# On the Same Wavelengths: Emergence of Multiple Synchronies Among Multiple Agents

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**Abstract.** People spontaneously synchronize their mental states and behavioral actions when they interact. This paper models general mechanisms that can lead to the emergence of interpersonal synchrony by multiple agents with internal cognitive and affective states. In our simulations, one agent was exposed to a repeated stimulus and the other agent started to synchronize consecutively its movements, affects, conscious emotions and verbal actions with the exposed agent. The behavior displayed by the agents was consistent with theory and empirical evidence from the psychological and neuroscience literature. These results shed new light on the emergence of interpersonal synchrony in a wide variety of settings, from close relationships to psychotherapy. Moreover, the present work could provide a basis for future development of socially responsive virtual agents.

**Keywords:** Social agent model · Emergent synchrony patterns · Social simulations · In-Sync model

## 1 Introduction

People spontaneously synchronize their movements, affective responses, and verbal actions when they interact with each other. Such interpersonal synchrony has been related to a variety of positive outcomes in social settings. For instance, Miles and colleagues [20] found that synchrony was the most pronounced for minimal groups of people who were most divergent in terms of their artistic taste, suggesting that synchrony might serve as a tool to bridge social distance and intergroup differences. Elevated levels of movement


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synchrony have further been shown to foster social affiliation [10], cooperation [45] and compassion [39]. Moreover, interpersonal synchrony has been suggested to be a key component of a good therapeutic alliance, or working relationship, between patients and therapists in psychotherapy [19].

Crucially, interpersonal synchrony has mostly been examined separately in the fields of movement science, psychophysiology and (cognitive) linguistics, respectively, without relating them to each other, e.g. [17, 26, 29]. Nevertheless, it is plausible that associations between these different types of interpersonal synchrony exist [4, 18, 21, 24, 33]. To date, only a few theories have attempted to integrate the different modalities of interpersonal synchrony into one model. One of these theories is the Interpersonal Synchrony (In-Sync) model [18]. The In-Sync model seeks to explain how two actors mutually synchronize their behaviors and experiences (for example, patient and therapist during psychotherapy). At its core, the model supposes that higher-level synchrony processes of language and emotion regulation are affected by more elementary synchrony processes of movement and physiology.

The present paper presents computational simulation experiments in which two agents synchronize with each other by an emergent process. The aim is to examine how agent-based simulations created through general mechanisms derived and operationalized from theories and findings in psychology (see Sect. 2.1) can achieve the emergence of interpersonal synchrony. These interpersonal synchrony patterns will be evaluated against the principles of the In-Sync model and other theories of interpersonal coordination, as discussed in more detail in Sect. 2.2. The simulations are based on agent models where the internal agent processes are, in addition to the interactions between the agents, also modeled in some detail. To achieve this, we use a network-oriented agent modeling approach, as previously presented in [37, 38]. In this approach, the internal agent processes are modeled by a dynamic interplay of mental states based on general psychological (and neural) mechanisms. Section 3 presents the multi-agent model in terms of its scientific background and architecture. Section 4 describes the simulation methods, including parameter specifications. Section 5 presents the results of the performed social simulations, followed by concluding remarks in Sect. 6.

## 2 Psychological Background

### 2.1 General Psychological Mechanisms Used to Design the Agent Models

When individuals prepare to execute a certain action, like a movement, they assess what the effect of this action will be as part of their decision-making process. According to Damasio [2, 3], through a prediction loop such internal simulations generate an internal sensory representation of the likely outcome of an action. In other words, mental predictions of actions are done before these actions are actually executed; these predictions are triggered by an action preparation which can be activated via a stimulus-response effect or based on a similar action observed in other individuals [6, 7, 11]. In the latter case, mirror neurons are a relevant general mechanism that have received extensive empirical support from patient, brain stimulation and brain imaging studies [12]. Mirror neurons are neurons that would fire both when individuals prepare for their own action or body change to perform and when individuals observe a corresponding action by somebody else [13, 31]. Incoming connections (from sensory representation states) to mirror neurons (modeled as preparation states) are called mirroring links in the current paper. The preparation of the action by mirror neurons serves as a starting point for the internal simulation of the prediction loop. The twin concepts of internal simulations and mirror neurons provide a neurobiological explanation for the attunement of actions and emotions [13]. The precise role of mirror neurons in human behavior is still being investigated. Nevertheless, the notions of internal simulations and mirroring serve as usable and operationalizable constructs for a simulation model on interpersonal synchrony.

### 2.2 Emerging Synchrony Among Individuals

Of the three interpersonal synchrony – movement, physiological/affective and language synchrony - types that we consider here, movement synchrony is probably the most well-documented. Controlled experiments have shown that people naturally synchronize their movements, such as in finger-tapping paradigms [29]. More generally, people display a consistent tendency to synchronize their movements with familiar and unfamiliar others, in both structured and unstructured environments [5, 30, 42].

