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Synch.Live: Collective problem-solving through flocking motion associated with higher connectedness to others

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Abstract

Background: Collective self-organising behaviour is ubiquitous in nature, whereby complex patterns emerge from the local interactions between individuals. Yet in humans, most group behaviour is attributed to explicit central control or pre-planning, rather than to the synergistic decentralised interplay between individuals.

Purpose: This paper introduces *Synch.Live*, a novel experimental paradigm for quantitatively studying collective motion in humans, framed as a game with an unspecified task and a group feedback mechanism that can be solved through cooperation by 10 participants walking together. We also present the results of a pilot study demonstrating its use.

Study sample: 10 partitipants took part in each trial, forming 16 independent groups.

Data collection and/or Analysis: We collected psychometrics, behavioural and trahectory data in order to explore the participants' state of mind and the strategies they developed collectively to solve the group challenge.

Results: We found that more than half of the groups participating in the study self-organised to achieve collective flocking motion, and winning players showed higher connectedness to others compared to those who failed. Furthermore, individuals with an awareness of working strategies were more likely to be part of winning groups, suggesting the importance of individual contributions to the collective task.

Conclusion: This work demonstrates that solving an unspecified group challenge in response to group feedback is possible, and moreover, that flock-like collective movement has the potential to yield social benefits and well-being, suggesting new directions for exploring social aspects of consciousness and cognition.

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Introduction

Collective intelligent behaviour is pervasive in nature, from eusocial insects to birds and mammals (Vicsek and Zafeiris 2012). Arguably its most important aspect is *self-organisation*, where global patterns emerge spontaneously from local interactions between individuals, rather than from a form of central control, authority, or pre-planning – especially in larger groups (Hemelrijk and Hildenbrandt 2012; Shaw 1978; Sumpter 2006). An example of such collective behaviour is the phenomenon of synchronisation: when individuals align their actions, movement, speech, or bodily functions such as breathing or heartbeats, and coordinate to act as one.

While human group behaviour is frequently driven by a system of rules or central control, people can also manifest group behaviour in a self-organised fashion: for instance, in the form of movement, such as group improvisation in theatre, music or dance (Noy 2015), 'moshpits' in rock concerts (Silverberg et al., 2013), and 'waves' in sports events (Farkas et al., 2002). Large-scale self-organising collective movement – from pedestrian flows to traffic – can be easily seen in cities. An understanding of its characteristics is crucial to urban planning, such as in the case of pedestrians walking on the Millennium bridge, who spontaneously and unexpectedly synchronised their stride, making the bridge shake (Strogatz et al., 2005).

There are strong similarities between self-organising collective movement in humans and flocking: the coordinated, collective movement of a group, driven by simple local interactions with neighbours, such as starling murmurations, sheep herds, and fish schools (Satz 2020).

Crucially, collective human behaviour often involves more than coordinated movement patterns, since it is strongly related to individual subjective experiences. Physical or physiological synchrony has been shown to correlate with a positive collective experience of art, such as music (Bernardi et al., 2017; Nozawa et al., 2023; Tschacher et al., 2023), dancing (Ellamil et al., 2016), and films (Bacha-Trams et al., 2020). Coordinated movement or physical synchrony has been shown to yield positive mental and emotional outcomes: building rapport and increasing inter-brain synchrony (Nozawa et al., 2019), improved cooperation (Jackson et al., 2018; Shockley et al., 2003) and team problem-solving performance (Gordon et al., 2020; Wiltshire et al., 2019), a sense of community (Xu et al., 2013), the perception of social cohesion and shared experience in crowds (Baranowski-Pinto et al., 2022), and the sense of bonding and 'identity fusion' in gatherings such as parades or protests (Wilson and Mansour 2020).

Given its potential benefits, an important question is what types of interventions can elicit collective behaviour in the form of coordinated flocking movement in humans. Previous small-scale research has shown it is possible to encourage human groups to show flocking behaviour by instructing subjects to follow their neighbours, either physically (Leonard et al., 2012) or in a virtual game environment (Belz et al., 2013). In another in-person experiment, groups of up to 50 people were asked to walk randomly in a large space without talking, with only a few group members being informed where to walk (Dyer et al). Despite the lack of verbal communication, informed individuals were followed by the others, forming a cohesive flock, putatively suggesting the emergence of effective leaders as seen in bird flocks and fish schools (Couzin et al., 2005; Múgica et al., 2022).

However, most work focussing on human flocking considers the mechanisms that produce the collective behaviour as given, for instance, by instructing participants to imitate or follow their neighbours (Belz et al., 2013; Leonard et al., 2012). While providing local interaction rules can result in flocking, such rules limit emergent behaviour by constraining individual spontaneity in interaction and coordination with others, as well as natural strategy development within the group. As such, we aim for a flexible paradigm that allows richer local interactions so that, in turn, we can study more complex forms of collective intelligence through movement. Additionally, the psychological effect of spontaneous collective movement in humans has rarely been studied in a general context and with larger groups. Although frequently studied in the joint action literature (Sebanz et al., 2006), this research often focuses on very small groups, such as dyads or triads. However, small groups have limited diversity, which restricts the complexity of problem-solving or decision-making processes that can be studied. To further emphasise this, prior research shows that moderate or large groups outperform individuals and pairs in cognitive tasks due to aggregation of knowledge, social learning, and consensus building (Vercammen et al., 2019). Finally, previous research does not attempt to quantify the flocking behaviour in human groups. A large body of work studies collective movement in animals with information-theoretic methods (Brown et al., 2018, 2021a; Crosato et al., 2018; Mediano et al., 2022; Rosas et al., 2020), but this analysis has rarely been applied to human motion.

To address these unanswered questions, we introduce a technological framework for the study of human flocking and use it to develop a novel experimental paradigm. Unlike previous work, we do not provide specific strategies to participants, neither do we state that collective movement is the goal. Instead, we quantify the participants' collective motion and use an implicit group feedback mechanism to let them know how close they are to succeeding in their task. This encourages them to create their own strategies and allows studying the individual behaviour in relation to the group. Moreover, we employ larger groups of 10 to allow more complex interactions and strategies to emerge among participants. Finally, we propose that collecting psychometric data and conducting phenomenological interviews alongside the collective movement task allow us to study how interactions and strategies, and ultimately success in the task, are related to experience, state of mind, and psychological traits.

