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THE EMERGENCE AND IMPACT OF SYNCHRONY IN DESIGN TEAMS: A COMPUTATIONAL STUDY

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ABSTRACT

Studies revealed that, while collaborating, humans tend to synchronise on multiple levels (e.g., neurocognitive or physiological). Inter-brain synchrony has been linked to improved problem-solving, decision-making, and creativity. Nevertheless, studies on synchrony in design teams started to emerge only recently. This study contributes to this stream of research by utilising a computational model of a design team to explore the relationships between team cohesion, synchrony, and team performance. The experiments revealed a positive link between team cohesion level and the emergence of (cognitive) synchrony. Furthermore, cohesive teams were found to be more efficient, converging quicker and producing solutions at a higher rate. In addition, the diversity of the solutions generated by highly cohesive teams tends to increase over time. Teams in medium- and low-cohesive settings initially generate highly diverse solutions, but such diversity decreases as the simulation progresses. Finally, highly-cohesive teams were found to be prone to premature convergence.

Keywords: Teamwork, Simulation, Design cognition, Synchrony

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1 INTRODUCTION

For decades, researchers have been intrigued by the emergence of spontaneous order in complex systems (Strogatz, 2003). Oscillations in various biological and physical systems have been found to synchronise over time, as evidenced, for example, by the aligned periodic dynamics of populations (Becks and Arndt, 2013), synchronised swinging of pendulum clocks, or fireflies flashing in unison. Humans are no exception in this regard (Shahal *et al.*, 2020). Numerous studies investigated the emergence of synchrony in crowds and teams, ranging from synchronised movement, such as clapping or walking (Strogatz *et al.*, 2005; Thomson *et al.*, 2018), to similarities in brain activities (Holroyd, 2022).

With the recent advancements in the fields of neuroscience and brain imaging, inter-brain synchrony started to attract significant attention from researchers interested in human cooperation and teamwork (Schirmer *et al.*, 2021). Namely, during social engagement, activations in human brains become correlated, i.e., synchronised (Reinero *et al.*, 2021). Such inter-brain synchrony in teams was found to improve problem-solving (Reinero *et al.*, 2021) and decision-making (Liu *et al.*, 2021). Furthermore, several studies explored the relationship between synchrony and creativity (Liang *et al.*, 2022; Mayseless *et al.*, 2019; Wang *et al.*, 2022) and idea generation (Won *et al.*, 2014).

Given its impact on team performance and creativity, (inter-brain) synchrony constitutes an important topic in design team research. Nevertheless, studies of synchrony in design teams have started to emerge only recently (Mayseless *et al.*, 2020). One reason for this lies in the difficulties of studying and assessing synchrony in real-world settings (due to, for example, differences in definitions, subjectiveness, or issues with data segmentation, annotation, and labelling) (Delaherche *et al.*, 2012; Holroyd, 2022). Furthermore, simultaneous tracking and evaluating activities of multiple individuals are particularly cumbersome and, therefore, the majority of current studies are conducted on dyads (Liu *et al.*, 2021).

This work aims to aid studies on the emergence of synchrony in teams and its effect on design performance by utilising a computational model of a design team (Perišić, 2020). More precisely, an agent-based system of a design team is utilised to simulate cognitive behaviour and communication among team members, manipulate their interactions, and study the impact of such manipulations on the degree of similarity in agents' cognitive behaviour. Furthermore, the team's exploration of the design space is tracked to enable studying the relationship between synchrony and team performance (with respect to success rate, efficacy, and the number and diversity of generated solutions).

The remainder of this paper is structured as follows. The next section presents a short overview of the related studies of synchrony in teams, as well as the studies on the effect of team cohesion on creativity and design space exploration. Next, the descriptions of the computational system and metrics are given in Section 3, and the results are presented in Section 4. The results are discussed in Section 5. The paper concludes with a brief outlook on the findings and the directions for future work.

2 RESEARCH BACKGROUND

Despite a large number of studies on the topic, there is no universally accepted definition of synchrony (Holroyd, 2022; Ravignani, 2017). Namely, in biological systems, synchrony is often seen as a loose pattern in coordination among individual entities, whereas in other domains, synchrony implies a precise coincidence of events in time (Ravignani, 2017). In studies on interpersonal synchrony, researchers such as Bernieri and Rosenthal (1991) and Delaherche et al. (2012) see synchrony as a dynamic phenomenon manifested in the degree to which behaviours of two (or more) interacting individuals are non-random, patterned, or synchronised in both form and timing. Such synchrony may emerge through one's processes of temporal self-regulation motivated by the desire to maintain cohesion within the group (Leroy *et al.*, 2015). Furthermore, shared attention, joint goals, and cooperation have all been found to result in higher synchrony among individuals (Cui *et al.*, 2012; Dikker *et al.*, 2017), demonstrating how synchrony could emerge in a cohesive group (Hu *et al.*, 2018). This relationship appears reciprocal, as physiological and behavioural synchrony have been shown to be predictive of one's experience of group cohesion (Gordon *et al.*, 2020; Liu *et al.*, 2021) and cooperation (Behrens *et al.*, 2020; Wiltermuth and Heath, 2009).