Physical experiences like movements have been argued to serve as grounding or scaffolding for higher-order mental processes [1, 14, 22, 43]. For example, emotional language comprehension has been shown to emerge faster when people's (facial) movements are congruent with the emotions from the text comprehension task [9]. Synchrony in language (also known as 'linguistic alignment', or 'accommodation') has also been reported to occur at several levels of representation, ranging from low-level speech properties to syntactic structure [15, 25, 27], and accommodation in speech is also well-documented.

Finally, a third type of interpersonal synchrony occurs for physiological responses. Physiological synchrony is shown to be important throughout development: Human infants in the uterus already adapt their physiological responses to their mother's [16, 41], and physiological synchrony between children and their caretaker during childhood prepares children to individually regulate their emotions [5]. Additionally, physiological synchrony emerges in close relationships between adults [23] and when unacquainted adults are involved in a collective ritual [17].

An influential account of affect is proposed by Russell [32] and states that physiological changes form the basis for core affect. Core affect is defined as 'a neurophysiological state consciously accessible as the simplest raw (nonreflective) feelings evident in moods and emotions'. Core affect is situated on two dimensions (valence and arousal) and fluctuates immediately after an event occurs to prepare people to act. Conscious emotions are enabled by core affect [32] and they arise when there is a conflict among lower-order processes (such as motor expressions and physiological responses). These conscious emotions at a higher-order level help to solve the insufficiency at the lower-order levels [8]. Verbal actions rely on language that can be generated once emotions are experienced in conscious awareness [8]. Once people put their feelings into words, this in turn can influence their emotional states [35]. Based on previous findings, we expect that the following patterns will be obtained in the agent simulations:

- Synchrony between people can be found in the form of comparable patterns over time.
- At the (intra-)individual level, movement will emerge first followed by conscious emotions (that are enabled by affect) to end with verbal actions.

- At the inter-individual level, movement synchrony will be followed by affective synchrony and language synchrony will emerge in the end.
- The different types of synchronies will be interdependent. Concretely, we expect that when the movements are disabled, the emergence of other types of synchrony will be complicated, as stated by the embodied cognition theories about synchrony.

# 3 The Two-Agent Model

## 3.1 General Approach of Agent Modeling

To model the emergence of interpersonal synchrony, two agents were designed with internal mental processes modeled as a dynamic interplay of mental states [36]. The structure of the two modeled agents is displayed in Fig. 1. The structure of the model is based on the general internal simulation and mirror neuron mechanisms outlined in Sect. 2.1 in order to test an emerging interplay of the different synchronies outlined in Sect. 2.2. These mechanisms are modeled by causal relations between mental states (e.g., the sensory representation of a stimulus, emotions, preparations). The mental states are represented by nodes with values that change over time (also simply called states) and the causal relations by connections between them, enabling interactive dynamics. In this way the mental states create an emergent mental process by which their activations dynamically change over time. These dynamical changes are affected by the input states and result in the output states, which in turn affect the input states of the agent itself and/or the other agent. Here the agent's input (sensing) states concern, for example, hearing the relevant verbal actions or seeing the relevant movements of the other agent. The output (execution) states concern the agents' actions and body states that are visible to the external world, including, for instance, the execution of a movement, the (facial) expression of affect and looking at the other agent. The interplay between internal (cognitive and affective) mental states involves, for example, the representations of the other agent's movement, the preparation of the agent's own movement, affect, and conscious emotion.

These causal networks are conceptualized by a labeled graph based on the following labels:

- A *connection weight* $\boldsymbol{\omega}_{X,Y}$ is associated with each connection from a state $X$ to state $Y$; this denotes the strength of that connection.
- A *combination function* $\mathbf{c}_Y$ for each state $Y$; this defines the aggregation of the impact from all incoming connections on that state.
- A *speed factor* $\boldsymbol{\eta}_Y$ for each state $Y$ to time the effect of the impact in a state-specific manner.

Each of these labels contain specific parameter values that need to be tuned. As can be seen, each agent has the same 15 states, from which 7 internal (invisible for the outside world; colored white), 3 input and 5 external states. A brief explanation of all the states of agent A is provided in Table 1 and all states of two agents A and B are presented in Table A1 from the 23-page Appendix (https://www.researchgate.net/publication/349694211). Furthermore, the role matrices used in our MATLAB software environment (as described in [37] and [38], Ch 9) for the different experiments are also available in this Appendix (part G).

