD-SR12) which was used to record the interaction (1920 × 1080 pixels, 25 fps). The purpose of this recording was to provide a means to quantify any spontaneous behavioural coordination that emerged during the discussion, hence actions that may have artificially increased (or decreased) coordination were minimized or eliminated. To this end, participants were instructed to remain seated throughout the procedure, and were not permitted to record (i.e., write) their answers during the 4 minute discussion period. Moreover, care was taken to ensure participants were positioned equidistant from the vertical centre of the frame and spaced sufficiently far apart that no part of their body crossed this line at any point during the interaction (Romero, Amaral, Fitzpatrick, Schmidt, Duncan, & Richardson, 2017). Once they had agreed on and recorded a joint solution, participants returned to individual cubicles and again completed ratings of their social perceptions, motivation and contribution to the collaborative problem-solving task (see **Appendix**).

Finally, participants completed the LotM problem again, this time individually. They were told that they could rank the items in any way they wished (i.e., they could change their rankings from their earlier attempts, but they did not have to do so) and were given 4 minutes to complete the problem, after which they were thanked for their time, debriefed, and dismissed.

4.3. Data Reduction and Analysis

Prior to analysis, the motion-tracking measurements from the coordination manipulation were reduced and cleaned. Initially, the first 10 seconds of movement data for each pair was removed in order to eliminate transients that may occur during the initiation of the arm curls. Next, each time series was centred around 0 and low-pass filtered using a Butterworth filter. The relative phase relationship between each participant's arm movements (in the vertical plane) was then calculated and normalized to a range of 0˚ - 180˚. The distribution of relative phase angles across nine 20˚ regions of relative phase (0˚ - 20˚, 21˚ - 40˚, ··· 161˚ - 180˚) was determined by calculating the frequency of coordination occurring within each of these regions. Thus, for each pair, their raw movement data was reduced to estimates of the time spent in each of the nine relative phase regions. Coordination is indicated by a concentration of relative phase angles in the portions of the distribution near 0˚ (i.e., in-phase coordination) and/or 180˚ (i.e., anti-phase coordination). At this point, pairs who were deemed not to have followed the instructions (i.e., those in the asynchrony condition but spent > 25% of the interaction in either the in-phase or anti-phase mode) were identified, removed from the data set, and replaced (see Participants and Design).

4.4. Manipulation Check

To confirm that the coordination manipulation was successful, the proportion of time spent in each phase region was compared as a function of condition using a 3 (Condition: Synchrony, Asynchrony, Control) × 9 (Phase region: 0˚ - 20˚, 21˚ - 40˚, ··· 161˚ - 180˚) mixed model analysis of variance (ANOVA) with repeated measures on the second factor. As expected, there was no effect of Condition, $F(2, 187) = 0.35$, $p = 0.708$, $\eta_p^2 = 0.004$, but a significant effect of Phase, $F(8, 1496) = 834.98$, $p < 0.001$, $\eta_p^2 = 0.817$, which was qualified by a Condition x Phase interaction, $F(16, 1496) = 1001.45$, $p < 0.001$, $\eta_p^2 = 0.915$. Inspection of **Figure 2** indicates a concentration of relative phase angles in the in-phase (i.e., 0˚ - 20˚) region for pairs in the Synchrony condition, but relatively even distributions (i.e., no systematic coordination) for those in the Asynchrony and Control