Given the diversity in definitions and scope of studies on interpersonal synchrony (Delaherche *et al.*, 2012), the existence of numerous synchrony metrics is not surprising. Namely, researchers have assessed cross-correlations, calculated weighted coherence and performed cross-recurrence quantification analysis on physiological cues such as concurrent cardiac (Verdiere *et al.*, 2020) or electrodermal (Guastello *et al.*, 2022) signals. Fernandes *et al.* (2018) explored the impact of emotional synchrony in teams (conceptualised as an accurate assessment of others' emotional state) on the outcomes of a design task, finding a positive relationship. Others adopt measures based on behaviour and movement, such as speech intonation or gestures (Chetouani *et al.*, 2017). For example, Won *et al.* (2014) tracked individuals' physical movements during collaboration and found the level of movement synchrony to be predictive of the level of creativity.

This work, however, focuses on cognitive synchrony, i.e., the alignment of cognitive processes in a design team. While there are multiple studies on shared cognition in design teams (e.g., Avnet, 2009; Badke-Schaub *et al.*, 2007; Dong *et al.*, 2013), their level of granularity does not permit assessing temporal (de-)synchronisation of cognitive processes during a design task. This research gap could be filled by the emergence of a promising new stream of research - design neurocognition. However, most current studies in the field focus on designers working in solitude (e.g., Fu *et al.*, 2019; Hay *et al.*, 2019). One of the pioneering works on inter-brain synchrony in design teams has been presented by Mayseless *et al.* (2019), who used functional near-infrared spectroscopy (fNIRS) to study creative problem-solving in teams. Their study revealed that, over time, cooperation among team members increases, whereas inter-brain synchrony decreases. A similar finding was obtained by Reinero *et al.* (2021), who further found a positive correlation between inter-brain synchrony and team performance on a series of tasks (e.g., sudoku puzzles, brainstorming, and memory tasks). In contrast to Mayseless *et al.* (2019) and Reinero *et al.* (2021), who studied changes in cooperation and synchrony over time, Hu *et al.* (2018) measured cooperation at a single point in the collaborative study. In this work, perceived cooperation among team members was found to promote inter-brain synchrony (Hu *et al.*, 2018). In accordance, a related study by Zhang *et al.* (2021) linked agreeableness, a personality trait associated with cooperative behaviour, to an increase in inter-brain synchrony in group decision-making tasks.

In their study on inter-brain synchrony, Liang *et al.* (2022) discuss the relationship between the creativity of design solutions and team synchrony. Although studies such as Mayseless *et al.* (2019) observed higher synchrony in creative than control tasks, the authors note that opposite trends could be observed as well. Namely, the shared neural response might indicate similarities in cognitive representations. Thus, finding creative solutions might require inhibiting such representations and diverging, consequently lowering the level of synchrony.

3 METHODS

The research reported here employs an agent-based model of a design team that has been used to study various aspects of team behaviour in design (see Perisic *et al.*, 2019, 2021; Perišić *et al.*, 2019). Space limitations do not permit a detailed overview of the computational system's theoretical background, implementation, and performance, but the relevant information can be found in (Perišić, 2020). In this section, we first briefly describe the basic mechanisms implemented in the system and then discuss how specific aspects of the system are utilized to study the relationships between team cohesion, synchrony, and team performance.

3.1 Overview of the computational model

The computational system utilised in this study comprises design agents, which represent individuals working in a design team. The cognitive processes of the agents implemented in the system are modelled to correspond to the design processes in the Function-Behaviour-Structure ontology (Gero, 1990). More precisely, each agent's mental model is represented as a network of design issues (functions, behaviours, and structures), and the design processes (eight processes in the FBS framework) are conceptualised as activations spreading from one node (i.e., design issue) to another. For example, the activation spreading from a function node to a behaviour node represents the formulation process. Activation spreading over the agent's mental model (network of design issues) captures the shifts in the designer's attention while designing.

While performing tasks, the agents learn and change their mental models. Namely, agents can generate new links among knowledge nodes, as well as ground or loosen the existing ones. The link grounding is manifested in the increase of the link's weight, associated with the ease of the link's processing (Anderson, 1983). If the link weight exceeds a predefined threshold, the link can be processed at virtually no cost, enabling the activation to spread from one node to another instantly (as a reflex). In that sense, a well-grounded, connected subnetwork of the agent's mental model forms a knowledge chunk. Each agent within a team has a unique knowledge network (i.e., known design issues and links among them), giving rise to differences in their cognitive processes. Thus, through modifications of the agents' knowledge, one can simulate and study the effects of differences in team members' backgrounds (i.e., expertise areas and experience) on the team performance and behaviour.

The agents can generate new structures and evaluate them. An abstract representation of a structure is used - each structure is represented as an undirected network of components. Behaviours are conceptualised as particular network properties (e.g., having a network diameter above a certain threshold). Thus, if a structure (i.e., the network associated with it) displays such a property, the agent can form a link between the structure and behaviour. A design task is a set of requirements placed upon the behaviours of the structures. The agents' goal is to modify and combine known structures to derive new ones that exhibit the required behaviours.