### 3.2 Conceptual Representations for the Agent Model

First, agents A and B can receive input from a stimulus world$^{sti}$ for some predefined time periods, meaning the activation of world$^{sti}$ alternates between 0 (*sti* not present) and 1 (*sti* present), with *sti* being an instance of a stimulus. The model structure of all agents is the same. Therefore, for the sake of simplicity, we focus in the current paper on the model of an agent A with respect to a single other agent B. Within the presented scenario, this external stimulus only influences A by a causal relation to the sensory representation $\text{rep}_{\text{A}}^{sti}$ of this stimulus which in turn directly triggers the agent's three internal preparation states: $\text{prep}_{\text{A}}^{mov}$, $\text{affect}_{\text{A}}^{aff}$ and $\text{prep}_{\text{A,B}}^{ver}$, with *mov*, *aff* and *ver* being an instance of movement, affective response and a verbal action of agent A, respectively. Note that $\text{prep}_{\text{A,B}}^{ver}$ has an A, B subscript as this state denotes the preparation of only those verbal actions from agent A to B. The agent model also includes a sensory representation state for the verbal actions $ver'$ ($\text{rep}_{\text{A}}^{ver'}$) and the movements $mov'$ of any **other** agent ($\text{rep}_{\text{A}}^{mov'}$), with the prime symbol $'$ indicating that the behavior comes from the other agent B (without prime means that it comes from agent A). Each of these two sensory representation states is affected by the agent's three input states: hearing the verbal cues $ver'$ ($\text{hear}_{\text{A,B}}^{ver'}$), seeing the affective expressions $aff'$ ($\text{see}_{\text{A,B}}^{aff'}$) and seeing the movements $mov'$ ($\text{see}_{\text{A,B}}^{mov'}$) of any **other** agent.

As $mov'$ is assumed to be a movement similar to *mov*, $\text{rep}_{\text{A}}^{mov'}$ is directly connected with $\text{prep}_{\text{A}}^{mov}$, $\text{affect}_{\text{A}}^{aff}$ and $\text{prep}_{\text{A,B}}^{ver}$ and these (reciprocal) causal links show how the sensory representation of lower movement processes serve as a base for (higher) internal action preparations and the connections from each preparation state to $\text{rep}_{\text{A}}^{mov'}$ in turn reflect the feedback from the higher-order to the lower-order processes. Furthermore, $\text{rep}_{\text{A}}^{mov'}$ directly influences the gaze direction of the agent ($\text{look}_{\text{A,B}}$), because the sensory representation of the other agent's movement $mov'$ can enhance the agent's visual focus. State $\text{rep}_{\text{A}}^{ver'}$ causally affects $\text{affect}_{\text{A}}^{aff}$ and $\text{prep}_{\text{A,B}}^{ver}$, but not the preparation state for movement because the latter is a lower-order process. The execution of $\text{listen}_{\text{A,B}}$ is also directly triggered by $\text{rep}_{\text{A}}^{ver'}$ because the sensory representation of the other agent's verbal action can alert the agent to listen more focused. The mental processes, starting from the representation states, ultimately lead to both conscious emotions (internal state $\text{emotion}_{\text{A}}^{aff}$) and executed actions in the physical world ($\text{look}_{\text{A,B}}$, $\text{listen}_{\text{A,B}}$, $\text{move}_{\text{A}}^{mov}$, $\text{exp\_affect}_{\text{A}}^{aff}$, $\text{talk}_{\text{A,B}}^{ver}$).

Regarding the preparation states, $\text{prep}_{\text{A}}^{mov}$ influences both the actual execution of the movement $\text{move}_{\text{A}}^{mov}$ and its representation $\text{rep}_{\text{A}}^{mov'}$, thereby highlighting the dynamic interplay of one's representation of $mov'$ and one's own execution *mov*. The state $\text{affect}_{\text{A}}^{aff}$ directly influences $\text{rep}_{\text{A}}^{mov'}$, the expression of the affective response *aff* ($\text{exp\_affect}_{\text{A}}^{aff}$) and the conscious $\text{emotion}_{\text{A}}^{aff}$ of *aff*. The fact that the sensory representation of $ver'$ does not get feedback from $\text{affect}_{\text{A}}^{aff}$ reflects the higher-order process of language compared to the lower-level affective changes. State $\text{prep}_{\text{A,B}}^{ver}$ has an immediate effect on $\text{rep}_{\text{A}}^{mov'}$,

$\text{rep}_{\text{A}}^{ver'}$ and the execution of the verbal action $\text{talk}_{\text{A,B}}^{ver}$. State $\text{talk}_{\text{A,B}}^{ver}$ in turn triggers $\text{emotion}_{\text{A}}^{aff}$ which in turn directly affects $\text{prep}_{\text{A,B}}^{ver}$. This feedback loop reflects the need of conscious emotions to initiate verbal actions *ver* and at the meantime how these verbal actions *ver* themselves further shape the conscious emotions of the affective response *aff*.

