Title
Which pairs coordinate and which do not?

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Which pairs coordinate and which do not?

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Abstract

Humans can coordinate their behavior with others through interactions; however, not all pairs can coordinate. From the perspective of predictive processing, different social interaction patterns can be explained by the diversity of individuals' belief strength. To investigate the relationship between coordination and belief strength, we conducted an interaction experiment using a Simon electronic light-sequence game in which participants memorize the order of color sequences. The results of our experiment, involving 23 pairs of participants, revealed diversity in the degree of coordination within pairs and the strength of belief between individuals. Our analysis supports the hypothesis that belief strength explains the success or failure of coordination: Coordination fails when both individuals in a pair have weak beliefs, whereas it succeeds when one person becomes the leader and the other becomes the follower because of the different strengths of their beliefs. Our findings suggest that predictive processing theory can be applied to situations involving social interactions.

Keywords: interpersonal coordination; prediction; interaction; dyadic imitation

Introduction

Humans exhibit various levels of interpersonal coordination with others' actions and mental states such as conformity, synchronization, and emotional empathy. Experimental psychological studies have conducted various interaction experiments (e.g., a joint finger-tapping task) to demonstrate that people achieve interpersonal coordination by predicting the actions of others (Konvalinka et al., 2010). However, not everyone coordinates well with everyone else. Some pairs have good chemistry; others do not. For example, children with autism often struggle to synchronize their behavior with that of others (Zampella et al., 2020) and are less likely to imitate others' behavior (Rogers et al., 2003).

The possibility that predictive processing theory can explain various interaction patterns has attracted attention. Predictive processing theory, which has become increasingly influential in cognitive neuroscience, considers the brain a machine that constantly makes and updates predictions (Friston, 2010). Computational studies based on the predictive processing theory have demonstrated that if both individuals share similar generative models, their posterior predictions tend to align through interactions, leading to synchronization (Friston & Frith, 2015). Furthermore, cognitive developmental diversity can be attributed to variations in individual belief strength, also known as prior predictions (cf. Nagai, 2019). According to the theory, people are supposed to have a belief (also called prior) about the environment. If the observed data from the environment are considerably different from the belief (i.e., a large prediction error), they update their belief (the updated belief is also called the posterior) to minimize the prediction error. The degree to which beliefs are updated is moderated by a parameter called belief strength (also called the precision of prior). When beliefs are strong, they are stable because people can ignore observations. When the beliefs are weak, people change their beliefs more frequently because they adjust immediately to the observed data. Autistic people often exhibit excessively strong or weak beliefs (Philippsen & Nagai, 2020, 2022). Even if two individuals share similar generative models, they may differ in their belief strengths. Neural network studies involving two robots imitating each other's actions have indicated that high synchronization rates are possible when one robot has strong beliefs (the leader) and the other has weak beliefs (the follower); however, this is less likely to occur with other pairs (Wirkuttis & Tani, 2021). When both robots have strong beliefs, they maintain the behavior generated by their beliefs, resulting in no synchronization. In contrast, two robots with weaker beliefs neither achieve a high synchronization nor sustain behavior.

We formulated the following hypothesis based on the theory of predictive processing: (i) When both individuals have beliefs that are too strong or weak, they cannot coordinate their behaviors with each other. (ii) When one individual has a stronger belief and another has a weaker belief, they can coordinate well. To test this hypothesis in human subjects, we conducted an interaction experiment using a sequence learning task called the Simon game (Mathy et al., 2016; Mathy & Friedman, 2020). We investigated whether interpersonal coordination occurs in certain pairs but not in others by repeatedly exchanging stimulus sequences. Compared with previous coordination tasks used in psychological experiments, such as a joint finger-tapping task (Konvalinka et al., 2010), a greater variety of outputs can be observed in the experimental tasks of this study. This feature allowed us to analyze the diversity of the interactions between participants. We focused on the unintentional interaction between participants to align the experimental setting with the situation of computational studies (Wirkuttis & Tani, 2021), where two agents learn actions from their partners and generate actions that are not intended to be coordinated with each other.