One simulation run can be summarised as follows. The agents are given a task, and the associated function and behaviour nodes receive an initial activation impulse in the agents' mental models. In each simulation step, each agent focuses on the most active knowledge node or a knowledge chunk in its mental model and spreads activation from the focused node(s) to the neighbouring nodes. If a knowledge node corresponding to a structure is focused, the agent can modify it or combine it with other activated structures to generate new structures, potentially deriving a solution to the task. In addition, the agent can communicate focused structures or knowledge links to their peers. The communicated knowledge elements are then added to the listening agents' mental models, where they receive an activation impulse to simulate the listeners' attention to the communicated design issues. When one of the agents proposes a potential solution, others evaluate it against their mental models to determine if it satisfies the required behaviours. As a response, the agents provide an evaluation score. If all agents rate the proposed structure sufficiently high, the structure is accepted as a solution, and the simulation stops (i.e., the agents' converged to a solution). Otherwise, the structure is discarded, and the search and generation continue. If more than half of the allocated time passes with no perceived advancement in the team performance, the team members start to gradually and intentionally redirect their attention to the previously discarded structures in an attempt to find a suitable solution (Stempfle and Badke-Schaub, 2002). The simulation terminates when the team agrees on a solution or the simulation time runs out.

3.2 Operationalisation of team cohesion, synchrony, and team performance

For synchrony to emerge, scientists emphasise that oscillators (entities or behaviours of interest that display a, more or less, periodic pattern) should be coupled, i.e., they should be able to interact and influence each other (Strogatz, 2003). The interactions among simulated team members represent communication and result in learning and activation of the communicated knowledge elements. Therefore, these communication mechanisms should be varied, and the effect of such variations on the level of synchrony and team performance can be studied. However, to determine how communication mechanisms should be modified, we turn to empirical studies.

The research presented in this section relates team cohesion to the emergence of synchrony. Casakin *et al.* (2015) operationalise team cohesion in terms of increased utterances signalling appreciation, agreement, and confirmation, noting that positive evaluations have a functional role in contributing to team cohesion and fuelling information exchange. Rodríguez-Sánchez *et al.* (2017) further note that highly cohesive teams are motivated to contribute to the joint collaborative goal by discussing and building on each other's ideas. Behaviours associated with agreement, appreciation, positive evaluations and adoption of others' ideas can be encompassed by the term "agreeableness". In accordance, Zhang *et al.* (2021) found agreeableness predictive of inter-brain synchrony. Other studies emphasising the impact of empathy on the emergence of synchrony are Guastello *et al.* (2020) and Palumbo *et al.* (2017), who also highlighted the importance of a shared focus on external events. Similarly, Liu *et al.* (2021) argue that shared attention and efficient information exchange are vital for the emergence of synchrony.

Building on these studies, we define *team cohesion* as a degree to which individuals pay attention to each other's messages (i.e., the amount of activation assigned to the communicated design issues) and assign positive evaluations to others' ideas (i.e., the scores assigned to solutions proposed by others). Thus, in a highly cohesive team, the design issues communicated in the current simulation step get activated to the level of 0.9 (where 1.0 indicates the maximal activation) in the listening agent's mental models. Consequently, these design issues are very likely to be focused on and built upon in the subsequent steps. In addition, the members of highly cohesive teams are biased to assign high scores to solutions proposed by others, further reinforcing their reuse in subsequent simulation steps. This behaviour can be understood as a form of conformity aimed at promoting team unity (Kaplan *et al.*, 2009). In contrast, teams with low levels of cohesion assign the activation impulse of only 0.1 to the communicated design issues. Further, their evaluations of others' ideas are biased to be negative. Teams with a medium cohesion level of cohesion evaluate others' ideas without bias (except that stemming from the incompleteness of their mental models) and assign an impulse level of 0.5 to the communicated design issues.

Keeping in mind the definitions of synchrony discussed in Section 2, *synchrony* is defined here as an overlap in the agents' focus at a particular simulation step. Thus, synchrony is viewed as a temporal alignment of cognitive processes among team members. To calculate the amount of overlap among sets of focused design issues, we utilise the Sørensen–Dice coefficient, which ranges from 0.0 (no overlap/synchrony) to 1.0 (complete synchrony). A similar metric was used by Avnet (2009) to evaluate the sharedness of mental models in engineering design teams. The metric can be employed to determine the degree of synchrony between two individuals at a particular simulation step. To obtain the team-level degree of synchrony, the average of all pairwise synchrony scores (in a specific time step) is taken.

Finally, team cohesion and synchrony should be linked to *team performance* and *design outcomes*. The computational system enables tracking the details of the design space explored by the simulated teams (i.e., details regarding the newly generated solutions). Further, we can extract whether and when the team managed to converge to a solution, as well as if the selected solution is indeed feasible (i.e., satisfies the requirements). Therefore, the following metrics of team performance are defined:

- Steps required for convergence,
- Number of solutions the team members generated over the course of the simulation,
- Rate at which new solutions are generated (number of solutions per simulation step),
- Success rate, i.e., the percentage of simulations in which the team managed to generate at least one feasible solution.

