Playing the Mirror Game in Virtual Reality with an Autonomous Character

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ABSTRACT

The mirror game paradigm has become a reference task in the joint action literature. It is one of the best available experimental paradigms to study how humans engage in joint tasks and how they tend to synchronise their behaviour. However, virtual reality characters do not take into account this fact. In this work we explored to what extent an autonomous virtual character and a human that plays the mirror game in a virtual reality can synchronise their behaviour. We created a full-body version of the mirror game with an autonomous virtual character. The movement of the autonomous character was driven by a coupled oscillator. Behavioural measures and subjective reports suggest that a small coupling factor in the oscillator can produce a subjective impression that is equivalent to doing the task with another human participant.

Introduction

Humans tend to engage in joint tasks and help others achieve their goals[1]. This tendency has several behavioural and cognitive benefits. People engaged in joint tasks tend to synchronise their behaviour[2], often without being aware of it. When humans synchronise their behaviour, they also tend to adopt pro-social attitudes[3,4], to improve the memory of the task[5] and to improve the estimation of cooperative goals[6]. Under appropriate circumstances, joint action experiments are also useful to illuminate psychological factors such as commitment[7,8].

The study of how people perform tasks together has also been explored with computational models. For example, Zhai et al.[9,10] showed that a virtual player can synchronise its behaviour with a human in an imitation task. Lombardi et al.[11] showed that this model could be extended to work on multiple agents, by using data captured with a specially designed computer mediated setup[12]. Lombardo et al.[11] also showed that the behaviour of a human in such tasks can be learnt, even to the extent that they captured the individual motor signature of the particular human being modelled, which is something beneficial for several therapy and rehabilitation scenarios. The dynamics of such patterns have also been modelled for groups of more than two humans[13–15]. The techniques used to implement such models are derived from the dynamical systems literature based on coupled Kuramoto oscillators[16].

Overall, despite the rich and growing literature on the topic, the study of motor coordination and joint action remains challenging due to its social nature. To understand how people coordinate in joint tasks, it is fundamental to design experiments where participants are asked to perform cooperative tasks. The need for two or more participants to engage in an experiment considerably limits the extent to which we can, for example, use brain imagery techniques to understand the neural mechanisms involved in social coordination. Another limitation of mirror game studies is that experiments do not involve full body interaction, but rather simplified representations such as, for example, a flat ping-pong game[17], a simple slider[18,19] or just two dots displayed on a screen[20]. As a consequence, it is still unclear to what extent the results and computational models that apply to uni-dimensional movements can generalise to full-body interaction. The feeling of flow and the quality of the interaction with autonomous virtual characters in motor tasks have neither been studied.

In this work, we explored whether it is possible to replicate a full-body version of the mirror game paradigm[18,21] with an autonomous virtual character. The mirror game paradigm has become a reference task in the joint action literature. It has been used, for example, to show that individuals have their own motor signatures[19,22], and that individuals with similar motor signatures tend to coordinate better[22]. It has also been used to study the physiological responses associated with *being in the zone*, and the enhanced feelings of togetherness associated with it[23]. It is one of the best available experimental paradigms used to study *sensorimotor communication*[24]. For this purpose, we developed a full-body version of the mirror game[18,21] for virtual reality (see Figure 1 and **Supplementary Video S1**). Results suggest an autonomous virtual character can elicit responses comparable to performing the task with another human.

