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

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Abstract

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 often attributed to explicit central control or social norms, rather than to synergistic interplay between individuals. Here we introduce Synch.Live, a participatory behavioural science experiment 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 moving together. More than half of the groups participating in the experiment succeeded in achieving 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. 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.

1 Introduction

Collective behaviour is pervasive in nature, from eusocial insects to birds and mammals [1]. Arguably its most important aspect is *self-organisation*, where global patterns emerge from the local interactions between individuals, rather than from a form of central control, authority, or *a priori* planning [2–4]. 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 Mexican waves in sports events [5], 'mosh-pits' in rock concerts [6], and the dynamics of group improvisation [7]. Emergent collective behaviour can be easily seen in cities, and an understanding of its spontaneous characteristics is crucial to urban planning, such as in the case of pedestrians walking on the Millennium bridge, who unexpectedly synchronised their stride, making the bridge shake [8].

Crucially, collective human behaviour often involves more than coordinated movement patterns, since it is strongly related to individuals' subjective experience. Physical or physiological synchrony has been shown to correlate with positive collective experience of art, such as music [9–11], dancing in clubs [12], or watching movies [13]. Moreover, coordinated movement or physical synchrony have been shown to yield positive mental and emotional outcomes, including building rapport and increasing inter-brain synchronisation [14], improved cooperation [15, 16], team problem-solving performance [17, 18] and a sense of community [19], as well as the perception of social cohesion and shared experience in crowds [20], especially the bonding and 'identity fusion' in gatherings such as parades or protests [21].

Given its potential benefits, we are interested in exploring what types of interventions can elicit collective behaviour. 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 in a virtual game environment [22] or physically, in the dance studio [23]. A series of in-person experiments have also been conducted [24] where groups of people were asked to walk randomly in a large space without talking. Only a few group members were given detailed information about where to walk. Despite the lack of verbal communication, the informed individuals were followed by others in the crowd, forming a cohesive structure, putatively suggesting the emergence of effective leaders as seen in bird flocks and fish schools [25, 26].

Nevertheless, in most work focusing on human flocking, the mechanisms that produce the collective behaviour are given, for instance, by instructing participants to imitate or follow their neighbours [22, 23], thus limiting our understanding of other possible mechanisms of spatial self-organisation. Secondly, the psychological effect of spontaneous collective movement in humans has rarely been studied in a general context and with larger groups. Although the joint action literature [27] frequently explores similar topics, this research often focuses on pairs of subjects or very small groups. Finally, previous research does not attempt to *quantify* the flocking behaviour in human groups. While a large body of work exists relating collective movement in animals with information flow [28–31] or higher-order properties such as synergy [32, 33], this analysis has rarely been applied to human motion.

To address these unanswered questions, we introduce a framework for the study of human collective behaviour, and exemplify it through a novel experimental set-up. Unlike previous work, we do not provide any specific strategies to participants, neither do we state that collective movement is their goal. Instead, we measure their degree of collective movement as a whole, and use an implicit group feedback mechanism to let participants know how close they are to succeeding in their task. This encourages them to create strategies on their own and allows the study of the individual behaviour in relation to the collective. Moreover, we employ larger groups of 10 participants to allow complex higher-order interactions to emerge between them, and we show that these interactions are correlated with their experience and psychological traits.

We hypothesise that players who demonstrate higher empathetic perspective-taking before the game and higher metacognitive awareness during the game 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.

2 Results

Our experiment uses *Synch.Live*[34], a technology inspired by the collective movement of animal groups and the synchronization of fireflies [35] that induces collective behaviour in human subjects by playing a game with a collective task and collective feedback. The *Synch.Live* set-up consists of groups of players wearing headsets equipped with flashing lights who must walk in a bounded space without talking or touching, with the goal of synchronising their lights (Fig. 1a).