Furthermore, generated solutions can be compared to assess the degree of diversity among them. To enable such comparison, we characterise each solution by the density of the corresponding network's largest connected component. Note that the simulated tasks' requirements are imposed on the whole network (rather than on the largest connected component) and that no requirements are related to the network density. Thus, the definition of the task does not directly impact the range of density values obtained. First, the density values of all generated solutions are calculated for each simulation run. Then, the diversity of the obtained values is estimated using the Gini coefficient (Sosa and Gero, 2004), where values close to 0.0 indicate low diversity and values close to 1.0 indicate high diversity of the generated solutions. The Gini coefficient can be calculated at any point of the simulation study, quantifying the diversity of solutions produced up until that point in the simulation.

Building on the metrics of team cohesion, synchrony, and team performance, simulations are utilised to study how the change in the team cohesion level (low, medium, or high) impacts the level of synchrony. Furthermore, team performance metrics are collected to enable establishing the relationship between cohesion, synchrony, and creativity. A set of 1000 tasks was generated, and each task was performed three times by a team of three agents, resulting in a set of 3000 simulations. The three repetitions of each task differed solely in the level of specified team cohesion. Team cohesion was held constant during one simulation run. The maximal number of simulation steps was set to 1000.

4 RESULTS

First, we studied how the level of synchrony changes with the change in team cohesion. The distributions of synchrony levels emerging in each of the three cohesion settings are shown in Figure 1.

Next, the temporal changes in synchrony were compared across three cohesion settings. The simulations were first normalized by dividing each simulation run into percentiles. Then, the temporal trends were extracted by averaging the synchrony values at a specific percentile. The results are shown in Figure 2a.

The average values of team performance metrics (i.e., number of steps, number of new solutions generated over the course of the simulation, the rate at which new solutions are produced, and the success rate) are presented in Table 1. The differences in the design solution space exploration among teams are further explored by tracking the change in the number of generated solutions over time (Figure 2b).

Finally, we explore the relationship between team cohesion and diversity of design solutions. The changes in Gini coefficients over the course of the simulations are depicted in Figure 2c.

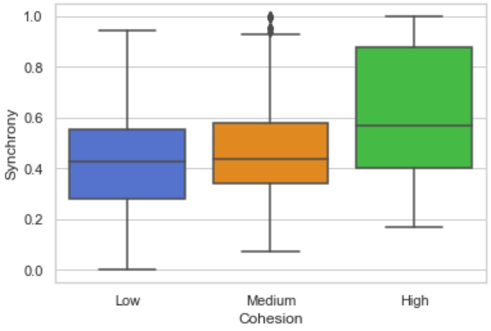

Figure 1. Team synchrony for different team cohesion settings

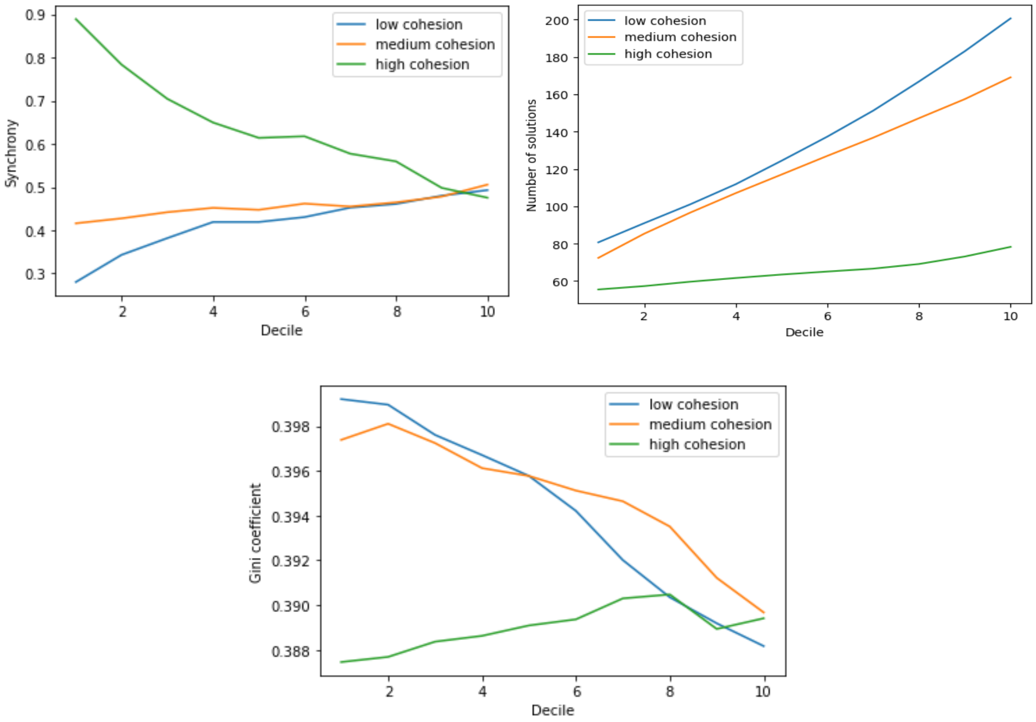

Figure 2. Change in a) team synchrony, b) number of generated solutions, and c) Gini coefficients (solution diversity) over the course of a simulation (averaged over all simulations)