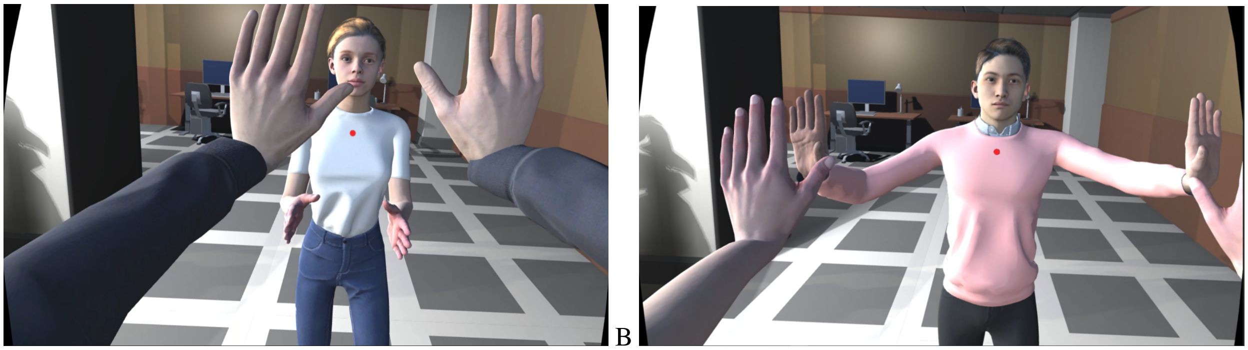

Figure 1. The virtual environment as seen from the perspective of two participants. In A we see an instant of time where behaviour is not synchronous. In B we see the same virtual scene from the perspective of the other participant, when the behaviour has synchronised. Note that the gender of the virtual character matched the gender reported at the beginning of the experiment by the other participant doing the task simultaneously.

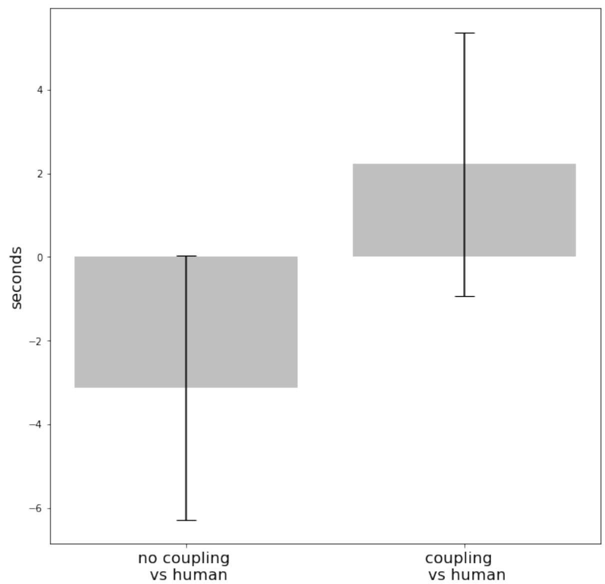

Figure 2. The amount of time participants reported the feeling of synchrony when playing the mirror game with an autonomous virtual character compared to when they did the same with humans.

Results

Participants were asked to do circular movements while trying to synchronise with a virtual character in front of them. The virtual character was animated either by the movements of another participant (**human** condition), either with a Kuramoto oscillator[16] with no coupling (**no coupling** condition) or with a small coupling factor (**coupling** condition).

We considered the **human** condition as a baseline, and tested to what extent doing the task in the **coupling** or **no coupling** condition produced a different result. First, we could not reject the null hypothesis that both samples are normally distributed (D'Agostino-Pearson Omnibus Test **coupling** $K^2 = 1.525$, $p = 0.467$, and **no-coupling** $K^2 = 1.185$, $p = 0.553$). We then compared the **coupling** condition (M 2.217, STD 16.464) and the **no coupling** condition (M -3.124, STD 19.833) with a paired Student test, which showed a statistically significant difference (t(33)=2.117 p=0.042). (see also Figure 2).

After each trial participants asked 10 questions exploring the self/other relation and the feeling of flow. (see Figure 3)

When comparing the **coupling** and **no coupling** conditions (see Table 1) the questions that show very significant differences (p<0.01) reflect, for the **coupling** condition, a greater fluidity of the task, a greater influence of the participants' own movements over the movements of the character in front, and a greater similarity with being in front of a mirror. Participants also reported (p<0.05) that, for the **no coupling** condition, the character in front of them influenced more their own movements, that they felt more as if it was another person, and they felt less that the arms that moved were their own arms. We found no significant

Question: During the last trial...	**coupling**	**no-coupling**	Z score	p	
1. I did the task fluidly and smoothly	1.2	0.0	372.5	0.010	**
2. I had no problem to concentrate during the task	1.4	1.0	530.0	0.546	
3. I felt just the right amount of challenge	1.0	1.0	586.0	0.925	
4. I did not notice time passing	1.2	0.6	503.5	0.354	
5. I felt like the arms that moved when I moved were my own arms	1.8	0.4	422.0	0.046	*
6. I felt as if the character in front of me was another person	0.4	1.4	751.0	0.030	*
7. my movements influenced the movements of the character that was in front of me	1.3	-0.1	354.0	0.005	**
8. the movements of the character in front of me influenced my own movements	0.9	1.8	735.0	0.047	*
9. the character in front of me moved exactly like me, as if I was looking at a mirror	0.3	-1.5	316.5	0.001	**
10. when the character in front of me moved, I felt the instinct to move	1.0	1.1	608.5	0.707	

Table 1. Wilcoxon tests comparing the graded responses to the **coupling** condition with the graded responses to the **no coupling** condition. The values reported are the median values for each condition, the Z score and the significance. * denotes $p < 0.05$, ** denotes $p < 0.01$

difference in concentration, challenge or time perception, nor in the influence of the other character on their movements.