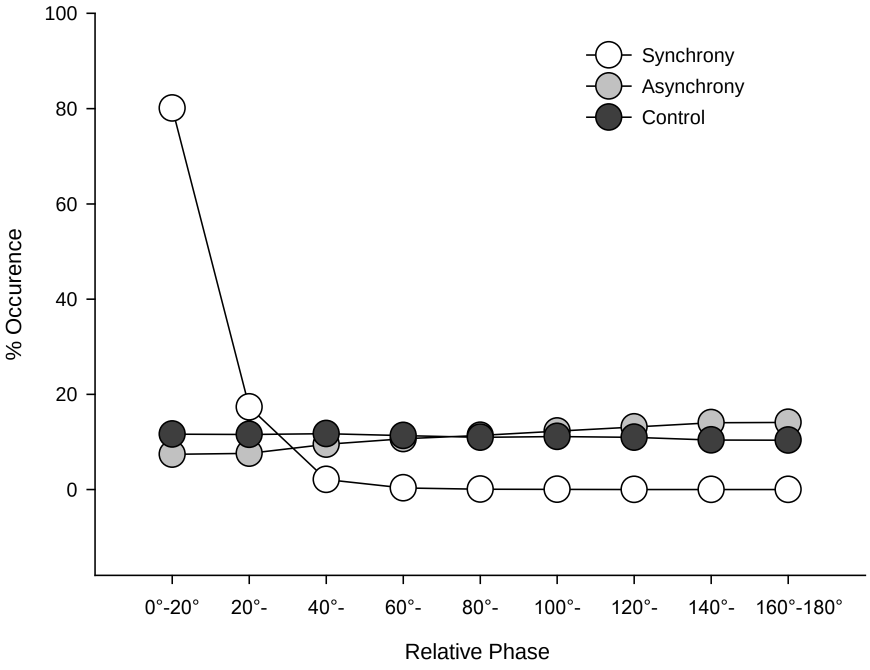

Figure 2. Coordination manipulation check showing distribution of the relative phase relationship between participants' movements as a function of condition (i.e., synchrony, asynchrony, control).

conditions. These patterns reveal that the intended coordination conditions were achieved.

4.5. Spontaneous Coordination

In order to objectively quantify spontaneously emerging coordination during the joint problem-solving task, we initially employed a frame-differencing method (FDM, see Paxton & Dale, 2013) whereby time series of pixel-change data were constructed on a frame-by-frame basis for each pair. Specifically, each video was first reduced in size and down-sampled (resulting files = 960 × 540 pixels, 24 fps; Aisosoft free video converter, version 3.1.3) and every third frame was extracted as a still image (.png format; VLC media player, version 2.0.8) to provide a sample rate of 8 Hz (as recommended by Paxton & Dale). Next, using a custom-written MATLAB script (Paxton & Dale) each image was halved (vertically) and compared to the corresponding half of the frame immediately previous in the time series in terms of pixel change (i.e., indicating individual participant movement). Raw pixel change scores were then low-pass filtered using a Butterworth filter to provide two time series (one per participant) of movement data for each 4 minute interaction. The first 5 seconds of each time series were removed to eliminate any transient behaviour at the beginning of the task (e.g., seeking clarification) and coordination was then calculated using a cross-wavelet analysis (see Issartel, Bardainne, Gaillot, & Marin, 2015; Schmidt, Nie, Franco, & Richardson, 2014). Specifically, we estimated global movement coordination across all time scales (i.e., frequencies) and normalised the resulting data to a range of 0˚ - 180˚. Thus, for each dyad, raw pixel change data were reduced to the time spent in each of the nine relative phase regions during the joint problem-solving stage of the procedure. It should be noted that this data represent coordination in time (i.e., 0˚ = simultaneous movements; 180˚ = alternating movements) but do not reference the form of movement (e.g., gestures vs. nodding) detected via the FDM.

4.6. Missing Data

Occasionally participants did not fully complete each questionnaire resulting in a small amount of missing data. Specifically, there was no record of 1 participant's age (Control), and missing data for 3 participants' (1 Asynchrony, 2 Control) ratings of an aspect of social perceptions (i.e., self-other overlap, see Appendix) following the intentional coordination manipulation, and 1 participant's (Synchrony) ratings of affiliation, motivation and contribution following the collaborative problem-solving task. In addition, due to technical issues, there was no motion-tracking recording of participants' movements for 1 dyad (Synchrony) during the intentional coordination manipulation and no video recording of the collaborative problem-solving discussion for 3 dyads (1 Synchrony, 2 Control). Participants with missing data were excluded from the relevant analyses.

4.7. Statistical Estimation

Effect sizes are included for all important results and distributional information is presented as 95% confidence intervals calculated via 1000 bias-corrected bootstrapped samples.