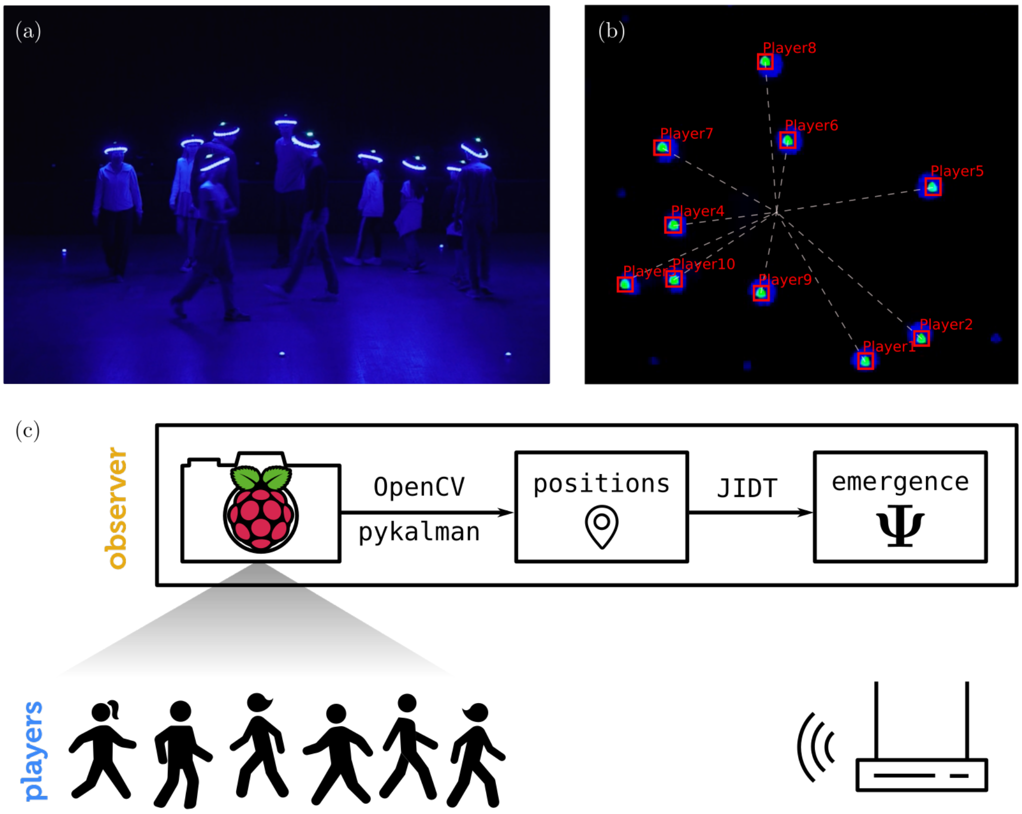

Figure 1: **The *Synch.Live* experimental set-up.** (a) Photo of a *Synch.Live* experiment. The players achieve a high enough value of Ψ to synchronise their blue lights, which are on at the same time in this instance. (b) Snapshot of the footage as seen by the overhead camera, taken at a very similar time in the game, overlaid with OpenCV tracking annotations. The dashed lines show distance from centre of mass, used as part of the computation of Ψ (see Section 4 for details). (c) Diagram for the *Synch.Live* system. The players wear headsets with flashing lights. The observer system contains an overhead camera tracking their trajectories and computes the emergence measure Ψ, which is broadcast wirelessly back to the player headsets.

An 'observer' system tracks the positions of the players (Fig. 1b) and computes an information-theoretic measure of emergence, denoted as Ψ [32]. When applied to movement trajectories, this measure can distinguish between chaotic and cohesive organised movement in flocks, therefore it is used to drive the group feedback mechanism, so that the lights become more phase-synchronised the higher the group's value of Ψ (Fig. 1c).

Overall, the system incentivises participants to work together to form collective movement patterns, without imposing any specific strategy for achieving this. Similar to some previous work [24], we disallow verbal communication in order to encourage more physical embodiment. Moreover, due to the distributed and collective nature of the feedback mechanism, players' attention needs to be distributed to all others, as synchrony should be observed for the whole group.

A complete technical description of the Synch.Live system is provided in Section 4.

2.1 Flocking without explicit instructions

We ran the *Synch.Live* experiment with 195 participants, who were organised in 20 groups of $n = 10$ participants. Data from four of these groups and some individual participants were excluded due to technical problems or lack of questionnaire responses (see Section 4), leaving $N = 109$ participants in 16 groups for analysis ($M = 7.1, SD = 1.8, n_{\min} = 3, n_{\max} = 10$).

Out of the 16 groups, 10 of them successfully completed the task of achieving a high enough value of the emergence marker $\Psi > 3$ (Fig. 2a). This provides a validation of the *Synch.Live* technology, showing that collective behaviour can emerge without direct instructions and through group feedback.