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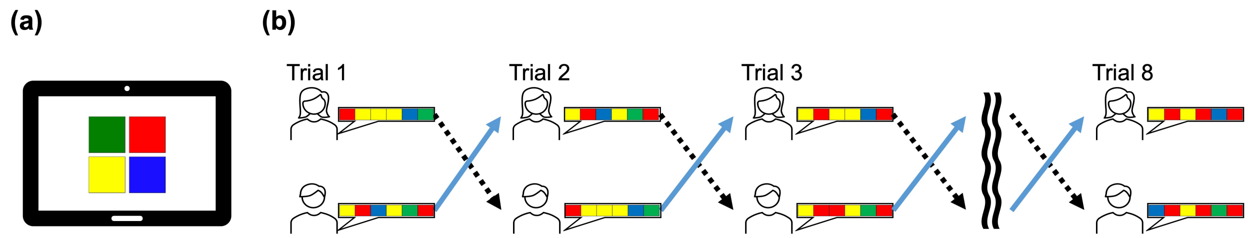

Figure 1. (a) Tablet screen of the Simon game task. Four colored panels flash sequentially. (b) Interaction design. Two participants are paired and shown random color sequences as seeds. After being shown the sequence, they try to reproduce it and their reproduced sequences are transmitted to the other participant. Participants work on 15 blocks of interactions, with eight trials as one interaction block.

Methods

Participants

We recruited 46 participants (mean age = 26.9 years, SD = 6.7, range=19–49 years, 17 women and 29 men). Two participants worked on the task simultaneously in the laboratory; the desk where the two participants worked was separated by a partition so that they could not see each other during the experiment. Participants were paid 1500 JPY for the 80 min experiment.

Task

The participants engaged in a Simon game task using tablets (Figure 1a). They were presented with four colored panels flashing in a sequence and instructed to remember the order of the colors. The length of the color sequences was set to 13 to observe the phenomenon in which the participants could not remember the sequence accurately and the color sequences changed gradually. Several previous studies have used a length of 12 (Cornish et al., 2013; Nakata & Takezawa, 2023), but in our experimental design, the same participant repeatedly learns a single-seed sequence that changes gradually (described later), so the accuracy of reproduction may be too high. To avoid this, we increased the length of the sequences slightly to 13. Following the display, participants tapped colored panels to reproduce the order of the sequence. After 13 taps, the reproduction accuracy was provided (see below for details). The experiment was conducted using oTree (Chen et al., 2016).

Procedure

Two participants were paired together (making 23 pairs), and there were 15 blocks of eight-trial interactions (i.e., 120 trials in total). In Trial 1, the participants were presented with a randomly ordered seed sequence. In Trials 2–8, they were presented with the sequences reproduced by the paired participant. In other words, in Trial 2, the color sequence reproduced by the paired participant in Trial 1 was presented, and in Trial 3 the color sequence reproduced by the paired participant in Trial 2 was presented (Figure 1b). To examine the emergent process of interpersonal coordination in which people unintentionally influence each other, participants were not informed about the interaction design. Participants believed that the task could be performed independently. This procedure corresponds to a computational study in which behavioral alignment was not the goal of the agents, but they aimed solely to learn the given stimulus. This study was approved by the Ethics Committee of the University of Tokyo.

Analysis

First, we assessed the reproduction accuracy to ensure the participants' involvement in and understanding of the task. Seed sequences should change within an interaction block because participants' memories are not perfect. If their errors were random, the reproduction accuracy would be constant. However, previous studies have shown that reproduction errors are biased, and biased errors make sequences easier for participants to remember (Cornish et al., 2013; Nakata & Takezawa, 2023). To measure the accuracy of the participants' reproductions, we introduced the Levenshtein distance (Levenshtein, 1966). The Levenshtein distance is defined as the minimum number of operations (insertion, deletion, and substitution of a character) required to convert one string into another. The three operations are treated equally and have no different effect on the operation order (Figure 2). In our analysis, the Levenshtein distance was divided by the length of the sequence to be standardized, and the similarity between the sequences was calculated using [1 - the standardized distance]. The similarity between the presented and reproduced sequences was fed back to the participants as the reproduction accuracy for each trial. The similarity between the strings x and y is denoted by sim(x, y).