Table 1. Performance achieved by teams with different cohesion levels

	Low cohesion	Medium cohesion	High cohesion
Average number of steps	997	474	161
Average number of new solutions	201	164	66
Rate at which new solutions are produced	0.193	0.335	0.410
Percentage of simulations in which at least one feasible solution is found	80.0	87.4	57.5

5 DISCUSSION

Within this work, the agent-based model of a design team was employed to simulate the cognitive behaviour of designers in teams of varying cohesion levels. The change in the level of mutual attention and agreeableness was hypothesised to have an impact on the emergence of synchrony among team members' cognitive processes. As seen in Figure 1, the change in cohesion settings (i.e., mutual attention and agreeableness) impacted the distributions of synchrony, with most cohesive teams displaying the highest synchrony values. Such findings are well-aligned with the literature on the relationship between synchrony and agreeableness, cooperation, and shared attention in teams. Namely, Dikker *et al.* (2017) argued that synchrony is likely driven by shared attention mechanisms and a common goal. A similar finding can be found in Liu *et al.* (2021), where the authors highlight shared mental representations and efficient information exchange as key components of synchrony. Finally, Zhang *et al.* (2021) found agreeableness to be a significant (positive) predictor of synchrony in group decision-making tasks.

However, when synchrony is observed over time, trends differ for different cohesion settings (Figure 2a). Namely, when teams are composed of highly agreeable agents that pay significant attention to each other's messages, their synchrony over time decreases. Although perhaps counter-intuitive, this finding aligns with the empirical data on inter-brain synchrony. Namely, studies (Mayseless *et al.*, 2019; Reinero *et al.*, 2021) found a decrease in inter-brain synchrony over time. The initial synchrony level is high, indicating that agents initiate the task by focusing on and discussing similar design issues (i.e., functions and behaviours related to the specified requirements). Nevertheless, as they progress and learn about the task, the ideas introduced get incorporated within and evaluated against their expertise areas, activating parts of their mental models not shared by others. Liang *et al.* (2022) observed a similar trend, noting that a decrease in synchrony can be related to difficulty in understanding design issues and novel solutions proposed by others and consequent disparity in evaluations of solution appropriateness in the middle stages of design.

In contrast, teams with medium and low cohesion experience an increase in the alignment of their mental models over time. This increase stems from the individuals performing a similar task. Despite moderate or very low levels of cohesion, team members in both settings are working on a similar task and share a common goal. Therefore, their mental models become more aligned as they discover similar design issues relevant to the task at hand. Furthermore, in both settings, agents are exposed to the ideas of others and, as the task progresses, can decide to build upon them (even though they have not paid much attention to them the first time they were introduced). Nevertheless, the synchrony level in medium- and low-cohesive settings remains lower than that in highly cohesive teams until the last decile of the simulation. The increase in synchrony in low-cohesion teams towards the end of the simulation is, in part, influenced by the time pressure that causes the agents to try to converge to a single solution (thus influencing the synchrony levels (Guastello *et al.*, 2020)). As a result, during the last simulation decile, even low-cohesive teams focus on a single (shared) solution and evaluate it against their mental models or get stuck in (different) local optima, unable to progress further. Therefore, their final synchrony levels are not different than those obtained by medium- and high-cohesive teams.

Table 1 and Figure 2b present details on the teams' performance with respect to the cohesive settings. As seen in the table, highly cohesive teams are more efficient (in terms of steps taken to converge to a solution) than medium- and low-cohesive ones. Furthermore, although they generate a smaller number of solutions during one simulation (Figure 2b and Table 1), the rate at which they produce solutions is higher than in the other two settings. Nevertheless, the very high cohesion setting decreased the overall success rate of the teams. Namely, the highly agreeable teams are inclined to accept solutions proposed by others and might, thus, settle for an infeasible solution (which occurs 35.7% of the time). This behaviour aligns with research on agreeableness that found more agreeable teams to be more prone to premature consensus (Ellis *et al.*, 2001). On the opposite side of the spectrum are low-cohesive teams that rarely reach a consensus within the specified number of simulation steps. As a result of a disagreement between team members, they explore a large section of the design space, generating significantly more solutions than other teams (Baer *et al.*, 2008). Nevertheless, as they work, non-cohesive teams disregard inputs from others and miss the opportunities for idea cross-fertilisation, resulting in a lower rate at which solutions are produced.