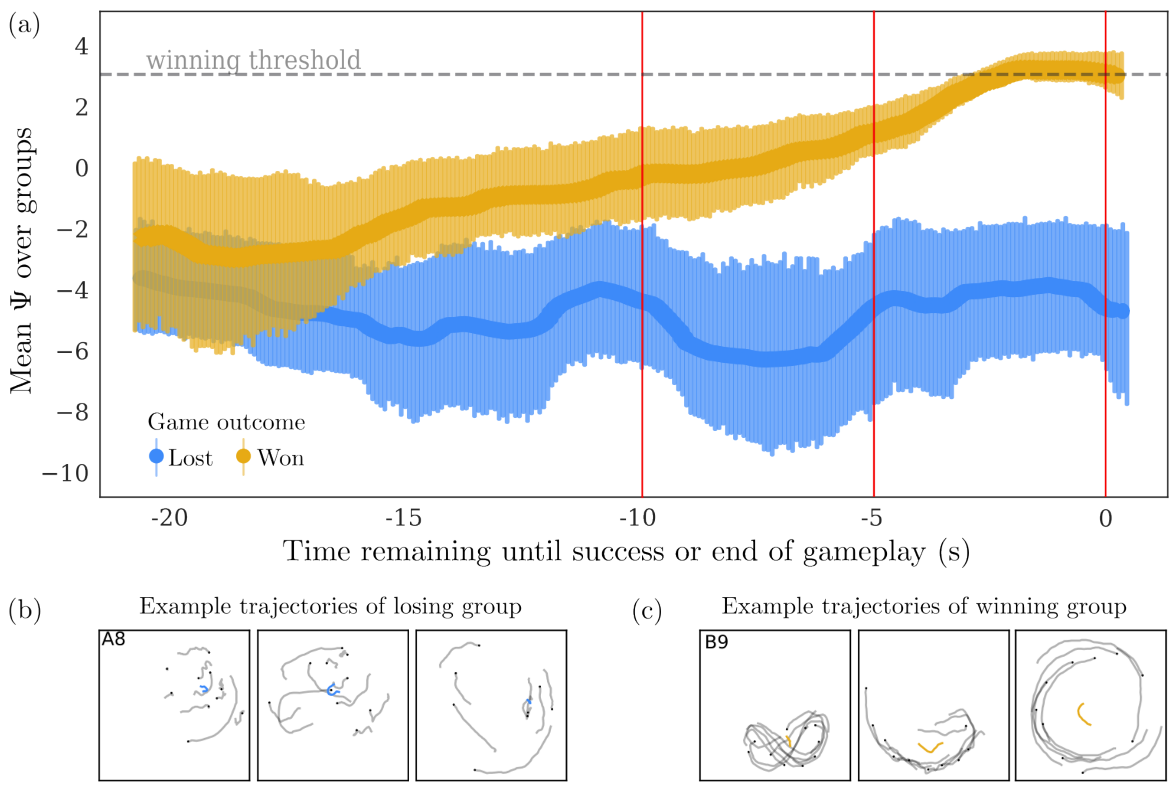

Figure 2: **Most subject groups succeeded in solving the task through collective behaviour**. (a) Average emergence measure Ψ from the last 20 s of 16 *Synch.Live* groups, separated by game outcome. Winning groups are characterised by a consistent trend of increasing Ψ. Shaded areas show standard deviation of the emergence marker Ψ across groups. The vertical bars show the times at which the snapshots in panels (b) and (c) have been taken. (b) Three snapshots with 5 s trajectories from an unsuccessful game, showing seemingly chaotic movement and no regular patterns in the positions. (c) Three snapshots with 5 s trajectories from a successful game. The participants have organised without talking or touching and managed to create complex patterns such as a figure-of-eight, a school, and a cyclone.

As can be seen in Figs. 2b and 2c respectively, the unsuccessful and successful groups display qualitatively different patterns, with the latter showing not only aggregation and cohesion, but higher-order complex structures such as the figure of eight.

2.2 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 [36]. 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* [37].