The *Synch.Live* experimental paradigm

Our experiment uses *Synch.Live* (Leone 2020), a technology inspired by the collective movement of animal groups and the synchronisation of fireflies (Moiseff and Copeland 2010) that induces collective behaviour in human subjects by playing a game with a group task and collective feedback.

The *Synch.Live* game consists of groups of 10 *players* wearing headsets equipped with flashing lights who must walk in a bounded space without talking or touching, with the goal of working together to synchronise all lights (Figure 1(a)). An *observer* system tracks the positions of the players in real time (Figure 1(b)) and computes an information-theoretic measure of *emergence*, denoted as Ψ (Rosas et al., 2020).

Emergent phenomena are understood here as properties or behaviours arising at the collective level from interactions between parts or individuals within a system or group, which cannot be explained solely by the properties or behaviours of the individuals alone (Clayton and Davies 2006; Jensen 2022). Using the Ψ measure allows us to detect collective movement as an emergent property of the group, without specifying a priori what kind of motion is required.

We use Ψ to quantify how much the trajectories form a cohesive structure around their centre of mass and how much is the centre of mass showing novel movements that

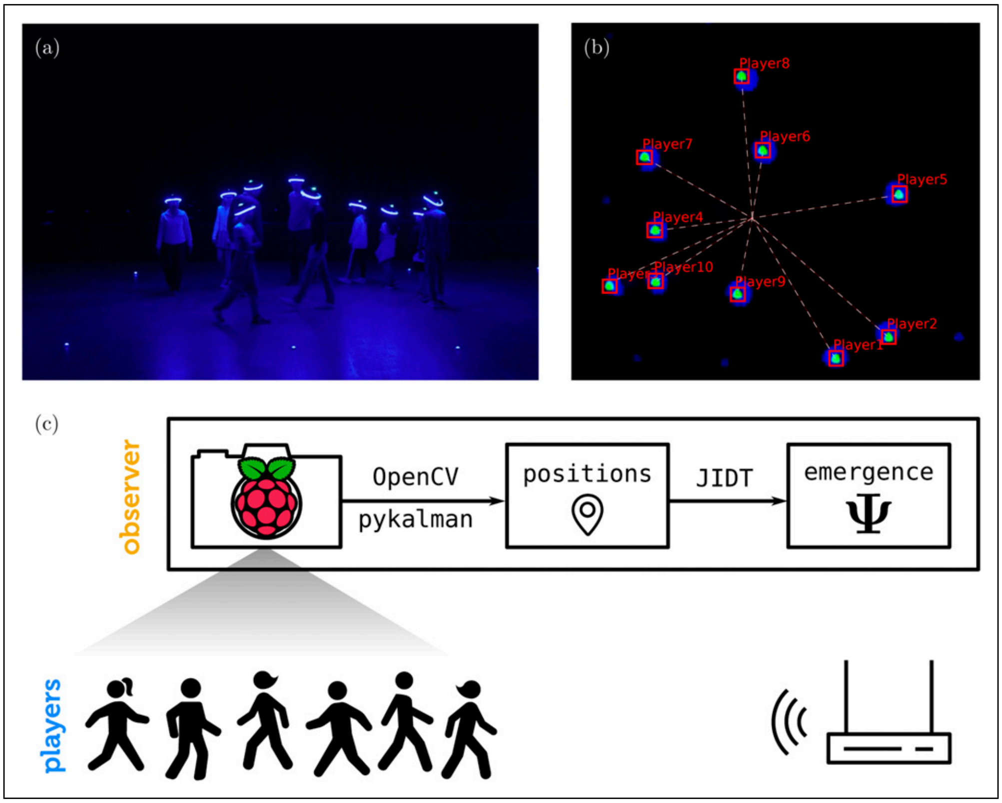

Figure 1. The *Synch.Live* experimental setup. (a) Photo of a *Synch.Live* experiment. Players achieved a high enough value of the emergence measure Ψ to synchronise their blue lights, which are on at the same time. (b) Snapshot of the footage as seen by the overhead camera, taken at a very similar time in the game, overlaid with OpenCV tracking annotations. The dashed lines show the distance from the centre of mass, used in the computation of Ψ (see Methods for details). (c) Diagram of the *Synch.Live* system. The *players* wear headsets with flashing lights. The *observer* system contains an overhead camera which tracks their movement and computes Ψ then broadcasts wirelessly back to the player headsets to control light synchrony.

cannot be reduced to any individual player's actions. Ψ, in turn, is used to drive the group feedback mechanism, so that the lights become more phase-synchronised the higher the group's value of Ψ (Figure 1(c)). As such, the players' indirect goal is to achieve collective motion, for example, flocking, by optimising the collective feedback mechanism of the synchronising lights.

Similar to some previous work (Dyer et al), we disallow verbal communication in order to encourage more physical embodiment. However, instead of enforcing specific behaviours, we only restrict them by three rules – *don't talk, don't touch, don't stop walking*, and give one goal – to synchronise the lights. This invites players to experiment and devise new interactions and collective strategies, instead of being limited to a finite set of interactions such as aligning direction (see Explicit instructions for details).

The game begins in an asynchronous state, with a negative value of the emergence measure Ψ. When the movement is scattered, the Ψ measure is negative and the lights blink randomly and fully out of sync, with delays of up to 2 s between each other. But when the group moves together in an increasingly coordinated way, Ψ begins to increase while the delay decreases until the lights blink fully in sync. When Ψ is above a certain threshold, the lights will also flash in rainbow colours, signalling the game is won.

However, even a single player breaking away from the group will cause synchrony to decrease globally. In other words, one person's actions affect the whole group. There is no individual signal or feedback; players cannot check if their strategies work by observing their own light, and must observe everyone else to assess how synchronous the lights are. Since players are not allowed to talk or touch, they cannot directly infer or plan strategies with others, but they can still watch for non-verbal cues and try new behaviours to observe how the lights and the other group members respond.

Overall, the system incentivises participants to work together to form collective movement patterns, without imposing any specific strategy for achieving this. Due to the distributed and collective nature of the feedback mechanism, each player's attention needs to be distributed to all others, as synchrony should be observed for the whole group. This is unlike past experiments, where the goal was stated directly at the local level of interaction with other players. Here, the goal is set indirectly at the group level through a feedback mechanism based on a group measure. Such group-level instructions allow a higher flexibility of individual behaviour, which in turn can result in more diverse group behaviour.