5. Results

5.1. Problem-Solving: Individual Performance

As the outcome measure of primary interest, individual LotM solutions (i.e., post-interaction) were compared between conditions using an analysis of covariance (ANCOVA) with baseline (i.e., pre-interaction) LOTM performance entered as a covariate. Importantly, this revealed a significant effect of condition, $F(1, 188) = 4.37$, $p = 0.014$, $\eta_p^2 = 0.04$ (see Figure 3), as well as an effect of the covariate, $F(1, 188) = 45.31$, $p < 0.001$, $\eta_p^2 = 0.19$. Post-hoc comparisons indicated that participants in the synchrony condition (adjusted $M = 40.07$, 95% CI [37.99, 42.35]) outperformed (i.e., made fewer errors) those in both the asynchrony (adjusted $M = 44.50$, 95% CI [42.26, 46.95]; $p = 0.005$, 95% CI of difference [−7.48, −1.22]) and the control (adjusted $M = 43.28$, 95% CI [41.22, 45.49]; $p = 0.029$, 95% CI of difference [−6.20, −0.64]) conditions. There was no difference in LotM performance between the latter two groups ($p = 0.416$, 95% CI of difference [−4.39, 1.75]).

These findings indicate that, independent of initial problem-solving ability, participants who experienced a short period of in-phase coordination (i.e., synchrony condition) prior to the discussion stage of the procedure went on to

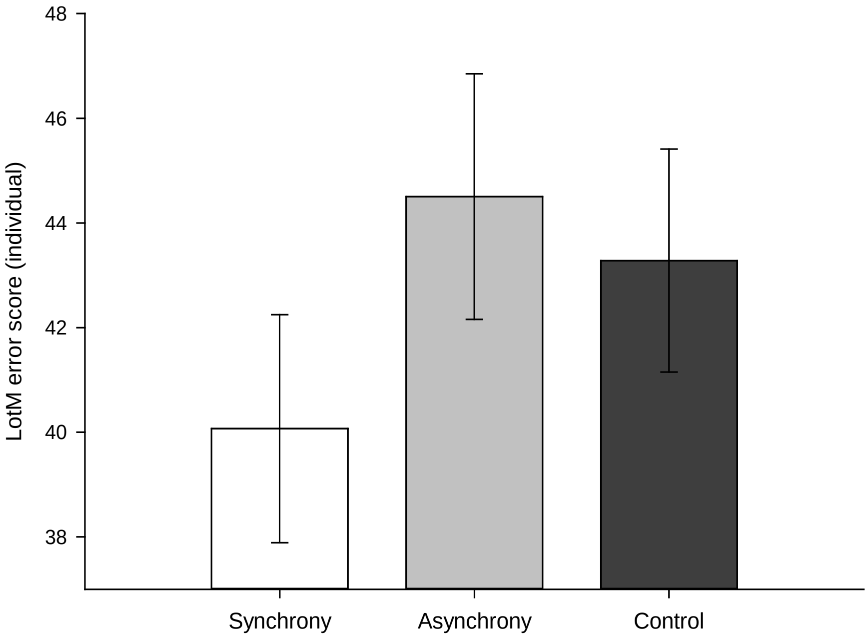

Figure 3. Post-discussion (individual) LotM error scores as a function of condition. Error bars represent bias-corrected 95% confidence intervals based on 1000 bootstrapped samples.

provide more accurate LotM solutions. An equivalent period of asynchronous interaction did not, however, impact problem-solving when compared to the no coordination control condition. To further explore the antecedents of this effect we next looked at the joint (i.e., agreed) solutions and the behavioural coordination that emerged when pairs collaboratively discussed the LotM problem.

5.2. Problem-Solving: Joint Performance

Initially we compared the agreed (i.e., joint) LotM solutions across conditions using a one-way analysis of variance (ANOVA). Although this revealed no significant effect, $F(2, 93) = 2.07$, $p = 0.132$, $\eta_p^2 = 0.04$ (see **Figure 4**, solid bars), inspection of the means suggests at least a numerical trend indicative of the effect reported above (Synchrony: $M = 39.49$, 95% CI [36.41, 42.61]; Asynchrony: $M = 44.34$, 95% CI [40.19, 48.24]; Control: $M = 43.03$, 95% CI [40.22, 46.25]). Acknowledging that performing this analysis at the level of the dyad (i.e., one LOTM score per pair) necessarily restricts statistical power, we followed-up the apparent trend by comparing joint LotM solutions with the expected performance level calculated for each pair. Rather than simply averaging individual baseline (i.e., pre-discussion) scores which is acknowledged to systematically underestimate the combined abilities of group members, here we adopted the correction advocated by Slevin (1978). This correction provides a statistically pooled average whereby errors made by individuals that are equivalent in magnitude but opposite in direction cancel each other out (as is likely the case when