**The Coupling Between the Sensing and Execution States**

In a situation with multiple agents, we can connect the execution states of any agent A to the sensory states of any agent B. Specifically, each of agent A's sensing states receives two input connections, one from their own execution state and one from an execution state of agent B. Specifically, $\text{hear}_{\text{A,B}}^{ver'}$ gets input from $\text{listen}_{\text{A,B}}$ because listening is required to receive auditory cues and from the execution $\text{talk}_{\text{B,A}}^{ver'}$ of the verbal action $ver'$ of agent B. Both $\text{see}_{\text{A,B}}^{aff'}$ and $\text{see}_{\text{A,B}}^{mov'}$ are activated by $\text{look}_{\text{A,B}}$ to capture the need of looking at agent B to get visual cues from this agent. Regarding the input connections from Agent B, the expression $\text{exp\_affect}_{\text{B}}^{aff'}$ of the affective response for $aff'$ is directly linked to state $\text{see}_{\text{A,B}}^{aff'}$ for seeing $aff'$ and similarly the execution state $\text{move}_{\text{B}}^{mov'}$ of the movement $mov'$ is directly linked to $\text{see}_{\text{A,B}}^{mov'}$.

**General Mechanisms**

In line with the general psychological mechanisms outlined in Sect. 2.1, in addition to stimulus-response links, each agent contains prediction loops and mirroring links. Both direct and indirect effects are predicted through the prediction loops. The prediction loops from $\text{prep}_{\text{A}}^{mov}$ to $\text{rep}_{\text{A}}^{mov'}$ and from $\text{prep}_{\text{A,B}}^{ver}$ to $\text{rep}_{\text{A}}^{ver'}$ consist of the prediction of direct effects (i.e., what the effect of the execution of a certain action will be on the sensory representation of this action). The indirect effects (i.e., the effect of a preparation of a certain action on the representation of another action) regard the prediction loops from $\text{prep}_{\text{A,B}}^{ver}$ to $\text{rep}_{\text{A}}^{mov'}$ and from $\text{affect}_{\text{A}}^{aff}$ to $\text{rep}_{\text{A}}^{mov'}$. Concerning the mirroring links, the connection from $\text{rep}_{\text{A}}^{mov'}$ to $\text{prep}_{\text{A}}^{mov}$ mirrors the action movement and the connection from $\text{rep}_{\text{A}}^{ver'}$ to $\text{prep}_{\text{A,B}}^{ver}$ mirrors the verbal action of another agent. In principle the connection from $\text{see}_{\text{A,B}}^{aff'}$ to $\text{affect}_{\text{A}}^{aff}$ through both $\text{rep}_{\text{A}}^{mov'}$ and $\text{rep}_{\text{A}}^{ver'}$ can also be interpreted as a mirroring path, because every sensory representation is a) influenced by $\text{see}_{\text{A,B}}^{aff'}$ and b) internally influences $\text{affect}_{\text{A}}^{aff}$ through the representation states of both the verbal action ($\text{rep}_{\text{A}}^{ver'}$) and the movement ($\text{rep}_{\text{A}}^{mov'}$). It is argueable that the model could also in addition contain a $\text{rep}_{\text{A}}^{aff'}$, however, we have decided to not include this additional state for reasons of simplicity. There were already multiple pathways from $\text{see}_{\text{A,B}}^{aff'}$ to $\text{affect}_{\text{A}}^{aff}$ itself.

**Connection Weights**

All the connection weight $\boldsymbol{\omega}_{X,Y}$ values were fixed on the value 1, except the $\boldsymbol{\omega}_{X,Y}$ of all incoming connections to $\text{affect}_{\text{A}}^{aff}$ and $\text{affect}_{\text{B}}^{aff'}$. The incoming connections to these affect states from respectively $\text{rep}_{\text{A}}^{mov'}$ and $\text{rep}_{\text{B}}^{mov}$ were set to 2 and all the other connections were set to 0.5. In this way, the less complex sensorimotor processes serve as a foundation or 'grounding' [1] for the affective responses. Furthermore, the connection weight $\boldsymbol{\omega}_{\mathrm{world}^{sti},\ \mathrm{rep}_{\mathrm{B}}^{sti}}$ is set to 0 because agent B did not receive a *sti*.