Using this experimental setup, we introduce the *Synch.Live experimental paradigm*: this consists of the *Synch.Live* technology, allowing us to measure collective movement in real-time and provide group feedback through flashing lights; the instructions to players; and a research question that relates collective behaviour to other variables (psychological, cognitive etc.). A complete technical description of the *Synch.Live* system is provided in Methods, alongside a mathematical description of the measure of emergence Ψ, the data collection, and the statistical tests undertaken.

In line with our research motivations, we also present an exploratory study where we apply the *Synch.Live* paradigm to the study of prosocial outcomes of coordination and collective intelligence. To do so, we enhance our data collection with psychometrics and interviews from participants. The *perspective-taking* scale (Davis, 1983) measures the tendency to adopt the psychological point of view of others and is relevant to social interaction and coordination within groups, facilitating smoother joint action and cooperation. The *connectedness* scale (Watts et al., 2022) measures a sense of connectedness to self, others, and the world, relating to how individuals feel socially bonded and integrated. Lastly, *metacognition* enables individuals to reflect on, communicate, and coordinate cognitive processes with others, thereby enhancing joint decision-making and collaborative understanding (Frith, 2012). We hypothesise that players who report higher *perspective-taking* and *metacognitive awareness* during the task will contribute to a positive outcome for the group and that succeeding in the group task will induce an overall feeling of belonging or *connectedness to others*. These hypotheses serve as guiding questions demonstrating how this novel paradigm may be applied, in our case to social aspects of collective intelligence.

Results

To demonstrate in practice how the *Synch.Live* paradigm can be used for studies of collective intelligence, we continue by presenting the results of a pilot study using this technology and experimental set-up.

We ran the *Synch.Live* experiment with 200 participants, who were organised in 20 groups of size $n = 10$. Four groups were excluded: three due to technical problems and one more due to lack of questionnaire responses. From the remaining 160 participants, 52 were children under 18 and did not fill questionnaires, leaving $N = 108$ participants in 16 groups for analysis ($M = 6.75$, $SD = 1.7$, $n_{\min} = 3$, $n_{\max} = 9$). Participants completed questionnaires on *perspective-taking* before the game, and *connectedness* and *metacognition* afterwards (see Data collection and Data analysis).

Flocking without explicit instructions

Out of the 16 groups, 10 successfully completed the task of achieving a high enough value of the emergence measure Ψ (Figure 2(a)). The threshold was set to $\Psi > 2.5$ (see Measuring emergence). This result validates the *Synch.Live* technology, showing that collective behaviour can emerge without direct instructions and through group feedback.

As can be seen in Figure 2(b) and 2(c), respectively, the unsuccessful and successful groups display qualitatively

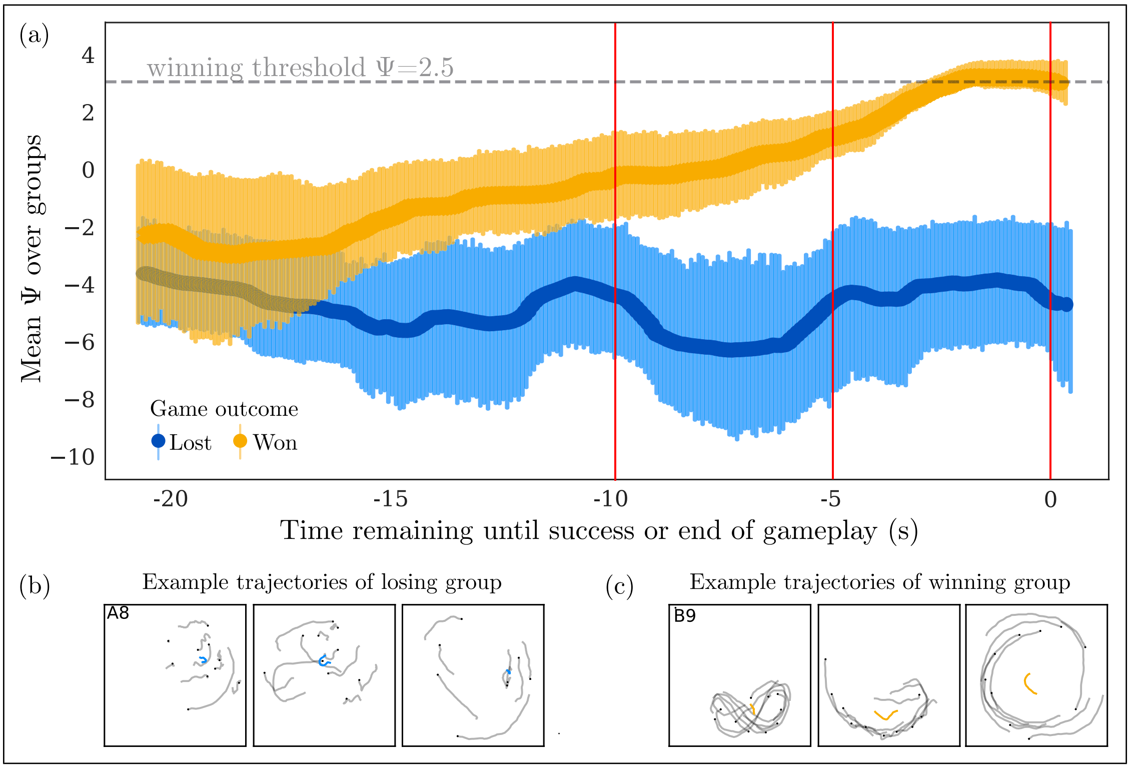

Figure 2. Most subject groups succeeded in solving the task through collective behaviour. (a) Average Ψ measure from the last 20 seconds of all 16 groups, separated by game outcome. Winning groups (top line, yellow) show a consistent trend of increasing Ψ, while for unsuccessful groups (bottom line, blue), the Ψ value remains negative. Shaded areas show standard deviation of Ψ across groups. The vertical bars show the times at which the snapshots in panels (b) and (c) were taken, while the horizontal dashed line marks the winning threshold $\Psi = 2.5$. (b) Three snapshots with 5 second trajectories from an unsuccessful game, showing no regular patterns in the positions. (c) Three snapshots with 5 second trajectories from a successful game. The participants have organised without talking or touching to create complex shapes.

different patterns, with the latter showing not only aggregation and cohesion but also more complex shapes resulting from the group's walking trajectories.