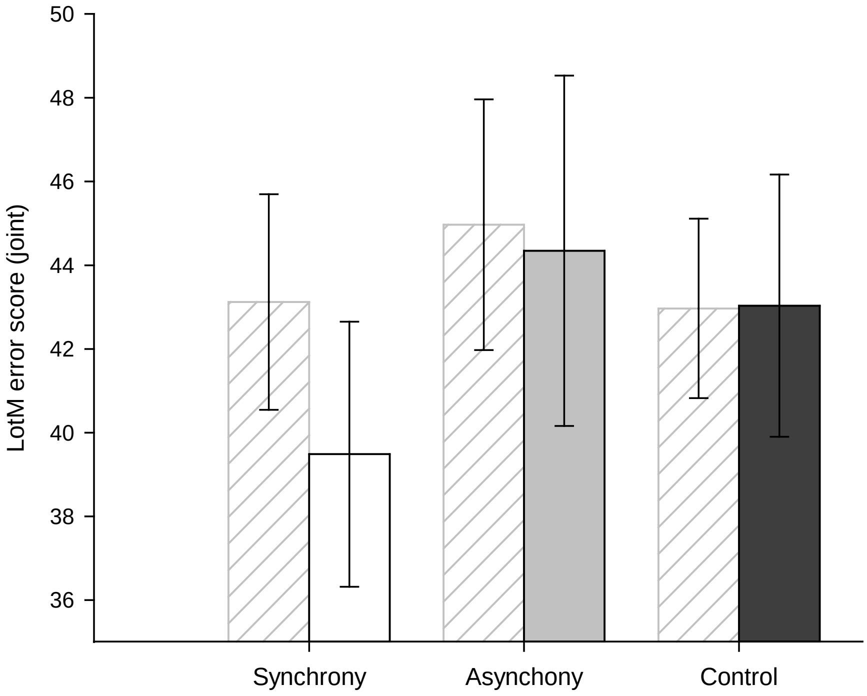

Figure 4. Joint LotM error scores (solid bars) and Slevin (1978) corrected predicted scores (hashed bars) as a function of condition. Error bars represent bias-corrected 95% confidence intervals based on 1000 bootstrapped samples.

individuals learn from each other during discussion). Thus, we compared actual with predicted (i.e., Slevin-corrected estimates, see **Figure 4**, hashed bars) problem-solving scores for each condition separately. This indicated that dyads in the synchrony condition outperformed their predicted LotM score (M_{Slevin} = 43.12, 95% CI [40.70, 45.85]; $t(32) = 2.56$, $p = 0.015$, $d = 0.43$, 95% CI of difference [0.74, 6.53]), while no such difference was observed within either the asynchrony (M_{Slevin} = 44.97, 95% CI [41.92, 47.91]; $t(31) = 0.39$, $p = 0.700$, $d = 0.06$, 95% CI of difference [−2.65, 3.90]) or control (M_{Slevin} = 42.97, 95% CI [40.88, 45.17]; $t(30) = 0.05$, $p = 0.964$, $d = 0.01$, 95% CI of difference [−2.96, 2.83]) conditions. Therefore, although at the level of the dyad there was no statistically significant effect of coordination condition, pairs in the synchrony condition performed better than expected based on their initial (individual) LotM scores. In terms of problem-solving performance, consistent with the effect reported above, those who had previously experienced a synchronous interaction benefitted most from the period of collaborative discussion.

5.3. Spontaneous Coordination

Next, as an exploratory goal estimates of global coordination during the joint discussion stage of the procedure were compared using a 3(Condition) × 9 (Phase region: 0˚ - 20˚, 20˚ - 40˚, ···, 160˚-180˚) mixed model ANOVA with repeated measures on the second factor. This revealed a main effect of Phase, $F(8, 1464) = 7455.99$, $p < 0.001$, $\eta_p^2 = 0.98$ (see **Figure 5**), but no effect of Condition, nor a Condition x Phase region interaction (Fs < 0.6), indicating that the