Disregarding others' solutions could result in a decline in the diversity of solutions observed in low- and medium-cohesive teams. As seen in Figure 2c, the diversity of solutions produced by cohesive teams seems to improve over time. This finding aligns with the findings presented by Rodríguez-Sánchez et al. (2017), where the authors noted an improvement in the creativity of solutions produced by a highly cohesive team. Similarly, Neumann *et al.* (2008) found that a strong team climate improves innovativeness. While their initial solutions are quite similar (due to all agents focusing on a similar, small set of solutions shared up until that point), as they progress, cohesive teams generate increasingly diverse solutions at a high rate. However, a change in such a trend can be observed in the middle to late stages of the simulation. In this period, the team has likely found a promising structure and attempts to converge, shifting their focus from the exploration to the implementation phase of design (Liang *et al.*, 2022). Thus, the team's focus narrows to a small number of structures, and slight modifications are introduced in order to fit one to the task requirements. This stage of the process could potentially result in groupthink (Mogan Naidu, 2018). Nevertheless, on average, the teams manage to revert to generating increasingly diverse solutions (Figure 2c), accompanied by a further decrease in synchrony levels (Figure 2a) and the increase in the number of generated solutions (Figure 2b) in the last deciles of the simulation. In contrast to the trends observed in the high-cohesion setting, less cohesive teams start by generating significantly diverse solutions, but the subsequently proposed designs lower the diversity score. The data revealed that such differences stem from the missed opportunities for cross-fertilisation. Namely, at each point in the simulation, cohesive teams focus on the proposed solutions, which then remain active in their mental models in several subsequent steps. As a result, these agents can evoke multiple solutions and use them when generating new solutions. Teams with lower cohesion settings, on the other hand, mostly focus on the solutions derived by themselves, disregarding the ideas of others. As a result, they generate increasingly similar solutions to the ones already proposed. This behaviour aligns well with the findings of Campbell et al. (2022), who emphasised the value of partially copying the solutions of others for maintaining diversity of the produced solutions. In the general team setting, Campbell *et al.* (2022) note that such a partial copying delays convergence but is vital to maintain the creativity of the solutions.

6 CONCLUSION

This work utilised a computational model of a design team to explore the relationships between team cohesion, synchrony, and team performance. The simulations revealed that mutual attention and agreeableness of the team members result in the higher alignment of members' cognitive processes. Nevertheless, synchrony in cohesive teams decreases over time, a finding that aligns with empirical studies (Mayseless *et al.*, 2019; Reinero *et al.*, 2021). Cohesive teams were also found to be more efficient than their non-cohesive counterparts, generating solutions at a higher rate and converging quicker. However, the results indicate that high levels of cohesion and synchrony could lead to premature convergence and the emergence of groupthink. Conflicting views on the effect of cohesion and synchrony on team performance can also be found in the literature (Liang *et al.*, 2022; Mogan Naidu, 2018). While many emphasise the benefits of cohesion (Guastello *et al.*, 2022), Rodríguez-Sánchez *et al.* (2017), for example, found cohesion in teams to be related only to better perceived (but not actual) performance. Thus, further exploring the conditions in which synchrony benefits design teams constitutes an important stream for future research.

This work employed one of many possible conceptualisations of team cohesion, modelling it as a (pre-fixed) level of attention and bias among agents. Further studies should extend this notion to capture different facets of team cohesion, enable its dynamic assessment, and track how cohesion and synchrony evolve over a series of design tasks. Herein, we simulated teams of homogeneous agents (regarding their mutual influence) in a constructive task. The next steps include studying the effect of leadership on the emergence of synchrony (Guastello *et al.*, 2020; Liang *et al.*, 2022) and adding solution diversity as a (simulated) requirement to further the study on the link between synchrony and (creative) performance (Liang *et al.*, 2022). In addition, the impact of the differences in the agents' initial knowledge (experience) on the emergence of team synchrony should be further explored. Finally, it is important to note that the agents' behaviour has not yet been calibrated to any real case of people interacting. Thus, further empirical studies are needed to validate and corroborate the findings of this work.

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REFERENCES

Anderson, J.R. (1983), “A spreading activation theory of memory”, Journal of Verbal Learning and Verbal Behavior, Vol. 22 No. 3, pp. 261–295.

Avnet, M.S. (2009), Socio-Cognitive Analysis of Engineering Systems Design: Shared Knowledge, Process, and Product, Massachusetts Institute of Technology.

Badke-Schaub, P., Neumann, A., Lauche, K. and Mohammed, S. (2007), “Mental models in design teams: a valid approach to performance in design collaboration?”, CoDesign, Taylor & Francis, Vol. 3 No. 1, pp. 5–20.

Baer, M., Oldham, G.R., Jacobsohn, G.C. and Hollingshead, A.B. (2008), “The personality composition of teams and creativity: The moderating role of team creative confidence”, The Journal of Creative Behavior, Vol. 42 No. 4, pp. 255–282.

Becks, L. and Arndt, H. (2013), “Different types of synchrony in chaotic and cyclic communities”, Nature Communications, Vol. 4 No. 1, p. 1359.

Behrens, F., Snijdewint, J.A., Moulder, R.G., Prochazkova, E., Sjak-Shie, E.E., Boker, S.M. and Kret, M.E. (2020), “Physiological synchrony is associated with cooperative success in real-life interactions”, Scientific Reports, Vol. 10 No. 1, p. 19609.

Bernieri, F.J. and Rosenthal, R. (1991), “Interpersonal coordination: Behavior matching and interactional synchrony”, in Feldman, R.S. and Rimé, B. (Eds.), Fundamentals of Nonverbal Behavior, Cambridge University Press, pp. 401–432.

Campbell, C.M., Izquierdo, E.J. and Goldstone, R.L. (2022), “Partial copying and the role of diversity in social learning performance”, Collective Intelligence, Vol. 1 No. 1, p. 263391372210818.

Casakin, H., Ball, L.J., Christensen, B.T. and Badke-Schaub, P. (2015), “How do analogizing and mental simulation influence team dynamics in innovative product design?”, Artificial Intelligence for Engineering Design, Analysis and Manufacturing, Vol. 29 No. 2, pp. 173–183.