At the individual level, participants reported trying to synchronise their pace or align walking direction with others, imitating another's movements, and developing gestures to communicate different group configurations with others. This allowed them to form shapes and movements at the group level, some unexpectedly complex. As hypothesised, we observed a large variety in both individual and group behaviours than ever seen before in studies of spontaneous human collective movement. The advantage of

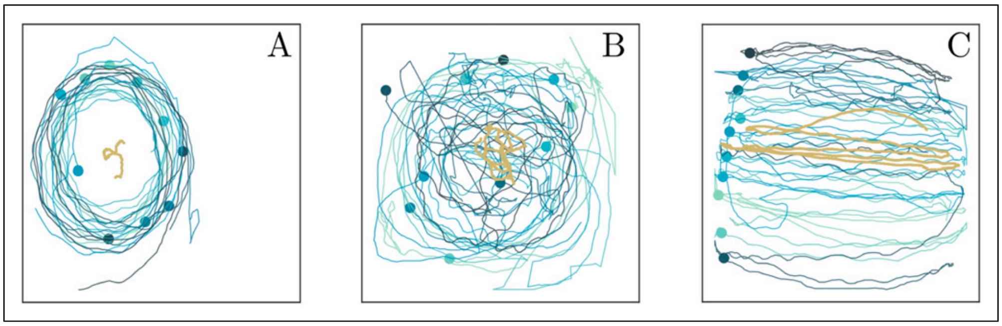

Figure 3. Qualitatively different collective motion emerging in *Synch.Live*. Blue lines represent players' trajectories while the thicker yellow line is the group's centre of mass. (a) The milling or circle configuration reminds of fish swimming in circles to confuse predators or reindeers trotting around their young to protect them. (b) In the swarming configuration, reminiscent of insects and birds, players remain aggregated without aligning, while avoiding collisions. (c) Parallel movement reminds of horses pacing in sync. Players line side-by-side and align direction and speed.

using the Ψ measure to quantify collective movement is that it allows us to detect collective patterns without specifying them *a priori*. This has allowed us to observe a variety of group motion patterns which have re-occurred across different winning groups, such as milling in a circle, walking in a line, or swarming (Figure 3).

In contrast, there are no specific patterns forming in the groups who do not succeed in the task. Players move chaotically and don't coordinate, with small sub-groups often acting together but not cooperating with others, or with individuals stopping or moving independently.

Successful players have increased strategy awareness

To understand individual contributions to success in solving the group task, we asked participants to report on the strategies used and whether they were aware strategies were successful. This allowed us to better understand the *meta-cognitive* aspects of their problem-solving process or how aware the players were of the effect of their individual actions onto others and onto the group as a whole.

The study of strategies as provided by participants in the final questionnaire shows results consistent with our hypothesis that new forms of decentralised collective strategies that are not necessarily driven by traditional rigid hierarchical structures can emerge amongst the *Synch.Live* players. Throughout the gameplay, most players in winning groups paid attention to all the other players in order to observe the group synchrony, while attempting various movements and walking patterns, both in isolation or with others, and most often with the players nearest to them.

Most players reported synchronising pace or direction with neighbours, following others or imitating movements (e.g. *following a person very closely in pace and movement*, *synchronising movements*, *following one small duo led to everyone joining without communicating*, and *walking along the same path*), but some also confidently lead other players (e.g. *leading by example*). In some groups, players tried to communicate with others via gestures or body language (e.g. *trying to listen to non-verbal guesses, body language from other people*) and successfully organised into higher-order patterns such as milling configurations, circles, and even the 'figure of 8' seen in Figure 2(c) (e.g. *walking in a sync circle equally spaced and a similar pace*, and *walking in a constricting circle*).

Chi-squared tests of independence showed that people who were aware of whether their strategies were successful were more likely to win the game than those who were not aware or not sure (χ^2 (1) = 4.91, p = .026). The effect size is medium according to Cramér's ϕ_c = .4648. This indicates that participants were able to learn a solution to a challenging multi-agent coordination problem (Wong et al., 2023), based on limited information provided through a sparse reward signal based on the emergence measure Ψ.

Winning players show higher connectedness to others

To better understand what makes certain groups of participants successful in this collective task, we assessed their tendency to adopt the psychological point of view of others. This was done through the *perspective-taking* scale of Davis' questionnaire on individual differences in empathy (Davis, 1983). We also investigated the effect of the collective experience on the participants' state of mind in relation to others through Watts' scale of *connectedness to others* (Watts et al., 2022).

A Mann-Whitney U-test shows succeeding in the task had a significant (W (38, 70) = 1012, p = .041) but small effect (Cliff's δ = .239) on *connectedness to others* (Figure 4(a)). The median connectedness for successful players was 68.8 (sd = 18.5), compared to 60 (sd = 16.1) for unsuccessful players. This suggests that collective movement, combined with a collective reward for achieving a joint goal, could be associated with a positive effect on the sense of feeling connected to others. On the other hand, contrary to our hypotheses, no significant difference was seen in *perspective-taking* based on game outcome (t (82.04) = −1.06, p = .291).

Additionally, we asked the following question: taking into account group differences, is the *connectedness to others* of a winning participant predicted by their *perspective-taking* and the game duration? Linear mixed-effects modelling of the standardised data revealed a weak positive effect of *perspective-taking* (β = 0.23, p = .052) and a weak negative effect of duration (β = −0.34, p = 0.07) on *connectedness*. The strongest positive effect on *connectedness to others* is from the interaction between *perspective-taking* and duration (β = 0.42, $s.e.$ = 0.12, t (65.3) = 3.44, p = 0.001), having a medium effect size (R^2 = 0.408) (see Figure 4(b)). The group random effect explains only about 24% of the variance in the model. However, we note this model is exploratory and these coefficients are only interpreted tentatively. See Table 1 in the Appendix for more details.

This result suggests that players with higher perspective-taking, especially when they quickly succeeded in the game, were likely to feel more positive outcomes in their emotional connection to others.