None of the questions showed a statistically significant difference between doing the task with another human and with an autonomous virtual character with coupling (see Figure 3). Responses to open questions in the post-experimental questionnaire (see **Supplementary Dataset S2**) also suggest participants did not perceive the difference.

Discussion

In this work, we developed a full-body version of the mirror game[18,21] and evaluated the subjective feeling of synchrony reported by people taking part in the mirror game, interacting with a virtual character that was either driven by another human or by a computational model. Results suggest that a relatively simple computational model of joint action, when used to drive the behaviour of an autonomous character in a joint action paradigm, induces a subjective sensation that is comparable to the experience of doing the task with a real human. This is shown in the amount of time in which participants reported the feeling of synchrony (see Figure 2).

In addition, some items of the proposed survey that participants answered after each experimental condition highlight fluency during the performance (Question 1), even if not cognitive absorption in the activity (Questions 3 to 4). We believe the lack of significance in the last questions may be related by the fact that the task was rather short.

Regarding the questions adapted from embodiment questionnaires, there was clearly an effect of the coupling factor, as seen in questions 5 to 9. We did not notice a significant effect on question 10, which suggests no volitional motor contagion[25,26], or a phenomenon that could be interpreted as a social version of the self-avatar follower effect[27]. The differences found in question 5 suggest that people felt differently about their virtual body in different conditions. However, it may also have been misinterpreted, and part of the participants might have understood that it referred to the arms of the character in front of them. Nevertheless, questions 6 and 9 consistently suggest that when the movements of the character in front of them were less coupled with their own, they felt as if the character was someone else. The reverse - that coupled movements tended to make people felt as if they were seeing themselves in front of a mirror - is consistent with the embodiment literature, where sensorimotor coupling is considered a crucial factor to induce the feeling of self-identification with a virtual body[28–30]. In addition, responses to questions 7 and 8 suggest that in the **coupling** condition they perceived greater influence of their movements on the virtual character, as well as the need to make a greater effort to match the movement of the other in the **no coupling** one.

In the past, VR has been successfully used to study bodily self-consciousness, and has shown that sensorimotor correlations are crucial to feel a virtual body as our own[30–34]. From this perspective, the main difference between this scenario and previous experiments inducing self-identification with a virtual body is that here the coupling between the movements done and the movements seen (in the other character) is small. Indeed, if the coupling factors were strong, the character seen in front of each participant would be perceived as a virtual mirror, as often used to induce ownership over a virtual body[28,29]. The self-other