Chetouani, M., Delaherche, E., Dumas, G. and Cohen, D. (2017), “Interpersonal synchrony: From social perception to social interaction”, Social Signal Processing, Cambridge University Press, pp. 202–212.

Cui, X., Bryant, D.M. and Reiss, A.L. (2012), “NIRS-based hyperscanning reveals increased interpersonal coherence in superior frontal cortex during cooperation”, NeuroImage, Vol. 59 No. 3, pp. 2430–2437.

Delaherche, E., Chetouani, M., Mahdhaoui, A., Saint-Georges, C., Viaux, S. and Cohen, D. (2012), “Interpersonal synchrony: A survey of evaluation methods across disciplines”, IEEE Transactions on Affective Computing, Vol. 3 No. 3, pp. 349–365.

Dikker, S., Wan, L., Davidesco, I., Kaggen, L., Oostrik, M., McClintock, J., Rowland, J., et al. (2017), “Brain-to-brain synchrony tracks real-world dynamic group interactions in the classroom”, Current Biology, Vol. 27 No. 9, pp. 1375–1380.

Dong, A., Kleinsmann, M.S. and Deken, F. (2013), “Investigating design cognition in the construction and enactment of team mental models”, Design Studies, Vol. 34 No. 1, pp. 1–33.

Ellis, A.P.J., Hollenbeck, J.R., Ilgen, D.R., Porter, C., West, B. and Moon, H. (2001), “Capacity, collaboration and commonality: a framework for understanding team learning”, Proceedings of the 6th International Command and Control Research and Technology Symposium, Annapolis, available at:https://doi.org/10.1.1.297.1942.

Fernandes, R., Arroyo, D. and Yamanaka, T. (2018), “Emotional synchrony effects on team design outcomes”, TGSW 2018 Art & Design Session Proceedings, pp. 77–80.

Fu, K.K., Sylcott, B. and Das, K. (2019), “Using fMRI to deepen our understanding of design fixation”, Design Science, Vol. 5, p. e22.

Gero, J.S. (1990), “Design prototypes: A knowledge representation schema for design”, AI Magazine, Vol. 11 No. 4, pp. 26–36.

Gordon, I., Gilboa, A., Cohen, S., Milstein, N., Haimovich, N., Pinhasi, S. and Siegman, S. (2020), “Physiological and behavioral synchrony predict group cohesion and performance”, Scientific Reports, Vol. 10 No. 1, p. 8484.

Guastello, S.J., Bednarczyk, C., Hagan, R., Johnson, C., Marscisek, L., McGuigan, L. and Peressini, A.F. (2022), “Team situation awareness, cohesion, and autonomic synchrony”, Human Factors: The Journal of the Human Factors and Ergonomics Society, p. 001872082211183.

Guastello, S.J., Palmer, C., Marra, D.E. and Peressini, A.F. (2020), “The effect of cooperation and competition dynamics on autonomic synchrony in teams”, Selbstorganisation – Ein Paradigma Für Die Humanwissenschaften, Springer Fachmedien Wiesbaden, Wiesbaden, pp. 317–332.

Hay, L., Duffy, A.H.B., Gilbert, S.J., Lyall, L., Campbell, G., Coyle, D. and Grealy, M.A. (2019), “The neural correlates of ideation in product design engineering practitioners”, Design Science, Vol. 5, p. e29.

Holroyd, C.B. (2022), “Interbrain synchrony: on wavy ground”, Trends in Neurosciences, Vol. 45 No. 5, pp. 346–357.

Hu, Y., Pan, Y., Shi, X., Cai, Q., Li, X. and Cheng, X. (2018), “Inter-brain synchrony and cooperation context in interactive decision making”, Biological Psychology, Vol. 133, pp. 54–62.

Kaplan, S., Brooks-Shesler, L., King, E.B. and Zaccaro, S. (2009), “Thinking inside the box: How conformity promotes creativity and innovation”, pp. 229–265.

Leroy, S., Shipp, A.J., Blount, S. and Licht, J.-G. (2015), “Synchrony preference: Why some people go with the flow, and some don’t”, Personnel Psychology, Vol. 68 No. 4, pp. 759–809.

Liang, Z., Li, S., Zhou, S., Chen, S., Li, Y., Chen, Y., Zhao, Q., et al. (2022), “Increased or decreased? Interpersonal neural synchronization in group creation”, NeuroImage, Vol. 260, p. 119448.

Liu, T., Duan, L., Dai, R., Pelowski, M. and Zhu, C. (2021), “Team-work, team-brain: Exploring synchrony and team interdependence in a nine-person drumming task via multiparticipant hyperscanning and inter-brain network topology with fNIRS”, NeuroImage, Vol. 237, p. 118147.

Mayseless, N., Hawthorne, G. and Reiss, A. (2020), “The neuroscience of team collaboration during a design thinking event in naturalistic settings”, Design Thinking Research . Understanding Innovation., Springer, Cham, pp. 143–154.

Mayseless, N., Hawthorne, G. and Reiss, A.L. (2019), “Real-life creative problem solving in teams: fNIRS based hyperscanning study”, NeuroImage, Vol. 203, p. 116161.