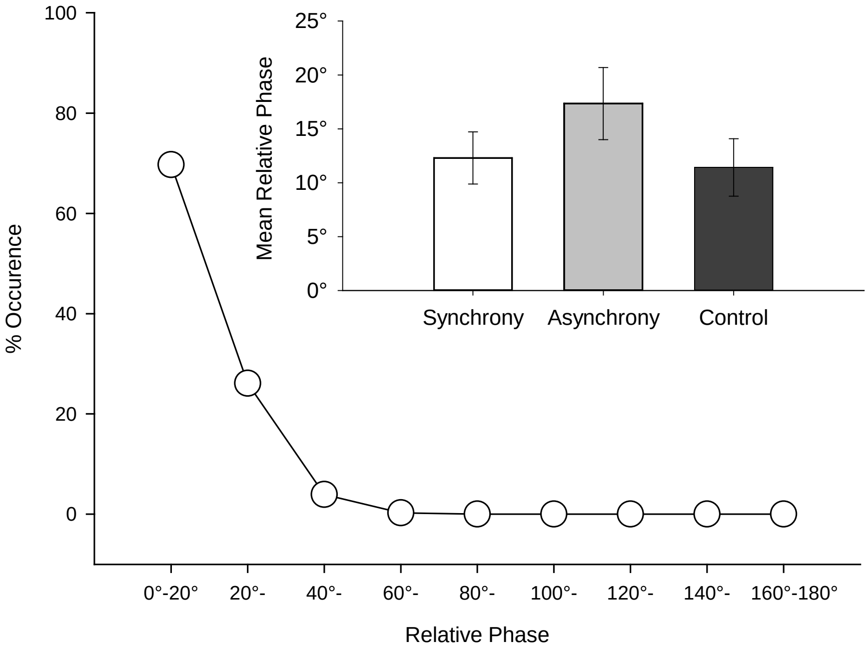

Figure 5. Distribution of relative phase relationship between participants' movements during the collaborative problem-solving stage of the procedure. Inset: Mean relative phase as a function of condition. Error bars represent bias-corrected 95% confidence intervals based on 1000 bootstrapped samples.

distribution of coordination was predominantly around the in-phase mode for all conditions. However, a univariate ANOVA comparing mean relative phase across conditions revealed a significant effect, $F(2, 183) = 4.79$, $p = 0.009$, $\eta_p^2 = 0.05$ (see **Figure 5**, inset).Post-hoc comparisons indicated that participants in the asynchrony condition ($M = 17.35˚$, 95% CI [14.19˚, 20.88˚]) showed higher values of mean relative phase (i.e., further from in-phase) than either participants in the synchrony condition ($M = 12.30˚$, 95% CI [9.93˚, 14.77˚]; $p = 0.023$, 95% CI of difference [1.02˚, 9.18˚]) or the control condition ($M = 11.43˚$, 95% CI [8.83˚, 14.16˚]; $p = 0.007$, 95% CI of difference [1.55˚, 10.50˚]). There was no difference between the latter two groups ($p = 0.643$, 95% CI of difference [−4.19˚, 5.92˚]). Thus although dyads across all conditions showed a tendency toward simultaneous movements (i.e., global in-phase coordination) while discussing the LotM problem, the actions of pairs who had previously experienced a short period of asynchronous interaction were not as closely matched in time.

5.4. Spontaneous Coordination and Problem-Solving

Given the evidence for differences in both problem-solving and spontaneous coordination as a function of condition, we next examined the relationship between these behaviours. Looking first at joint problem-solving, bivariate correlations indicated a relationship between mean relative phase and joint LotM error score for participants in the control condition, $r(29) = 0.45$, $p = 0.016$, 95% CI [0.20, 0.69], but not so for those in either the synchrony, $r(32) = −0.16$, $p = 0.366$, 95% CI [−0.45, 0.19], or asynchrony conditions, $r(32) = −0.10$, $p = 0.580$, 95% CI [−0.53, 0.23]. Comparison of the magnitude of these correlations (Diedenhofen & Musch, 2015; with confidence intervals estimated using the method proposed by Zou, 2007) confirmed that the relationship for the control condition was stronger than either the synchrony, $z = 2.38$, $p = 0.017$, 95% CI of difference [0.10, 1.02], or asynchrony, $z = 2.15$, $p = 0.032$, 95% CI of difference [0.05, 0.97] conditions, while the latter two groups did not differ from each other, $z = 0.24$, $p = 0.816$, 95% CI of difference [−0.43, 0.54]. An identical pattern of results was found when individual problem-solving (i.e., post discussion) scores were considered. That is, participants in the control condition who showed higher levels of mean relative phase (i.e., further from in-phase) during the discussion also made more errors on the (individual) LotM task, $r(58) = 0.46$, $p < 0.001$, 95% CI [0.19, 0.66]. This was not the case for the synchrony, $r(64) = −0.09$, $p = 0.470$, 95% CI [−0.33, 0.16], or asynchrony, $r(64) = 0.06$, $p = 0.657$, 95% CI [−0.27, 0.33], conditions. Again, the magnitude of this relationship was greater for the control than the synchrony, $z = 3.16$, $p = 0.002$, 95% CI of difference [0.21, 0.85], or asynchrony, $z = 2.36$, $p = 0.018$, 95% CI of difference [0.07, 0.71] conditions, which did not differ from each other, $z = 0.82$, $p = 0.407$, 95% CI of difference [−0.20, 0.49]. It appears that the interpersonal coordination that emerged spontaneously while participants discussed the LotM problem was indeed functional (i.e., positively related to problem-solving), but only for those who had not previously experienced any form of coordination (i.e., control condition).