A Mann-Whitney U-test shows members of successful groups had a significantly higher *connectedness to others* than non-successful groups ($W(38, 71) = 1012, p = .041$; Fig. 3a). The median connectedness for successful players was 68.8 ($s.d. = 18.5$), compared to 60 ($s.d. = 18.5$) for unsuccessful players. This suggests that more emergent collective movement, combined with a collective reward for achieving a joint goal, has a positive effect on the sense of feeling connected to others. On the other hand, no significant difference was seen in *perspective-taking* based on game outcome ($t(82) = -1.06, p = .29$).

Additionally, we asked the 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 on the standardised data revealed a weak positive effect of *perspective-taking* ($\beta = 0.23, p = .051$) and a weak negative effect of duration ($\beta = -0.34, p = 0.07$) on *connectedness*. The

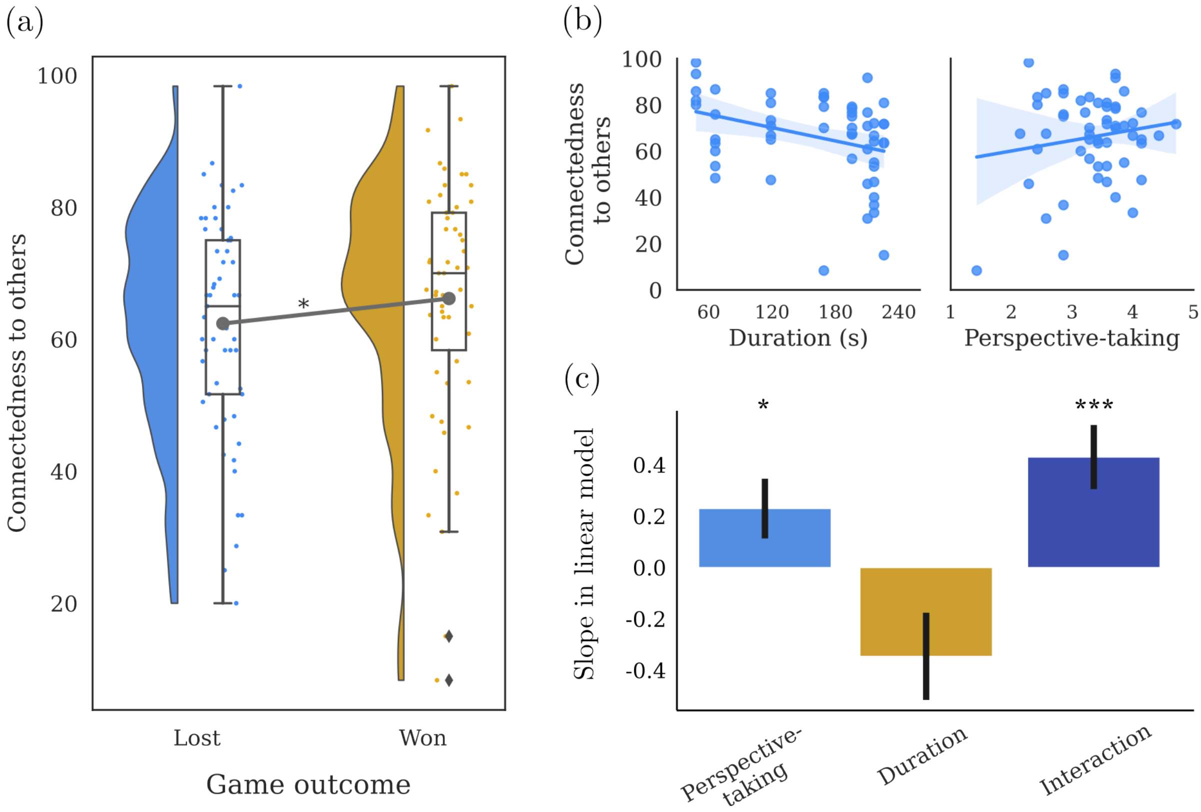

Figure 3: **Relating game outcome to duration, state and trait psychometric measures.** (a) Raincloud plots of audience responses to connectedness, grouped by game outcome. There is a significant difference in *connectedness to others* ($W(38, 71) = 1012, p = .041$) depending on the game outcome. (b) Linear regression plots showing the relationship between duration and *connectedness to others* ($F(1, 68) = 2.760 = .19$), and *perspective-taking* and *connectedness to others* ($F(1, 68) = 1.73,$), respectively, for all the players belonging to successful groups. Both are non-significant in isolation. (c) Bar graph showing the slopes (mean estimates) in the linear mixed-effects model (with *connectedness to others* as the target) for each variable: *perspective-taking*, duration, and their significant interaction ($\beta = 0.42, s.e. = 0.12, t(65.3) = 3.44, p = 0.001$). Error bars represent standard error for the fixed effects.