Discussion

In the current global landscape, the study of human collective behaviour is a crucial discipline with huge implications for social policy, government, and political issues (Bak-Coleman et al., 2021). In this paper, we provided a framework for the study of collective behaviour through flocking motion in human groups. To show how this

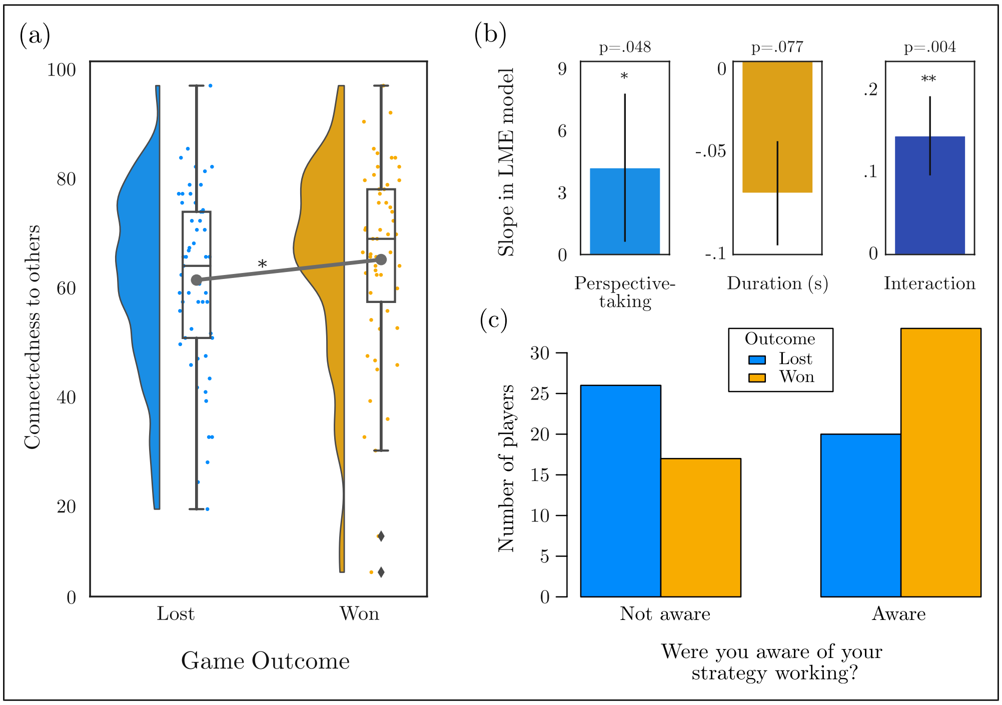

Figure 4. Relating game outcome to duration, state and trait psychometric measures, and metacognitive awareness. (a) Raincloud plots of audience responses to connectedness, grouped by game outcome. A significant difference in *connectedness to others* (W (38, 70) = 1012, $p = .041$) is found depending on the game outcome. (b) Bar graph showing the slopes (average estimates) in the linear mixed-effects model with *connectedness to others* as the target for each variable: *perspective-taking*, duration, and their significant interaction ($\beta = 0.42$, s. e. = 0.12, t (65.3) = 3.44, $p = .001$). Error bars represent standard error for the fixed effects. (c) Most players who were aware that their strategies were working belonged to the successful groups, while more players who were not aware, or unsure, were part of unsuccessful ones (χ^2 (1) = 4.91, p = .026).

paradigm can be applied to study social well-being, team cohesion, or collective intelligence in groups, we applied our framework to an exploratory case study where we focus on participants' social psychology and the strategies that emerge collectively as solutions to the task.

Our study shows that groups of people can spontaneously work together – without following a predefined leader or interaction rules, and using only non-verbal communication – to solve a task only guided by a group feedback mechanism. Interestingly, the groups' solutions manifested as various forms of flocking movement displaying emergent spatio-temporal patterns. Amongst groups, we observed a wide variety of strategies for addressing the collective challenge including imitation, improvisation, the arising of different effective leaders who proposed various strategies, and even the development of non-verbal forms of communication and planning through gestures.

Our results revealed that winning groups experienced a small but significantly higher effect on their *connectedness to others*. This result opens up the possibility that such collective movement, incorporating group problem-solving and shared experience, could be a non-intrusive and non-pharmaceutical means of boosting well-being in a post-pandemic age of uncertainty, alienation (Dean 1961), social isolation (Cornwell and Waite 2009), and their negative impact on mental health (Brown et al., 2021b; Zhu et al., 2021).

In contrast, we hypothesised that a higher degree of empathetic *perspective-taking* would have a significant effect on game outcome due to an improved ability to predict other's strategies or behaviours, but we were unable to confirm this hypothesis.

We also found that participants who were more aware of the strategies used and whether such strategies were effective were significantly more likely to succeed in the group task than those who were not aware or not sure. This result suggests the two-fold aspect of collective behaviour: namely, the interplay between individuals' agency, confidence, and metacognitive awareness on one hand, and their social interactions with peers on the other. This connection between metacognition and success in a collective intelligence-based social game is in line with suggestions that consciousness may have evolved to manage complex social needs (Frith, 2007, 2008, 2010; Kanaev, 2022), further supporting views of the importance of consciousness for detecting and capitalising on high-level patterns (Bor, 2012; Bor and Seth, 2012).

Previous research within organisations (Woolley et al., 2022) as well as through modelling and game theory suggests that decentralisation favours learning in groups. While the feedback mechanism is fundamentally a centralised form of control, the inexplicit, ambiguous feedback as well as its sparsity and distributiveness over the whole group invites the emergence of new forms of decentralised collective strategy that are not necessarily driven by traditional rigid hierarchical structures.

Our study shows that decentralisation may indeed be key to group learning: more than a half of the groups succeeded in solving the collective task by self-organisation. Moreover, as the questionnaire responses suggest, the majority of successful strategies related to peer-to-peer relationships as well as following others.

Limitations

Due to the study's framing as exploratory research and its execution in a naturalistic context, some aspects of experimental control were limited. The demographics of group composition and pre-existing social relationships in the group would all have an effect on the collective outcome; however, we were unable to collect this data or control for these variables at the time. Other motor and synchrony-related skills – for example, dancing or team sports – are also very likely to affect the *Synch.Live* outcome in some way.

Our inquiry on *perspective-taking* did not yield any significant findings; given our study was run with a small number of groups, a larger sample would be necessary to make stronger claims. As such, another limitation of our work is the lack of an in-depth, high-powered study of the psychological aspects of the players and how that affects the collective outcome.

It remains unclear whether the state of increased connectedness is a result of the collective motion and its inherent physiological synchrony, of the social and cognitive aspects of successful group problem-solving, or of the collective artistic experience of *Synch.Live* itself. Therefore, the next step is to organise a follow-up study, in different venues, with more diverse participants in more groups, and pre-registered hypotheses.

At this stage, we were unable to observe how and if the collective behaviour changes with group size; due to technological limitations, we could not support groups large enough to test how the technology and the collective behaviour will scale. Nevertheless, we expect exciting new forms of collective behaviour to emerge, including higher-order synergies with multiple groups and complex inter-group relationships.