6. Discussion

Complex cognitive tasks often call for collaboration. Here we showed that a short period of interpersonal synchrony augmented the benefits of such teamwork—enhanced problem-solving was associated with in-phase coordination. Of both theoretical and practical significance, the short-term history of each dyad determined both when and in what form synchrony was functional. For pairs who had been instructed to either intentionally synchronize or avoid synchrony, this initial coordinative mode determined both subsequent patterns of spontaneous coordination (cf. Valdesolo et al., 2010) and, importantly, problem-solving efficacy (i.e., synchrony > asynchrony). In contrast, pairs who had not experienced a prior interaction (i.e., control condition) only realised productivity benefits to the extent that in-phase synchrony emerged spontaneously (cf. Won et al., 2014).

These results add further support to the view that movement coordination plays a central role in governing interpersonal processes (Marsh, 2013). Although all participants initially performed essentially identical actions (i.e., 190s of arm curls at equivalent tempos), for those in the synchrony and asynchrony conditions, the relationship between the movements of each pair was a critical factor in shaping subsequent collaborative efficacy. Assuming communication was the key dependency for optimizing LotM solutions (Civettini, 2007; Hall & Watson, 1970), it follows that the social-cognitive attunements promoted by dynamically stable coordination (i.e., in-phase synchrony) served to enhance communicative effectiveness. Consistent with Semin's (2007) model of interpersonal communication systems, synchronous actions can be seen to provide a "scaffold" on which to build effective communication strategies—an effect echoed in the control condition when considering the emergence of synchrony during the interaction. Together, these results suggest that the initial coordinative experience of a dyad, potentially divorced from the form (i.e., intentional or spontaneous) or timing (i.e., prior to or during a task) of such coordination, exerts a primary influence on shaping functional outcomes. Consistent the recent proposition by Abney and colleagues (2015), rather than a straightforward "more-is-better" effect here we add to an increasingly nuanced picture regarding the role of coordination in daily social exchange.

Identification of the specific behavioural mechanism(s) by which coordination affords effective collaboration is an important next step when considering the functional outcomes of interpersonal synchrony. It is well documented that the quality of complex decisions can often suffer if groups adopt a consensus-seeking approach (e.g., group polarisation, Myers & Lamm, 1975; groupthink, Janis, 1982), while appropriate levels of disagreement and discussion can prompt a more broad exploration of the problem space and enhance solution quality (Amason, 1996; Wall, Galanes, & Love, 1987). Consideration of the current

LotM task suggests a similar scenario—sharing and debating opinions would likely lead to better solutions than a primary motivation to seek consensus or agree in the first instance (Civettini, 2007). Indeed, the optimization of communication is a recurring theme among researchers concerned with the functions of interpersonal coordination (e.g., Abney et al., 2015; Fusaroli, Rączaszek-Leonardi, & Tylén, 2014; Marsh, 2013; Riley, Richardson, Shockley, & Ramenzoni, 2011; Shockley, Richardson, & Dale, 2009; Semin, 2007). Here we speculate that the effects of in-phase behavioural synchrony facilitated styles of communication conducive to group-based problem solving. Future research designed to provide more in-depth analyses of the content and linguistic patterns of the verbal interactions during collaboration, and how these relate to patterns of movement coordination, will go some way towards evaluating this proposed explanation.