Mogan Naidu, R. (2018), Aligning Bodies and Minds: New Insights about Synchrony’s Effects on Creative Thinking, Cohesion and Positive Affect, Victoria University of Wellington.

Neumann, A., Badke-Schaub, P. and Lauche, K. (2008), “Team cohesion and process aspects of teamwork in design”, Proceedings DESIGN 2008, the 10th International Design Conference, Dubrovnik, Croatia, pp. 1105–1112.

Palumbo, R. V., Marraccini, M.E., Weyandt, L.L., Wilder-Smith, O., McGee, H.A., Liu, S. and Goodwin, M.S. (2017), “Interpersonal autonomic physiology: A systematic review of the literature”, Personality and Social Psychology Review, Vol. 21 No. 2, pp. 99–141.

Perišić, M.M. (2020), Multi-Agent System for Simulation of Team Behaviour in Product Development, Dissertation, University of Zagreb.

Perisic, M.M., Martinec, T., Storga, M. and Gero, J.S. (2019), “A Computational Study of the Effect of Experience on Problem/Solution Space Exploration in Teams”, Proceedings of the Design Society: International Conference on Engineering Design, Vol. 1 No. 1, pp. 11–20.

Perisic, M.M., Štorga, M. and Gero, J.S. (2021), “Computational study on design space expansion during teamwork”, Proceedings of the Design Society, Vol. 1, pp. 691–700.

Perišić, M.M., Štorga, M. and Gero, J.S. (2019), “Exploring the Effect of Experience on Team Behavior: A Computational Approach”, Design Computing and Cognition ’18, Springer International Publishing, Cham, pp. 595–612.

Ravignani, A. (2017), “Agree on definitions of synchrony”, Nature, Vol. 545 No. 7653, pp. 158–158.

Reinero, D.A., Dikker, S. and Van Bavel, J.J. (2021), “Inter-brain synchrony in teams predicts collective performance”, Social Cognitive and Affective Neuroscience, Vol. 16 No. 1–2, pp. 43–57.

Rodríguez-Sánchez, A.M., Devloo, T., Rico, R., Salanova, M. and Anseel, F. (2017), “What makes creative teams tick? Cohesion, engagement, and performance across creativity tasks: A three-wave study”, Group & Organization Management, Vol. 42 No. 4, pp. 521–547.

Schirmer, A., Fairhurst, M. and Hoehl, S. (2021), “Being ‘in sync’—is interactional synchrony the key to understanding the social brain?”, Social Cognitive and Affective Neuroscience, Vol. 16 No. 1–2, pp. 1–4.

Shahal, S., Wurzberg, A., Sibony, I., Duadi, H., Shniderman, E., Weymouth, D., Davidson, N., et al. (2020), “Synchronization of complex human networks”, Nature Communications, Vol. 11 No. 1, p. 3854.

Sosa, R. and Gero, J.S. (2004), “A computational framework for the study of creativity and innovation in design: Effects of social ties”, Design Computing and Cognition ’04, Springer Netherlands, Dordrecht, pp. 499–517.

Stempfle, J. and Badke-Schaub, P. (2002), “Thinking in design teams - an analysis of team communication”, Design Studies, Vol. 23 No. 5, pp. 473–496.

Strogatz, S.H. (2003), Sync: The Emerging Science of Spontaneous Order, Hyperion, New York, New York, USA.

Strogatz, S.H., Abrams, D.M., McRobie, A., Eckhardt, B. and Ott, E. (2005), “Crowd synchrony on the Millennium Bridge”, Nature, Vol. 438 No. 7064, pp. 43–44.

Thomson, M., Murphy, K. and Lukeman, R. (2018), “Groups clapping in unison undergo size-dependent error-induced frequency increase”, Scientific Reports, Vol. 8 No. 1, p. 808.

Verdiere, K.J., Albert, M., Dehais, F. and Roy, R.N. (2020), “Physiological synchrony revealed by delayed coincidence count: Application to a cooperative complex environment”, IEEE Transactions on Human-Machine Systems, Vol. 50 No. 5, pp. 395–404.

Wang, X., Zhang, Y., He, Y., Lu, K. and Hao, N. (2022), “Dynamic inter-brain networks correspond with specific communication behaviors: Using functional near-infrared spectroscopy hyperscanning during creative and non-creative communication”, Frontiers in Human Neuroscience, Vol. 16, available at:https://doi.org/10.3389/fnhum.2022.907332.

Wiltermuth, S.S. and Heath, C. (2009), “Synchrony and cooperation”, Psychological Science, Vol. 20 No. 1, pp. 1–5.

Won, A.S., Bailenson, J.N., Stathatos, S.C. and Dai, W. (2014), “Automatically detected nonverbal behavior predicts creativity in collaborating dyads”, Journal of Nonverbal Behavior, Vol. 38 No. 3, pp. 389–408.

Zhang, M., Jia, H., Zheng, M. and Liu, T. (2021), “Group decision-making behavior in social dilemmas: Inter-brain synchrony and the predictive role of personality traits”, Personality and Individual Differences, Vol. 168, p. 110315.