strongest positive effect on *connectedness to others* is from the interaction between *perspective-taking* and duration ($\beta = 0.42, t(65.3) = 3.44, p = 0.001$), even though there is some variation between subjects ($s.e. = 0.12$). (Fig. 3b-c). The group random effect explains only about 24% of the variance in the model. See Table 4.6.2 for more details.

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

2.3 Successful players have increased metacognitive awareness

To understand individual contributions to success in solving the group task, we asked participants to report on strategies used and whether they were aware the strategies were successful. See Section 4.5 for details of data collection and Section 4.6 for details of statistical tests.

Chi-squared tests of independence showed that people who were aware of using strategies were more likely to succeed in the game than those who were not aware or not sure ($\chi^2(1) = 4.91$, p = .026), as can be seen in Fig. 2.3. This indicates that participants were able to learn a solution to a challenging multi-agent coordination problem [38] based on limited information and provided through a sparse reward signal based on the emergence measure Ψ.

Moreover, by testing the dependence of the ratio of metacognitively aware players in a group against game outcome, we observed a non-significant but positive trend (p=0.11): groups with more aware players are more likely to succeed.

The study of strategies as provided by participants in the final questionnaire confirms our hypothesis that a range of explicit strategies were used to obtain complex collective movement in human groups. 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.

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*, *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 (e.g. *trying to listen to nonverbal guesses/ body language from other people*) and successfully organised higher order patterns such as milling configurations, circles, and even the figure of 8 seen in Fig. 2c (e.g. *walking in a sync circle equally spaced and a similar pace*, *Walking in a constricting circle*).

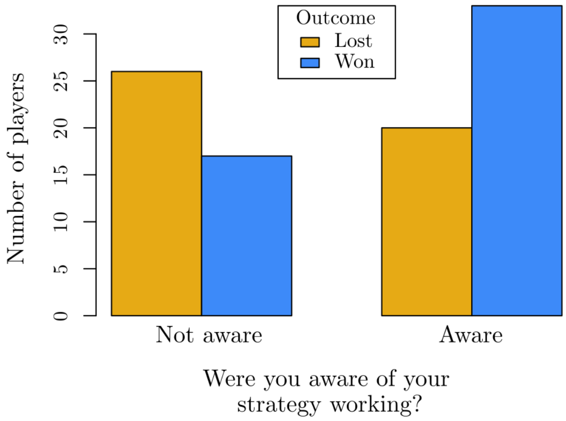

Figure 4: **Metacognitive awareness of game strategies correlated with game outcome.** Most players who were aware that their strategies were working belonged to the successful groups, while more players who were not aware, or unsure, were part of the unsuccessful ones ($\chi^2(1) = 4.91$, p = .026).

3 Discussion

In the current global landscape, the study of human collective behaviour is a crucial discipline with huge consequences on social policy, government, and political issues [39, 40]. In this work, we provide a framework for the study of collective behaviour through flocking motion in human groups, and we exemplify it with an experiment revealing its various psychological, metacognitive, and well-being aspects.

Our study shows how groups of people can spontaneously work together — without following a predefined leader or 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 significantly higher *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 [41], social isolation [42] and their negative impact on mental health [43, 44].

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. However, our results showed no significant difference between successful and unsuccessful groups, but only a weak trend. Instead, results showed a significant link between *perspective-taking* and *connectedness to others* in the winning groups, with a strong interaction with game duration: players with higher empathy from groups that succeeded very quickly were more likely to feel more strongly connected to others. This could be interpreted as a form of improved social cohesion, in response to group success. Studying other psychological dimensions with well-being and social implications (such as the *Mental Well-Being Scale* [45], *Communitas Scale* [46], and the *Inclusion of Other in the Self Scale* [47]) is an exciting avenue for future work.