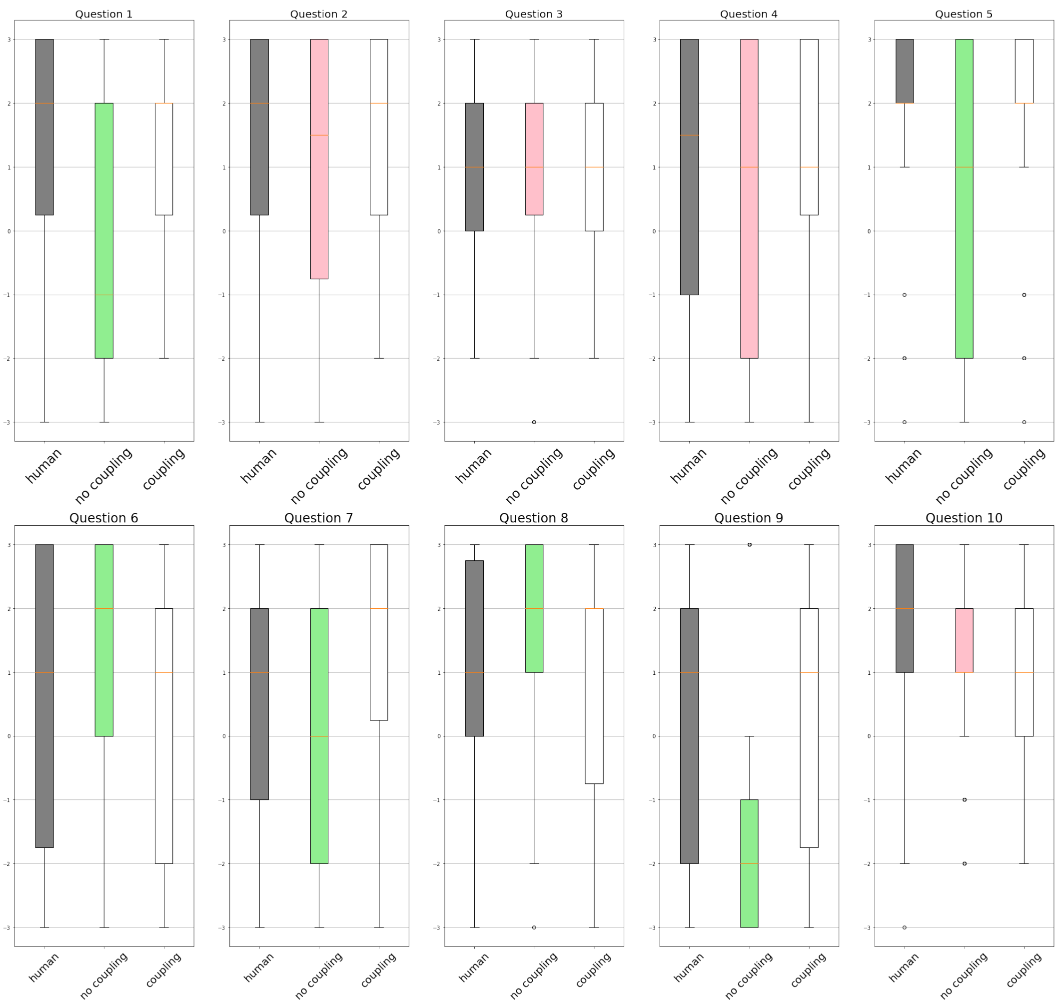

Figure 3. Boxplots of the graded responses to the questions. First column (grey) shows responses when participants did the task with another human. Second column (green or pink) shows responses when participants did the task with an automated virtual human in the no coupling condition. Responses in green are the responses which are significantly different from the condition with human coupling ($p<0.05$), and in red otherwise. Third column shows responses when participants did the task with an autonomous virtual character with coupling.

distinction in this setup seems to appear because the coupling is small, or zero.

The responses to questions 6 to 9, adapted from embodiment questionnaires, suggest that virtual characters showing coupled behaviour with participants can be used to explore in a more nuanced way the distinction between ones' bodily self and the body of others', as well as to investigate the neural basis of interpersonal coordination and the motor planning and coordination related to joint action tasks. It can also be useful to study agency and virtual agency[35,36].

Results also suggest a relation between the feeling of synchrony with an autonomous virtual character and the feeling of flow. The use of VR would bring better experimental control than with respect to current methods. It would also reduce the need to rely on the use of hyper-scanning techniques[37,38], something that is far from accessible to the wider neuroscience community.

Crucially, we did not find significant differences in any metric between the **coupling** and **human** conditions. Acknowledging the fact that the task was quite specific, this suggest relatively simple methods like the use of coupled oscillators are a viable strategy to create autonomous virtual characters that are perceived as more engaging by human VR users collaborating with them. This strategy may open the door to the use of VR as a training tool for acquiring skills that require significant inter-subject coordination. Insofar, VR training for real world tasks has been demonstrated for activities that introduce significant physical constraints, such as billiards[39] or table tennis[40]. Generalising the use of joint action computational models to a variety of tasks where inter-subject coordination plays a significant part of the task success could unlock the use of VR in a wider variety of training, education and therapy scenarios.

Methods

Participants and Ethical approval

A total of 38 adult participants (10 women) took part in the study. Two couples were excluded from the study. In one case, one of the participants never reported the feeling of synchrony. The other couple was excluded because of the malfunctioning of a hand controller. As a result, the data analysis involved 34 participants (10 women).

The experiment was approved by the Ethics committee of the University of Geneva, and all experiments were performed in accordance with the relevant regulations. All participants received an information sheet and an informed consent form, which they signed. They also received a financial compensation of 20 Swiss Francs for their participation.