At this point it might be tempting to also search for neural or representational mechanisms underpinning these findings. However, consistent with the view that social phenomena can be self-organizing (Coey, Varlet, & Richardson, 2012; Dale, Fusaroli, Duran, & Richardson, 2013; Kelso, 1995; Marsh, 2013; Schmidt & Richardson, 2008) we suggest there is also utility in identifying the relational structures that emerge between individuals, and how these give rise to new opportunities for interaction (Mathieu, Maynard, Rapp, & Gilson, 2008; Richardson, Marsh, & Baron, 2007). Thus, beyond the piecemeal identification of social-cognitive attunements promoted by synchronous acts, further emphasis should now be placed on understanding how such outcomes shape the emergent properties of joint action contexts and, in turn, impact dependencies between team members. To this end, future work may profit from renewed focus on the group (e.g., dyad) as the unit of analysis when investigating complex social phenomena (Semin, 2007; Steiner, 1986).

7. Conclusion

The present work revealed that the dynamics governing interpersonal synchrony impact the potential for collaboration to enhance problem-solving success. While it remains for future work to uncover the precise behavioural outcomes that give rise to these effects, it is apparent that when teamwork is concerned, coordination matters.

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Appendix

Pre-Interaction Measures

Prior to the beginning of the procedure we collected basic demographic information (i.e., participant age and sex) along with assessments of personality characteristics previously shown to relate to interpersonal synchrony (e.g., social value orientation, see Lumsden, Miles, Richardson, Smith, & Macrae, 2012; social anxiety, see Varlet et al., 2014) and Lost on the Moon (LotM) problem-solving performance. As shown in **Table A1** (categorical measures) and **Table A2** (continuous measures) there were no systematic differences between conditions on any of the measures.

Table A1. Categorical baseline (pre-interaction) demographic and personality measures.

Variable	Condition					
	Synchrony	Asynchrony	Control			
	n	*n*	*n*	χ^2	df	*p*
Sex (individual)						
F	45	38	44	2.08	2	0.354
M	21	26	18			
Sex (dyad)						
FF	16	12	16	4.23	4	0.376
MM	4	6	1			
FM	13	14	14			
SVO^a						
Prosocial	43	33	29	9.51	6	0.147
Individualist	13	13	12			
Competitive	2	8	5			
No classification	8	10	16			

Notes: ^{a}Social Value Orientation (SVO) as measured by the 9-item triple dominance measure (see Van Lange, 1999). Combining the "Individualist" and "Competitive" orientations into a general "Pro-self" category also yielded a non-significant test of independence, χ^2 (4) = 6.96, $p = 0.138$. "No classification" refers to participants who failed to make at least 6/9 consistent (i.e., same orientation) choices.

Table A2. Continuous baseline (pre-interaction) demographic and personality measures.

Variable	Condition						
	Synchrony	Asynchrony	Control				
	M (95% CI)	M (95% CI)	M (95% CI)	F	df	*p*	η_p^2
Age (yrs)	20.6 (19.9, 21.3)	21.2 (20.3, 22.3)	21.3 (20.3, 22.4)	0.44	2188	0.643	0.005
LSAS	47.8 (42.7, 52.9)	46.8 (40.6, 52.6)	43.2 (38.4, 49.0)	0.74	2189	0.477	0.008
LotM (base)	47.5 (45.0, 49.7)	49.8 (46.6, 53.3)	47.7 (45.6, 50.0)	0.86	2189	0.426	0.009

Notes: LSAS = Liebowitz Social Anxiety Scale (Liebowitz, 1987) total score (subscales, Cronbach's α = 0.898); LotM = Lost on the Moon problem-solving task (see Hall & Watson, 1970). Confidence intervals were estimated using bias-corrected bootstrapping based on 1000 samples.

Social and Task Perceptions

Immediately after the intentional coordination manipulation and the collaborative problem-solving task, participants were asked about their social experience (IOS, Aron, Aron & Smollan (1992); affiliation scale[2]), their motivation[3] and individual contribution[4] to the problem-solving task. As can be seen in **Table A3**, the only significant differences as a function of condition were found for IOS and affiliation ratings following the coordination manipulation. Inspection of the means for these measures indicate, consistent with previous research, a trend towards synchrony being associated with higher levels of social connection. However post-hoc pair-wise comparisons only confirmed the difference between the control and either the synchrony or asynchrony conditions. This difference is potentially grounded in the fact that those in the control condition had not

Table A3. Participant perceptions following the coordination manipulation and problem-solving task.