Iterative design and future work

In this study, we present a research prototype of the *Synch.Live* system as a novel experimental paradigm for studying human collective behaviour. Unlike tasks designed solely as research instruments, *Synch.Live* was originally conceived as a participatory art experience, and its realisation required engineering a rigorous technological and experimental framework. This dual origin is central to the paradigm's utility: *Synch.Live* is designed to function simultaneously as a high-resolution measurement environment and as a medium for embodied collective experience.

The current work only exemplifies the potential of the *Synch.Live* paradigm. For our study, we selected the game rules according to our aims and polished the instructions and game mechanics through the development and testing phases. Through an iterative process with groups of volunteers, we ran a number of pilot studies aimed at fine-tuning the cut-off duration for the game, the threshold value of Ψ, and the behaviour of the flashing lights. In order to research other collective behaviours, other experimental setups could be designed around the *Synch.Live* paradigm through a similar process.

Many more hypotheses can be tested with this technology. To start, studying other psychological dimensions with well-being and social implications (such as the *Mental Well-Being Scale* (Tennant et al., 2007), *Communitas Scale* (Kettner et al., 2021), and the *Inclusion of Other in the Self Scale* (Aron et al., 1992)) would allow us to learn more about the prosocial effects of the collective activity and to use *Synch.Live* as a novel experimental tool in the field of social consciousness and cognition.

Going further, it is important to identify not just what social or psychological aspects are affected by *Synch.Live*, but also how various traits, team compositions, leadership structures, and social relations affect the outcome of *Synch.Live*. Conversely, *Synch.Live* itself can be used as a control for other collective intelligence tasks: groups may attempt a different task with or without having played *Synch.Live*, in order to observe its effect on group performance or cohesion.

But the *Synch.Live* paradigm is much more flexible. Multiple parameters can be varied to obtain a different experimental design: the group size, the game duration or the number of games, the dimensions and other features of the space, the threshold value for emergence Ψ, and the game rules or the data collection. Looking even further into the future, other measures of emergence or other solution concepts entirely could be added to the game, such as, for example, to handle multiple groups or higher-order interactions.

It would also be interesting to ascertain whether groups that manifest collective motion would also manifest synchronised physiological markers, such as breathing rate, heart rate variability, and arousal, and even more so to study the neural activity of the players. As such, a natural extension of the *Synch.Live* paradigm is to add data collection and even real-time feedback for physiological markers.

Applications

The implementation described in this paper is one experimental instantiation of the *Synch.Live* paradigm. More broadly, the paradigm could be extended into a family of embodied group-coordination tasks with potential applications in real-world settings, from small groups to large gatherings. Here, we note two illustrative near-term directions.

Team training and development. *Synch.Live*-based variants could be developed as structured, feedback-driven exercises for groups in domains such as safety-critical operations, sport, and leadership. Movement-based metrics capturing team coordination and individual contributions to group behaviour could be further developed to complement existing organisational assessments and team development practices.

Community engagement. Variants of *Synch.Live* could be designed and staged as facilitated workshops or participatory art installations to support social connection and community-building.

In light of our finding that unscripted collective movement is associated with increased feelings of connectedness, this paradigm offers a conceptual and methodological framework for designing embodied collective experiences that could support social connection, community-building, and well-being. Overall, this study shows the potential benefits of harnessing the novel study of collective movement to elicit well-being and social cohesion in a deeply divided world.

Methods

In this section, we report the details of our experimental technology as well as how we determined our sample size, all data exclusions, and all measures in the study.

Experimental technology

The *Synch.Live* experimental system is built on the top of open technology and open source software, making use of Raspberry Pi devices and the Raspberry Pi OS Lite (v2021-01-11 *Buster*) operating system, and custom software written in Python 3, which is publicly available (Sas et al., 2023). The entire system was designed, developed, and built in-house by the research team.

The system consists of the headsets worn by the study participants (referred to as *players*) and an overhead camera and central computer (referred to as *observer*). Each of the 10 *player* systems is built around a black hat fitted with a Raspberry Pi Zero W. The device is equipped with a real-time clock (RTC) module, which ensures higher timing accuracy and lower temporal drift when devices are off. Individually-addressable LED lights using the WS2801 controller are wired around the brim and on the top of the hat, and a portable 1350mAh battery wires both the Pi and the lights, providing approximately 4 h of gameplay. The green light on the top of the hat is perpetually turned on during the gameplay to be used for motion tracking. At the beginning of each game, the clocks on the players are synchronised and the brim lights blink at the same fixed frequency with a random delay (phase) at each blink. The amount of delay is dynamically adjusted in response to the players' value of the emergence measure Ψ (see below), such that the delay is reduced as Ψ increases, up to a full synchronisation with no delay when a high enough value of Ψ is reached.

The *observer* system uses a Raspberry Pi 4 and a Raspberry Pi High Quality Camera with C-mount lens. For the experiment, the system was mounted in a custom-built hard metal case, with a clamp to attach to scaffolding, and safety wires. A varifocal 2.8–12 mm lens was used, allowing an angle of view range of 30–140°. The *observer* system records the movement from above at 12 fps, and similar to past work (Leonard et al., 2012) performs hue-based object detection in real-time using OpenCV (Bradski 2000) and object tracking using Kalman filters (Kalman 1960) to obtain player trajectories. The observer also runs a web server that streams the camera video, computes the Ψ measure, and broadcasts to the players the corresponding delay parameter that governs the synchronisation of the lights through a simple HTTP endpoint.

For a wiring diagram of the *player* system, photographs of the *player*s and *observer*, or a screenshot of the web server, see the Supplemental materials.

Measuring emergence

We use an information-theoretic measure, denoted by Ψ, as a quantifier of spatial synergistic patterns in the group's trajectories (Mediano et al., 2022; Rosas et al., 2020). Essentially, Ψ quantifies whether the information existing in a *macroscopic* feature at the system level exceeds the information contained in the *microscopic* features of each system component. In *Synch.Live*, Ψ is calculated from the players' trajectory data as measured by the observer system. Inspired by previous work on Granger causality in flocking models (Seth 2010), we take the 2D positions of each player as microscopic features and the centre of mass of the group as macroscopic feature. Mathematically, Ψ is given by:

$$\Psi^{(1,0)} = I(V_t; V_{t+1}) - \sum_i I(X_t^i; V_{t+1})$$

To improve accuracy of the emergence criterion, the information shared by all trajectories is re-added to the whole-minus-sum estimator (Sas et al., 2025):

$$\Psi^{(1,1)} = I(V_t; V_{t+1}) - \sum_i I\left(X_t^i; V_{t+1}\right) + (n-1)\min_i I\left(X_t^i; V_{t+1}\right)$$

where X_t^i represents the 2D position of player i at time t, V_t represents the 2D position of the group's centre of mass at time t, and I represents Shannon's mutual information (Cover and Thomas 1999).