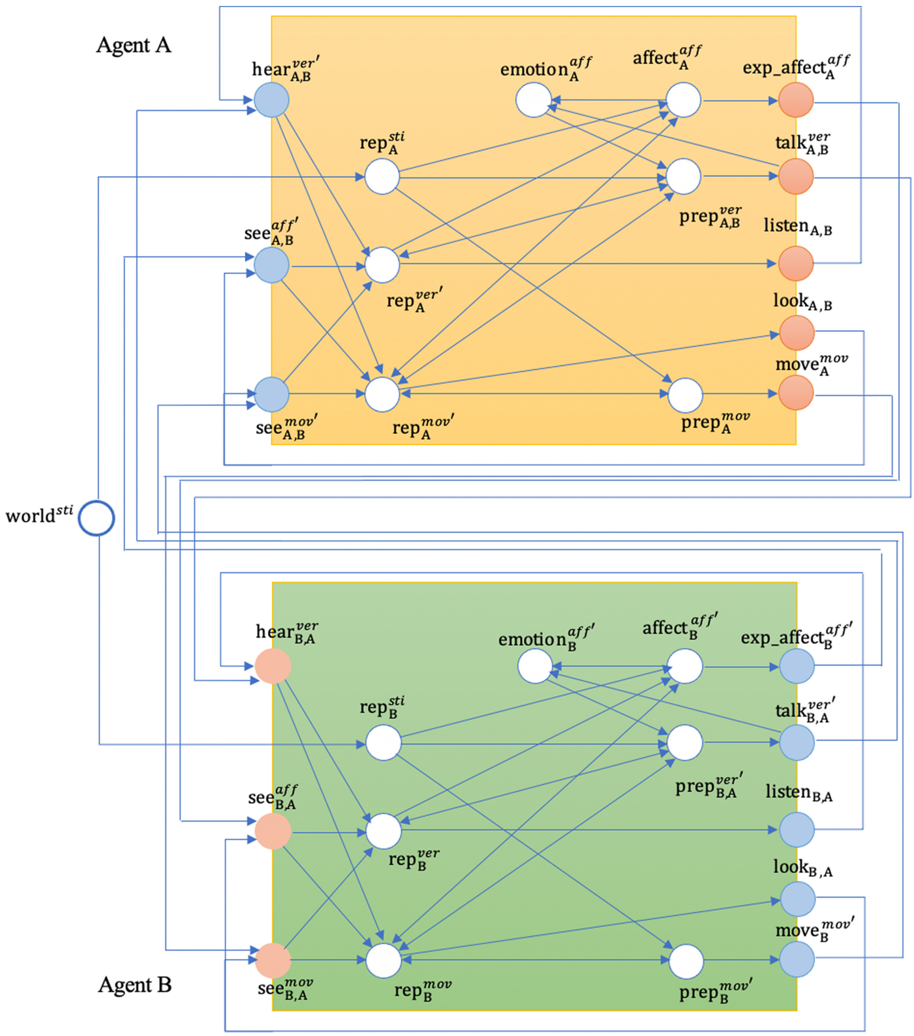


**Fig. 1.** The model for the two agents and the stimulus from the world.

### 3.3 Numerical Representations for the Agent Model

We used the software environment described in [37] and [38], Ch 9. In this software environment, the conceptual representations of the multi-agent model are mapped onto their associated numerical representations as follows:

**Table 1.** The description of all the states of agent A

| State | Explanation |
|---|---|
| $\text{world}^{sti}$ | World state for stimulus *sti* |
| $\text{see}_{\text{A,B}}^{aff'}$ | Agent A receives the visual cues of the affective expression *aff*′ of agent B |
| $\text{see}_{\text{A,B}}^{mov'}$ | Agent A receives the visual cues of the agent B movement *mov*′ |
| $\text{hear}_{\text{A,B}}^{ver'}$ | Agent A receives the verbal cues *ver*′ of agent B by hearing them |
| $\text{rep}_{\text{A}}^{sti}$ | Sensory representation state for stimulus *sti* in agent A |
| $\text{rep}_{\text{A}}^{ver'}$ | Sensory representation state of agent B verbal action *ver*′ in agent A |
| $\text{rep}_{\text{A}}^{mov'}$ | Sensory representation state of agent B movement *mov*′ in agent A |
| $\text{prep}_{\text{A}}^{mov}$ | Preparation state for movement *mov* in agent A |
| $\text{affect}_{\text{A}}^{aff}$ | Preparation state for affective response *aff* in agent A |
| $\text{prep}_{\text{A,B}}^{ver}$ | Preparation state for verbal action *ver* of agent A to agent B |
| $\text{move}_{\text{A}}^{mov}$ | Execution state for movement *mov* in agent A |
| $\text{emotion}_{\text{A}}^{aff}$ | The conscious emotional state for *aff* in agent A |
| $\text{exp\_affect}_{\text{A}}^{aff}$ | The expression of the affective response *aff* in agent A |
| $\text{talk}_{\text{A,B}}^{ver}$ | Verbal action *ver* of agent A to agent B |
| $\text{look}_{\text{A,B}}$ | Agent A looks at agent B |
| $\text{listen}_{\text{A,B}}$ | Agent A listens to agent B |