Last, but not least, our study shows 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 meta-cognitive awareness, and their interaction with others. This connection between metacognition and success in an emergence-based social game is in line with suggestions that consciousness may have evolved to manage complex social needs [48–51], further supporting views of the importance of consciousness for detecting and capitalising on high-level patterns [52, 53].

In summary, our results demonstrate that collective movement can be elicited within human groups as a solution to a collective task without explicit instructions, resulting in increased feelings of connectedness to others even in groups of strangers. Overall, this study shows the potential benefits of harnessing the study of collective movement, and not just art, sport or music, to elicit well-being and social cohesion in a deeply divided world.

4 Methods

4.1 Experimental technology

The *Synch.Live* experimental system is built on 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, which is publicly available [54]. 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, on which a Raspberry Pi Zero W is installed. The device is equipped with a real-time clock (RTC) module, which ensures successful synchronisation. Individually-addressable LED lights using the WS2801 controller are wired around the brim and on top of the hat, and a portable 1350mAh battery wires both the Pi and the lights, providing approximately 4h of gameplay. Figure **??** shows the technical design of the player system.

Beside the lights used by the synchronisation feedback mechanism, a bright green light is continuously turned on at the top of the headset to be used for motion tracking. At the beginning of each game, the brim lights blink at 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 $\Psi = 2.5$.

The observer system consists of a Raspberry Pi High Quality Camera and Raspberry Pi 4 which records the movement from above at 12 fps, and similar to [23] performs hue-based object detection in real-time using OpenCV [55], and object tracking using Kalman filters [56], to obtain player trajectories. The observer also runs a server that computes the emergence parameter Ψ and communicates to the players the corresponding delay parameter that governs the synchronisation of the lights.

4.2 Measuring emergence

We use an information-theoretic measure, denoted by Ψ, as a quantifier of spatial synergistic patterns in the group's trajectories [32, 33]. 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 [30], we take the 2D positions of each player as microscopic features, and the center of mass of the group as macroscopic feature. Mathematically, Ψ is given by

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

where X_t^i represents the 2D position of player i at time t, V_t represents the 2D position of the group's center of mass at time t, and I represents Shannon's mutual information [57].

To estimate Ψ numerically, mutual information was calculated with the Gaussian estimator implemented in the JIDT package [58]. The first 180 frames are used to estimate joint probability distributions on trajectories before computing mutual information in real time for the remaining frames.

4.3 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 metres, bounded by an array of blue lights.

The participants were first instructed to answer questionnaires, and were then invited in the gameplay area. Then, instructions of 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 minutes of gameplay have elapsed. 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 $\Psi 3$.

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 groups coordination [59] This music was inspired by successful outcomes in music-assisted psychedelic therapy [60, 61].

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

4.4 Participants

195 subjects in 20 groups 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 which 3 Saturday groups were not included (groups A2, A5, 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 both strangers as well as acquaintances, friends and families. Children above 12 were allowed to participate, but only adults over 18 submitted questionnaire data. We had a total number of 136 responding subjects from the total of 195 participants.

4.5 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) [36], 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) [37], which has been used previously to quantify positive outcomes of psychedelic experience [46], and is split in 3 subscales focusing 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 two 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?*

4.6 Data analysis

4.6.1 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.

4.6.2 Statistical tests

The data was analysed using R (v4.0.4), in particular the software package `lme4` (v1.1-33) [62], while the significance of the statistical tests was computed using the package `lmerTest` (v3.1-3) [63]. For all studies involving game outcomes, groups with missing data or technical error were excluded, so questionnaire data from 109 participants over 16 groups was used.

Normality of the psychometric data was tested using the Shapiro-Wilkes 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 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:

`ConnectednessOthers ~ Duration * PerspectiveTaking + (1|Group)`

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.

Ethical approval

This study was approved by the Science, Engineering and Technology Research Ethics Committee (SETREC), Imperial College London (Approval No. 22IC7800), and was conducted according to the Declaration of Helsinki. Written consent was obtained from all participants.

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Supplementary material

Explicit instructions

"Welcome to Synch.Live. Please choose a hat and put it on your head and keep it there for the remainder of the game. We have shower caps available. If you have any bags or belongings, please leave them on one of the chairs. If you have a phone, please put it on the chair with the belongings, as no phones are allowed in the game.

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

	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 $\times$ Perspective	0.4296	0.1247	65.3092	3.444	0.001

Table 1: 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.

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