To estimate Ψ numerically, mutual information was calculated with the Gaussian estimator implemented in the JIDT package (Lizier 2014). The first 180 frames are used to estimate joint probability distributions on trajectories before computing mutual information in real time for the remaining frames.

Depending on experimental conditions such as group size, there is an optimal value of the threshold of the emergence measure Ψ which balances the difficulty of the task with the responsiveness of the feedback mechanism. The same kind of movement in a smaller group would yield a higher value of Ψ than a larger group, due to the nature of the Ψ measure as a synergy-redundancy index.

Moreover, the Ψ threshold not only affects how much synergy there needs to be in the collective movement for the players to win but also how quickly or slowly the lights respond to group movements. If the lights change their blinking rate too suddenly, as it happens for a low Ψ threshold, then players may find it difficult to associate their movements with feedback, and the task is completed too quickly, often without them noticing or realising how. If the Ψ threshold is too high, feedback is too slow and the task is too difficult; players become frustrated and also struggle to associate their movements with feedback. The threshold value 2.5 of Ψ was selected after a number of technological pilots and tests, through iteration and feedback from testers.

Experimental setup

The experiment was performed on 18–19 June 2022, in the Great Hall of Imperial College London, UK, in the context of the Great Exhibition Road Festival (GERF), with 20 groups of 10 participants each, in a space approximately 10 by 15 m, bounded by an array of blue lights. The Great Hall, including the separate registration and gameplay areas, was fully isolated from the rest of the festival. Volunteers made sure that interruptions would not occur in the game itself. We had full control over the lighting and sound in the room, and there was no audience: only the research team was allowed to observe the gameplay area.

The participants were first instructed to answer questionnaires and were then invited in the gameplay area. Then, instructions for the game were given to all groups, which consisted of three rules

1. No talking
2. No touching
3. Keep walking within the boundaries of the play areas

and one goal: to synchronise their lights by working together before 10 min of gameplay have elapsed. The full instructions, which were repeated identically to all groups, can be found in the Appendix: Explicit instructions.

A gong sound indicates the beginning and end of the 10-minute period. A visual display of rainbow lights was shown once the participants' motion produces a high enough value of Ψ, namely, $\Psi > 2.5$ (with some minor variations due to technical setup e.g. 2.5 ± 0.1).

Atmospheric music without any explicit rhythm from Jon Hopkins' album *Music for psychedelic therapy* was played during the gameplay. We chose music without any clear rhythmic elements as to not affect the group coordination (Tunçgenç et al., 2021) but also inspired by successful outcomes in music-assisted psychedelic therapy (Bonny and Pahnke, 1972; Kaelen et al., 2018).

The same sounds, instructions, and lighting conditions were used for all groups. Only one group was allowed in at a time, and no other participants were able to observe the current group.

After the game, participants were asked to complete more questionnaires about their experience, including semi-structured interviews, and were also given a small presentation about the science of collective behaviour and emergence.

Participants

200 subjects signed up to participate in the experiment using the GERF website and advertising channels. These subjects were distributed across 20 groups, 10 on Saturday (groups A1 to A10) and 10 on Sunday (groups B1 to B10). Of all groups, 3 Saturday groups were not included (groups A2, A5, and A7) due to issues with the experimental equipment. Group A10 did not complete any psychometric questionnaires.

We collected no information related to age, gender, ethnicity, or social relationships with other group members. Nonetheless, due to the recruitment strategy, we can assume each group likely contained strangers as well as acquaintances, friends, and families.

Children above 12 were allowed to participate, but only adults over 18 submitted questionnaire data. As some groups had a larger number of young participants than others, the smallest number of respondents per group was $n = 3$, while the largest was $n = 9$. We had a total number of 135 responding subjects from the total of 200 participants. 27 more participants were excluded from the analysis due to technical problems, leaving $N = 108$ subjects for analysis.

Data collection

For each group, the trajectories of players and instantaneous emergence values were stored for the entire duration of the experiment.

Before the experiment, participants responded to the *perspective-taking* subscale of the Interpersonal Reactivity

Index (IRI) (Davis 1983), which measures the tendency to adopt the psychological point of view of others.

After the experience, participants responded to a slightly modified version of Watts Connectedness Scale (WCS) (Watts et al., 2022), which has been used previously to quantify positive outcomes of psychedelic experience (Kettner et al., 2021), and it is split into three subscales focussing on *connectedness to self, others,* and *the world*. In particular, we specifically asked participants to rate their feelings during the experience, as opposed to the past 2 weeks, as in the original questionnaire. We focused only on the *connectedness to others* subscale, as it was the one most closely related to the goals in this study.

Participants' awareness of their strategies used during the game was recorded through a free-form questionnaire asking the participants the following questions:

1. *What strategies did you use?*
2. *Were you aware of your strategy working?*
3. *What emotions did the experience induce?*
4. *Would you recommend the experience to others?*

Data analysis

Psychometrics. Psychometric questionnaire responses were processed to produce a value for *perspective-taking* between 0 and 5, and a value for *connectedness to others* between 0 and 100. The answers to free-form questions 2 and 4 were manually labelled as positive or negative, and used as a binary variable in analysis.

Statistical tests. The data was analysed using R v4.0.4, in particular the software package lme4 v1.1-33 (Bates et al., 2015), while the significance of the statistical tests was computed using the package lmerTest v3.1-3 (Kuznetsova et al., 2017). For all studies involving game outcomes, groups with missing data or technical error were excluded, so questionnaire data from 108 participants over 16 groups was used.

Normality of the psychometric data was tested using the Shapiro-Wilk test (`shapiro.test` in R). This analysis revealed one dataset whose data does not follow a normal distribution – specifically, *connectedness to others* in winning groups ($W = 0.95$, $p = .005$). Therefore, we proceed with a non-parametric test to compare *connectedness to others* for the two outcomes.

To compare between participants with different game outcomes in normally distributed data, we use Welch's two-sample t-test using the `t.test` function in R with `paired=FALSE`.