- $Y(t)$ denotes the activation value for state $Y$ of an agent at time point $t$; this is a real number, usually in the range [0, 1].
- The single causal impact $\mathbf{impact}_{X,Y}(t) = \boldsymbol{\omega}_{X,Y}X(t)$ defines at each time point $t$ the single impact from state $X$ connected to state $Y$ on state $Y$, where $\boldsymbol{\omega}_{X,Y}$ is the weight of the connection from $X$ to $Y$.
- Aggregating of multiple single causal impacts through combination function $\mathbf{c}_Y(\ldots)$ is defined by

$$\mathbf{aggimpact}_Y(t) = \mathbf{c}_Y\left(\mathbf{impact}_{X_1,Y}(t), \ldots, \mathbf{impact}_{X_k,Y}(t)\right) = \mathbf{c}_Y\left(\boldsymbol{\omega}_{X_1,Y}X_1(t), \ldots, \boldsymbol{\omega}_{X_k,Y}X_k(t)\right)$$

  for the states $X_1, \ldots, X_k$ from which $Y$ has incoming connections.
- The speed factor $\boldsymbol{\eta}_Y$ determines how the effect of $\mathbf{aggimpact}_Y(t)$ on state $Y$ is exerted gradually over time:

$$Y(t + \Delta t) = Y(t) + \boldsymbol{\eta}_Y\left[\mathbf{aggimpact}_Y(t) - Y(t)\right]\Delta t$$

- This leads to the following difference or differential equation for $Y$: $Y(t + \Delta t) = Y(t) + \boldsymbol{\eta}_Y\left[\mathbf{c}_Y\left(\boldsymbol{\omega}_{X_1,Y}X_1(t), \ldots, \boldsymbol{\omega}_{X_k,Y}X_k(t)\right) - Y(t)\right]\Delta t$, or $\frac{dY(t)}{dt} = \boldsymbol{\eta}_Y\left[\mathbf{c}_Y\left(\boldsymbol{\omega}_{X_1,Y}X_1(t), \ldots, \boldsymbol{\omega}_{X_k,Y}X_k(t)\right) - Y(t)\right]$

All agent states use the advanced logistic sum combination function $\mathbf{c}_Y(\ldots)$, whereas the world state for stimulus *sti* uses the step-modulo combination function $\mathbf{c}_Y(\ldots)$; see Table 2.

**Table 2.** The two combination functions used

| Name | Formula | Parameters |
|---|---|---|
| Advanced logistic sum combination function $\mathbf{alogistic}_{\sigma,\tau}(V_1, \ldots, V_k)$ | $\left[\frac{1}{1+e^{-\sigma(V_1+\cdots+V_k-\tau)}} - \frac{1}{1+e^{\sigma\tau}}\right](1 + e^{-\sigma\tau})$ | Steepness $\sigma$<br>Excitability threshold $\tau$ |
| Step-mod function $\mathbf{stepmod}_{\rho,\delta}(V_1, \ldots, V_k)$ | for time $t$<br>if $mod(t, \rho) < \delta$ then $x = 0$, else 1 | Repeated time interval $\rho$<br>Duration of value 0 $\delta$ |

## 4 Simulation Method for the Agents

We will present three scenarios. All initial state values were set to 0 in all simulations. Regarding the first/main simulation, as specified with the input parameters of the step-modulo combination function (see Table 3), agent A is exposed to an external stimulus *sti* for 150 time units every time after 150 time units without stimulation. This process (a total of 300 time units) is repeated until the end of the simulations. We deliberately do not further specify stimulus *sti* because there are numerous situations that can provoke interpersonal synchrony. Such repeated stimuli may concretely regard, for instance, daily life events that one person shares with another person, a series of therapy sessions or a dance choreography, meaning these agent simulations might have a wide variety of applications. The activation level of *sti* can vary over specific applications, however, for the sake of simplicity, we have decided to use activation level 1 over all simulations. The (length of the) stimulus *sti* intervals for this main social simulation were selected such that, as can be seen in Fig. 2 and Fig. B1-4 from the Appendix, (most of) the mental states ended in their equilibrium phase for both the stimulus *sti* present and absent periods. In Fig. 2 and the Appendix Fig. B1-4 and C1-4 is it shown that emerging limit cycle behavior occurs right from the start.

The characteristics of the two agents have been set according to the homeostatic regulation of neuronal excitability principle, which refers to the adaptation of neurons' internal properties to control a desired activation level; e.g., [44]. More specifically, as agent B (the agent not directly receiving the stimulus) gets less incoming activation than agent A, we have mimicked this principle by putting some of the excitability threshold and steepness values from the advanced logistic sum combination function of agent B lower than for agent A. The speed factors of almost all states equaled 0.5. The speed factor of the stimulus was set to 2 to ensure the fast appearance and disappearance of the stimulus. In contrast, the speed factors of the looking direction and the focus of listening were set to 0.2 (possible scale range: 0 to 1, with higher speed factors indicating that the specific state will change quicker) for both agents because in the real world these actions often do not rapidly change.