Variable	Condition						
	Synchrony	Asynchrony	Control				
	M (95% CI)	M (95% CI)	M (95% CI)	*F*	df	*p*	η_p^2
		Intentional Coordination Manipulation					
Social							
IOS	2.0_x (1.7, 2.3)	1.8_x (1.6, 2.0)	1.5_y (1.3, 1.7)	3.92	2186	0.021	0.041
Affiliation	35.2_x (31.5, 39.4)	33.6_x (29.9, 37.7)	25.8_y (22.5, 29.2)	6.82	2189	0.001	0.067
Task							
Motivated	44.5 (37.8, 51.2)	46.8 (41.3, 52.4)	45.0 (39.0, 51.6)	0.16	2189	0.849	0.002
Contribute	52.0 (50.0, 54.0)	51.3 (48.2, 54.0)	50.8 (48.6, 53.1)	0.23	2189	0.796	0.002
		Collaborative Problem-solving Task					
Social							
IOS	3.2 (2.9, 3.6)	3.1 (2.8, 3.4)	2.7 (2.4, 3.0)	2.62	2189	0.076	0.027
Affiliation	49.7 (45.1, 54.4)	46.5 (41.9, 50.8)	42.7 (37.8, 47.6)	2.28	2188	0.105	0.024
Task							
Motivated	56.0 (49.1, 63.0)	56.2 (50.0, 62.5)	53.0 (46.7, 59.2	0.31	2189	0.738	0.003
Contribute	50.6 (48.0, 53.1)	50.5 (47.7, 53.2)	50.8 (47.7, 53.9)	0.15	2189	0.985	0.000

Notes: IOS = Inclusion of Other in the Self scale (Aron, Aron, & Smollan, 1992); Affiliation items (see Lumsden et al., 2014): liking; similarity, connectedness, closeness (Following coordination manipulation: Cronbach's α = 0.807; Following collaborative problem-solving: Cronbach's α = 0.879). Means in the same row with different subscripts differ at $p < 0.05$ (Bonferroni-corrected post-hoc pair-wise comparisons).

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[2] Affiliation scale items: How likeable is the other participant?; How similar is the other participant to you?; How connected to the other participant do you feel?; How close to the other participant do you feel?. Participants responded by placing a mark on a 100 mm analogue scale anchored by "Not at all" and "Very much".

[3] Participants were asked how important it is (was) for them to do well on the joint LotM task using a 100 mm analogue scale anchored by "Not at all important" and "Extremely important".

[4] Participants were asked how much they thought they will (did) contribute to the joint LotM task relative to the other person using a 100 mm analogue scale anchored by "0%—all the other person" and "100%—all me".

experienced any substantive social contact with their partner at this point (i.e., no contact during the task), while those in the other conditions had just spent two minutes in a face-to-face interaction with a shared goal (i.e., synchronize or avoid synchronizing). Nonetheless, neither measure showed any relationship to post-interaction problem-solving (IOS: $r(189) = 0.07$, $p = 0.355$, 95% CI [−0.10, 0.21], Affiliation: $r(192) = 0.02$, $p = 0.790$, 95% CI [−0.15, 0.20]), nor did they influence the reported effect of coordination condition on LotM performance when considered as a covariate (IOS: covariate, $F(1, 184) = 0.14$, $p = 0.705$, $\eta_p^2 = 0.001$, effect of condition, $F(2, 184) = 4.35$, $p = 0.014$, $\eta_p^2 = 0.045$; Affiliation: covariate, $F(1, 187) = 0.34$, $p = 0.558$, $\eta_p^2 = 0.002$, effect of condition, $F(2, 187) = 4.10$, $p = 0.018$, $\eta_p^2 = 0.042$). Identical patterns of results were found when baseline LotM scores were omitted as a covariate.

Finally, IOS ratings following the collaborative problem-solving task also revealed a trend towards an effect of condition, however, post-hoc pair-wise comparisons revealed no significant differences, and this measure showed no relationship to post-interaction problem-solving, r(192) = 0.053, $p = 0.468$, 95% CI [−0.10, 0.20], nor did it influence the reported effect of coordination condition (covariate: F(1, 187) = 0.58, $p = 0.449$, $\eta_p^2 = 0.003$, effect of condition, F(2, 187) = 4.51, $p = 0.012$, $\eta_p^2 = 0.046$). Again, an identical pattern of results was found when baseline LotM scores were omitted as a covariate.