For data that is not normally distributed, we perform two-tailed Mann-Whitney U-tests (also known as Wilcoxon rank-sum test) on the psychometric data of the two groups using the `wilcox.test` R function. The Mann-Whitney U-test can be used to test whether there is a difference between two groups, and the data need not be normally distributed. To compute effect size in this case, we chose Cliff's δ (Meissel and Yao 2024), which acts as an equivalent to Cohen's d for non-parametric tests. This was computed with the effsize package in R using `cliff.delta`.

To better understand the conditions under which players succeed as well as the positive outcomes of a successful game, we studied the relationships between psychometrics and game duration in the winning groups. First the data was standardised by subtracting the mean and dividing by the standard deviation, due to the large variety in scale between the questionnaires (on scales 0–5 and 0–100, respectively) and duration (from 50s to 375s). Linear mixed-effects models were used with *connectedness to others* as dependent variable, game duration and *perspective-taking* as fixed effects, and group ID as random effect, using the following formula:

$$\text{Connectedness} \sim \text{Duration} * \text{Perspective} + (1|\text{Group})$$

Effect size is computed with the conditional R^2 measure using the function `r.squaredGLMM` from the MuMIn package in R.

To study metacognition, we counted participants based on game outcome and whether the answer to the metacognitive question (Question 2 in the free-form questionnaire) was positive or negative, resulting in four categories. The χ^2 test was used to obtain statistical significance, by using the function `chisq.test` with `correction=FALSE` in R. To report effect size, we use the function `esc_phi` from the esc package in R, which calculates Cramér ϕ_C measure, which is recommended for a 2×2 χ^2 test (Ben-Shachar et al., 2023).

Technical limitations

Due to the recruitment strategy, we were unable to collect information about the demographics of the participants, their personality traits, or their social relationships. The number of participants was constrained by the availability of slots in the public outreach event where the study was organised, so the statistical power of our study is constrained by the practical limitations of organising such a large-scale public event. Moreover, the number of participants was further reduced by the exclusion of players under 16, which were able to take part in the experience but whose questionnaire data we were not able to collect at that time. We are eager to reproduce the results of this study in a randomised controlled trial, but also to collect a much bigger volume of data for analysis.

As all technology is developed in-house and at the time of the study it was in pilot stage, some data was lost due to technical error. Moreover, we were unable to relate the questionnaire results of a participant to the specific trajectory of that participant, and thus we were unable to study quantitative relationships between individual movement and state or trait psychology.

Transparency and openness

To facilitate reproducibility, *Synch.Live* is based on Raspberry Pi and Linux. The version of the software used in this study (tagged v1.0) is open-source and publicly available under the MIT license (Sas et al., 2023). This version reflects the state of the system prototype as used in the experiment, including how trajectories are extracted from video data with OpenCV and Kalman filters and how Ψ is computed in real-time with JIDT on the *observer*, as well as how Ψ affects the blinking patterns for each light on the *player* headsets.

Videos recorded by the *observer*, raw and pre-processed trajectories, and all the results and figures presented in this paper can be also found in a Git repository alongside code to reproduce them (Sas, 2023). Subject data and analysis code are available on the Open Science Framework repository odf. io/kzrq6, including anonymised questionnaire responses and code for statistical tests.

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Ethical considerations

This study was approved by the Science, Engineering and Technology Research Ethics Committee (SETREC), Imperial College London (Approval No. 22IC7800), and it was conducted according to the Declaration of Helsinki. Written consent was obtained from all participants. This study was not preregistered.

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Declaration of conflicting interests

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Open science statement

All data and analysis code are available on osf.io/kzrq6/. Data was analysed using R (v4.0.4) and the packages lme and lmerTest. The version of the software used in this study (tagged v1.0) is publicly available at github.com/Synch-Live/Synch.Live1.0/releases/tag/v1.0-beta. This version reflects the state of the system as used in the experiment. This study was not preregistered.

Significance statement

Humans are remarkably adept at coordinating in groups to solve challenging problems, often aided by shared rule systems and verbal communication. In this paper, we push the boundaries of human problem-solving: can human groups solve collective problems through spontaneous self-organisation, without verbal communication or explicit leadership? We introduce *Synch.Live*, a novel experimental paradigm that reinforces collective motion via real-time feedback, showing that groups can successfully coordinate in complex flocking-like behaviours to solve unknown challenges. We demonstrate that this successful coordination is linked to individual awareness of group strategies, effectively linking individual cognition to emergent group performance. Crucially, we bridge complexity science and social psychology by establishing a direct link between emergent physical coordination and psychological well-being: participants in groups that achieved collective motion reported significantly higher social connectedness than those who failed. By quantifying the relationship between collective movement and subjective experience, we propose that embodied group problem-solving can serve as a potent intervention for fostering social cohesion. *Synch.Live* is designed to function simultaneously as a data-rich measurement environment and a medium for embodied collective experience. Flexible and generalisable, it can be adapted for use in a range of real-world applications, from team training to community engagement. Our finding that unscripted collective movement is associated with increased social connectedness provides early evidence that *Synch.Live* could be developed into a vital public health tool in these divided times: a non-intrusive means of strengthening social bonds and well-being.

Supplemental material

Supplemental material for this article is available online.

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Appendix

Explicit instructions

'Take a moment to notice each other's hats - everyone's lights are flashing on and off randomly. Your challenge today is to see if you can figure out - as a group - how to walk in such a way that all the lights in the group flash on and off at the same time. The more you move together, as a group, the more all the lights will flash on and off at the same time. You have no individual control over your own hat lights. You can only solve this as a group. You will know you've won the game when your blue lights turn rainbow.

Here are the rules: no talking, no touching, and keep walking. The lights in the corners mark the boundary of the play area. Please stay within this area. There is no right or wrong way to play Synch.Live as long as you follow the rules. We're excited to see how your group meets this challenge.

Right now, I would like each of you to spread out. As soon as you hear the sound of the bell, start walking!'

LMER results

Table 1. Complete linear mixed effects model results for the *connectedness to others* metric in successful players, with group intercept as random effect, and duration and *perspective-taking* as interacting fixed effects.

	β	s.e.	df	t	p
Random effects					
(Intercept)	−0.0939	0.1723	7.8396	−0.545	0.601
Fixed effects					
Game duration	−0.3451	0.1697	8.1901	−2.033	0.075
Perspective-taking	0.2294	0.1162	65.4773	1.974	0.052
Interactions					
Duration × perspective	0.4296	0.1247	65.3092	3.444	0.001