The second simulation consists of shorter stimulus and non-stimulus intervals (each of them lasting 10 time units instead of 150), and this is the only difference from the main simulation. This is a representative example for the cases where no equilibria are reached within the stimulus and non-stimulus periods. The third simulation is exactly the same as the main simulation except that the states related to movement were disabled in both agents (see Appendix, part H). The aim of this third simulation was to test whether synchrony can emerge without movement.

**Table 3.** The values for the main characteristics of the model: speed factors $\boldsymbol{\eta}$ and combination function parameters $\boldsymbol{\sigma}$ and $\boldsymbol{\tau}$ for each agent state and combination function parameters $\boldsymbol{\rho}$ and $\boldsymbol{\delta}$ for the stimulus *sti*

| State | $\eta$ | $\sigma$ | $\tau$ | State | $\eta$ | $\sigma$ | $\tau$ |
|---|---|---|---|---|---|---|---|
| $\text{see}_{A,B}^{aff'}$ | 0.5 | 1 | 0.4 | $\text{see}_{B,A}^{aff}$ | 0.5 | 1 | 0.4 |
| $\text{see}_{A,B}^{mov'}$ | 0.5 | 1 | 0.4 | $\text{see}_{B,A}^{mov}$ | 0.5 | 1 | 0.4 |
| $\text{hear}_{A,B}^{ver'}$ | 0.5 | 1 | 0.4 | $\text{hear}_{B,A}^{ver}$ | 0.5 | 1 | 0.4 |
| $\text{rep}_{A}^{sti}$ | 0.5 | 20 | 0.6 | $\text{rep}_{B}^{sti}$ | 0.5 | 20 | 0.6 |
| $\text{rep}_{A}^{ver'}$ | 0.5 | 1 | 0.4 | $\text{rep}_{B}^{ver}$ | 0.5 | 1 | 0.4 |
| $\text{rep}_{A}^{mov'}$ | 0.5 | 1 | 3 | $\text{rep}_{B}^{mov}$ | 0.5 | 1 | 2 |
| $\text{prep}_{A}^{mov}$ | 0.5 | 4 | 0.8 | $\text{prep}_{B}^{mov'}$ | 0.5 | 2 | 0.3 |
| $\text{affect}_{A}^{aff}$ | 0.5 | 5 | 0.8 | $\text{affect}_{B}^{aff'}$ | 0.5 | 2 | 0.6 |
| $\text{prep}_{A,B}^{ver}$ | 0.5 | 1 | 3.5 | $\text{prep}_{B,A}^{ver'}$ | 0.5 | 1 | 2.5 |
| $\text{move}_{A}^{mov}$ | 0.5 | 4 | 0.3 | $\text{move}_{B}^{mov'}$ | 0.5 | 4 | 0.1 |
| $\text{emotion}_{A}^{aff}$ | 0.5 | 2 | 0.3 | $\text{emotion}_{B}^{aff'}$ | 0.5 | 2 | 0.1 |
| $\text{exp\_affect}_{A}^{aff}$ | 0.5 | 2 | 0.4 | $\text{exp\_affect}_{B}^{aff'}$ | 0.5 | 2 | 0.4 |
| $\text{talk}_{A,B}^{ver}$ | 0.5 | 4 | 0.3 | $\text{talk}_{B,A}^{ver'}$ | 0.5 | 4 | 0.3 |
| $\text{look}_{A,B}$ | 0.2 | 1 | 0.3 | $\text{look}_{B,A}$ | 0.2 | 1 | 0.5 |
| $\text{listen}_{A,B}$ | 0.2 | 2 | 0.3 | $\text{listen}_{B,A}$ | 0.2 | 1 | 0.4 |
| $\text{world}^{sti}$ | 2 | $\rho$<br>300 | $\delta$<br>150 | | | | |

## 5 Analysis of the Two-Agent Model: Main Simulation

To validate the two-agent model, we derived some testable predictions from the literature (as discussed in Sect. 2). First, the occurrence of a limit cycle. Synchrony is quantified as the same states of agent A and B that exhibit comparable patterns over time. Therefore, we focus for each agent on corresponding actions. Equivalent states of agent A (solid lines) and B (dashed lines) are colored the same in all figures. As shown in Fig. 2, Fig. B1-4 and Fig. C1-4 from the Appendix regarding the main simulation, all the states of both agent A and B are activated after the stimulus *sti* is presented to agent A and deactivated when *sti* is no longer present, resulting in a limit cycle for the model.