Experimental setup

The material used during the experiments included:

1. Two Head Mounted Displays (HMD), model Oculus Rift with handheld Oculus Touch Controllers.
2. Two PCs with graphics card NVIDIA GeForce GTX 1080, CPU Intel Core i7 (3.60 GHz), and 32 GB of RAM. Both machines run on Windows 10.
3. The connection between the two computers was established through a wired Ethernet network.

The virtual environment was developed using Unity3D, version 2020.3.19f1. UDP was used for communication between the two machines and this communication was implemented with the standard .NET socket library.

Procedure

Upon arrival, participants were briefed and informed about the nature of the experiment in dyads, including the kind of movement they would have been asked to perform. After this, each participant was given an information sheet and an informed consent form to complete and sign. Once the informed consent form signed, they were handed a Head Mounted Display (HMD) and two hand controllers. To acoustically isolate them from the environment, they were also equipped with headphones playing white noise.

Inside the VR, a series of panels explained the task and gave instructions on where to stand. Participants were informed that they would be placed in front of a partner in the virtual environment and were asked to watch a fixation point, a red dot on the chest of the virtual character in front of them. An animation showed the movement to be performed. Specifically, they were asked to perform circular movements with their arms, palms facing outwards. They were also told that both them and their partner should imitate each other. Then, the gender of the participant was asked. Based on their response, each participant was given a female or a male avatar. The height of each participant was automatically obtained from the position of the HMD and their avatar was scaled appropriately. Participants were then asked to look at their virtual palms to make sure they understood that the arms of the virtual body co-located with them matched their own movements. It was also a way to make sure participants were placed correctly with respect to their virtual avatar. In the last two panels, participants were introduced to the notion of synchrony and then they were instructed to push a button on the controller when they felt synchronisation during the interaction. Finally, participants were informed that the experiment consisted in a first training trial, followed by three other trials, all lasting one minute.

When both participants finished reading the instructions and confirmed they were ready, the avatar of their partner appeared in front of them and the training trial started. After the training trial, they were reminded to look at the fixation point and to report when they felt in synchrony by holding down a button on the controller. Then, the following trial started in one of three conditions: **human**, **no coupling**, **coupling** (see section *Stimuli*, below, for further details on differences between conditions).

After each trial, participants were asked to answer a total of 10 randomised questions, on a Likert scale from -3 to $+3$. They were asked to answer within the VR, using their hand controller. Once the questionnaires were completed, they waited for a random amount of seconds sampled uniformly between 1 and 10 seconds or, if the **human** condition was selected, until the other participant had completed the previous task. Once they had completed the three trials and answered the corresponding questions, they removed the HMD and completed a short written questionnaire with open-ended questions.

Questionnaires

Participants were asked to answer 10 graded questions after each trial (see 3), with a score between -3 and +3, presented in random order. The 10 graded questions were adapted from two existing questionnaires. First, the short flow scale [41, see the appendix], balancing questions focused on fluency of performance (questions 1, 2) and on cognitive absorption on activity (questions 3, 4). Second, we adapted embodiment questionnaires[42] to explore embodiment and the self-other relation as typically perceived in an imitation task (questions 6 to 10). Participants were also asked to complete a written post-experimental questionnaire with the following open-ended questions:

1. In this experiment you did four trials. The first was a trial to check if you could do the task well. Then there were 3 more. Among these last 3 trials, did you notice any difference between the three trials?
2. What were the differences that you felt between the different trials?
3. Was there a particular trial that felt differently from the others two? If so, which one?
4. If there was one trial that felt differently, what was the difference?

The goal of the open-ended questions was to capture any additional subjective aspects that may have not emerged from the first questionnaire.

Stimuli

The virtual characters shown in Figure 1 were downloaded from the free repository Mixamo (https://www.mixamo.com/). The assets forming the virtual room were obtained from the Unity3D Asset store. For the character doing the task in front of the participants, both male and female versions were used to match the gender reported by the other participant. The characters were animated using an idle animation from Mixamo, over which the movements of the arms were animated using the Inverse Kinematics (IK) system built in Unity3D. The hands' position of the character interacting with the participant was modelled with two Kuramoto oscillators[16], parameterized with features extracted from training trial data (see section Procedure). The target positions for the right and left hands ($p_R(t)$ and $p_L(t)$) were calculated as a circular movement on the YZ plane, given by the following equations:

$$(z,y)_R(t) = c_R + r_R(t)cos(\omega_R(t)*t)\hat{z} + r_R(t)sin(\omega_R(t)*t)\hat{y} \tag{1}$$

$$(z,y)_L(t) = c_L - r_L(t)cos(\omega_L(t)*t)\hat{z} + r_L(t)sin(\omega_L(t)*t)\hat{y} \tag{2}$$

where:

- R and L denote the right and left hands, respectively
- $c_{R,L}$ is the average position of each hand of the other participant during the training trial
- The radius for each hand at time t is updated with a noise term:

  $$r_{R,L}(t) = r_{R,L}(0) + n_{R,L}(t)$$

  where $n_{R,L}(t)$ is a Perlin noise[43] between $[-0.085, 0.085]$ with sampling frequency equal to $50Hz$, and $r_{R,L}(0)$ is the average radius of the other participant during the training trial (Perlin noise was used instead of White noise to have a continuous noise signal).

Parameter	Value (mean $\pm$ std)
$r_R(0)$	$0.163 \pm 0.049[m]$
$r_L(0)$	$0.161 \pm 0.046[m]$
$\omega_R(0)$	$2.695 \pm 1.025[s^{-1}]$
$\omega_L(0)$	$2.698 \pm 1.025[s^{-1}]$

Table 2. The values of the model parameters estimated in the training condition

- The angular velocity is updated with the following equation:

$$\omega_{R,L}(t) = \omega_{R,L}(t_{k-1}) + \dot{\omega}_{R,L}(t_k) * \Delta t \tag{3}$$

where $\omega_{R,L}(0)$ is the average angular velocity of the other participant's hand during the training trial (see also Table 2), 't_k' and 't_{k-1}' correspond to two successive simulation steps, and Δt is the inverse of the sampling frequency) ($50Hz$). The angular velocity dynamics is described by the formula:

$$\dot{\omega}_{R,L}(t) = K_{inter} * sin(\theta^H_{L,R}(t) - \theta^V_{R,L}(t)) + K_{intra} * sin(\theta^V_{L,R}(t) - \theta^V_{R,L}(t)) \tag{4}$$

where:

  - H and V denote the human and the virtual character, respectively
  - $\theta(t)$ is the phase at time t of the corresponding hand
  - K_{intra} is the intra-subject coupling factor, fixed at 0.005
  - K_{inter} is the inter-subject coupling factor, and it will depend on the condition (see below)

The previous computational model was used differently in the three experimental conditions:

1. in the **human** condition, the hand position of the other participant was used as target position, and the computational model was not used;
2. in the **no coupling** condition, the model was used with a null K_{inter}. The position of the YZ plane were the hands moved was fixed at 0.343 meters from the position of the character;
3. in the **coupling** condition, the model was used with a K_{inter} equal to 0.0075. The value was adjusted manually where the influence of the participant's movement could be felt but it did not feel like a virtual mirror. In addition, with this value the autonomous character would still move when the player did not, helping to not give away the fact that it was an autonomous virtual character, and not a human participant. The position of the YZ plane was also fixed at 0.343.

In each of the three conditions, the virtual character in front of them was placed at 1.246 meters from the participant. To help differentiate each trial, the virtual character in front of them had a sweater of a different colour (white, pink, green or blue) each time.

Data analysis

Questionnaire responses were analysed using non-parametric Wilcoxon tests. The reports of subjective synchrony were summarized as the amount of time participants reported the feeling in the **coupling** or the **no coupling** condition, minus the reported time when performing the task with another human. The resulting metrics were tested for normality (Pearson Omnibus test[44,45]) and then compared with paired-samples Student t-tests. All the data and Python scripts used for the analysis are available in the Supplementary Materials).

Supplementary Materials

Supplementary Video S1. A video showing the experimental protocol and the VR experience.
Supplementary Code and Dataset S2. A data repository with the anonymous experimental data and scripts for the data analysis.

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Acknowledgements

We thank Prof Mario di Bernardo for helping us getting acquainted with Kuramoto oscillators and their use in behaviour modelling.

Author contributions statement

J.L. conceived the experiment, analysed the data, interpreted the results and wrote the manuscript, V.J. implemented the virtual environment and conducted the experiment, C.C. helped design the computational model for the animated character and reviewed the manuscript, C.C. interpreted the results and reviewed the manuscript.

Additional information

Competing interests The authors do not have any competing interests with this work.