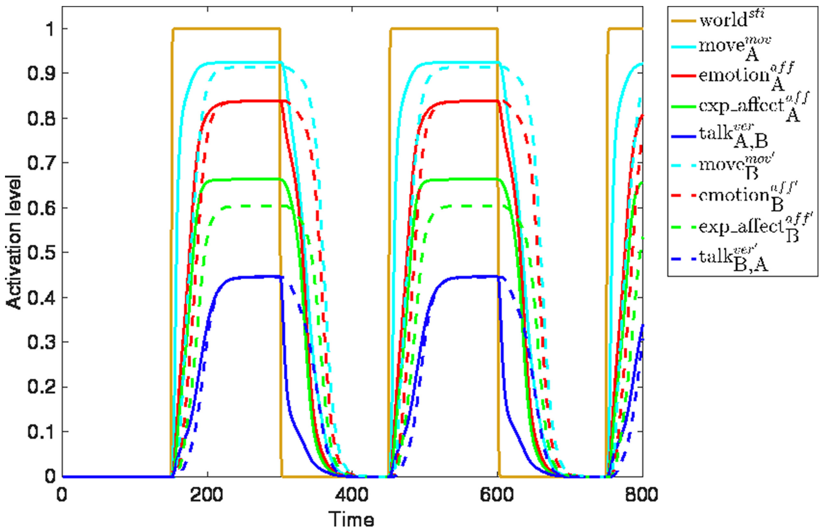


**Fig. 2.** Activation levels over 800 time units (with 150 non-stimulus time units alternated with 150 stimulus time units) for the execution states of the two agents. Corresponding states of agent A (solid lines) and B (dashed lines) are indicated in the same color, whereas the stimulus *sti* is indicated in yellow. (Color figure online)

This finding demonstrates that emergent synchrony patterns between agents can originate through communication/interaction when only one agent actually receives a stimulus *sti*. Note that such synchrony patterns would not be able to emerge when agent B cannot receive sensing information from agent A as an input (i.e., see or hear agent A). These emergent synchrony patterns remain consistent over time, indicated by the repetitive (equally high) peaks of each of two agents' states across the stimulus *sti* episodes. Furthermore, as can be seen in Fig. 2 and Fig. B1-4 from the Appendix, each of the state activations of agent A precedes activation of the equivalent state of agent B, except the input and representation states. The reasoning behind the latter is that the input states, and thereby the representation states that are directly dependent on the input states, of agent A require input from the output states of agent B and thus cannot precede these states of agent B in terms of activation. The analysis of the simulation with shorter stimulus and non-stimulus intervals, a more extensive evaluation of the sequence of the different types of synchrony and the simulation without movement can be retrieved from the Appendix, part H.

## 6 Discussion

Our agent models demonstrate the emergence of movement, expression of affective response, and language synchrony in two agents. Moreover, conscious emotional synchrony occurred as well. The social simulations based on the described general psychological mechanisms succeeded in reproducing emerging synchrony patterns that are widely reported in the literature, in the same order as predicted by several theories about synchrony. Obviously, certain parameter settings for these general mechanisms represent certain types of persons. The example simulation settings describe a specific dyad. When the parameter settings are tuned differently, other types of dyads can be represented as well. Thus, by considering realistic input, internal and output states in the agent models, we were able to capture a complex process of mental representations of the physical world and perceived similarities that do occur during interpersonal synchrony under specific circumstances. In particular, the importance of embodiment through movements for cognition is demonstrated [1].

Interpersonal synchrony belongs to a broader class of synchrony patterns that is observed in the natural life and behavioral sciences [28, 34]. This means that our simulations can potentially be extended to other domains as well. Based on our agent modeling and the conceptual In-Sync model, therapeutic sessions between therapists and patients can be an interesting application field. Agent-based computational models like our model can be the basis for the development of virtual agents that might be used in settings to interact with humans.

There are also some limitations that could be explored in future work. First, we modeled only two agents. How synchrony patterns evolve in, for example, triads and with different stimulus episodes across agents are potential future simulations. Second, future work should verify whether the same synchrony patterns in the agents hold on empirical data. Third, the current agents are non-adaptive: for example, the excitability thresholds are fixed over time. Adaptive agents might be able to automatically tune their synchrony behavior in varying situations, thereby maintaining their equilibria states in even more unpredictable environments. Fourth, the internal states of our agent models could always be extended, for example by including more specific states. A typical example would be to include a representation state of the affective expression of other agents or to separate the representation states for one's own movements and the movements of other agents. Fifth, we did not include some anticipation theories from psychology in our agent models. Based on some finger tapping experiments [40], it would also be possible that the follower (in our case agent B) anticipates on the leader (agent A) and thereby becomes effectively the leader in synchrony. Sixth, in the future, variable stimulus intervals and/or levels might be incorporated to explore how the emerging synchrony and common ground evolve. Finally, future work is needed in which more extensive analysis on the interplay between limit cycles, equilibria and synchronization is conducted.

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