Second, we examined the relationship between participants' belief strength and their interpersonal coordination by analyzing pair similarity. The similarity between the sequences reproduced by a pair of participants in the t-th trial in the i-th interaction block ($\mathrm{sim}(a_{i,t}, b_{i,t})$) was measured as the pair similarity. An increase in this value through an interaction block indicates that the two sequences generated from different seeds become similar as the pair coordinates them.

Third, to measure the extent to which individuals rely on their beliefs, we calculated the similarity among the

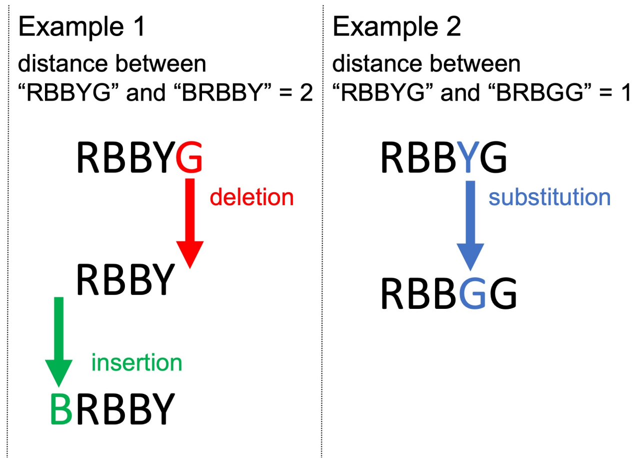

Figure 2. Examples of Levenshtein distance calculations. Example 1: Changing "RBBYG" to "BRBBY" requires one deletion and one insertion, then the distance is two. Example 2: Changing "RBBYG" to "RBBGG" requires only one substitution, then the distance is one.

sequences reproduced by each participant. If a participant has a very strong belief, the participant should ignore the observed order and generate consistent patterns of color order in all trials. The consistency was calculated in two ways. The first measure used only the sequence of the first trial in each interaction block. As we had 15 blocks, the consistency (1) was defined by: $\sum_{i=2}^{15}\sum_{j=1}^{i-1} sim\left(a_{i,1}, a_{j,1}\right)/15$. This value indicates the strength of the beliefs that an individual had prior to participating in the experiment. The second measure assumed that individuals formed their beliefs during the experiment, influenced by the sequences displayed in previous trials. We calculated the consistency (past) by averaging the similarity between the sequences displayed in a given trial and those displayed earlier. In other words, if a' represents the sequence displayed at the *t*-th trial in the *i*-th interaction block, the consistency (past) is defined by: $\sum_{i=1}^{15}\sum_{j=1}^{i}\sum_{t=1}^{8}\sum_{u=1}^{t} sim(a_{i,t}, a'_{j,u})/7260$. This value increases when a participant reproduces a consistent pattern influenced by previously observed sequences. We analyzed the data using Python 3.11 and R 4.3.1.

Results

Accuracy

To determine the extent to which the participants varied the sequences, we examined the accuracy of reproduction in each trial. Figure 3 shows that the mean accuracy of each individual (colored lines) and the overall mean (black line) gradually increased between trials. We constructed a linear mixed model (LMM), in which the independent variable was accuracy, the dependent variable was trial, and the random intercept was pair ID. On the basis of this analysis, the effect of trial was significant ($\beta = 0.06, SD = 0.00, t = 56.94, p = 0.00$). However, when we entered the interaction block (categorical variables) as the dependent variable into

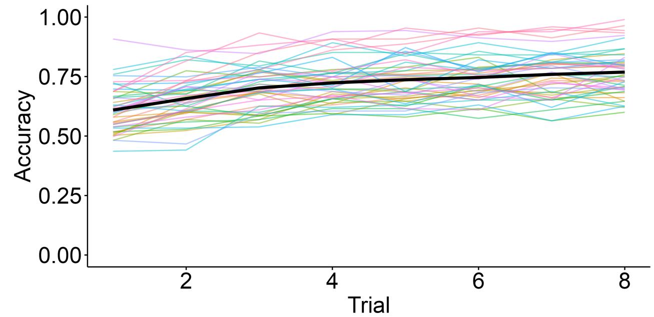

Figure 3. Change in accuracy within an interaction block. Colored lines show the mean accuracy of each individual on each trial. A black line shows the mean accuracy of all pairs on each trial.

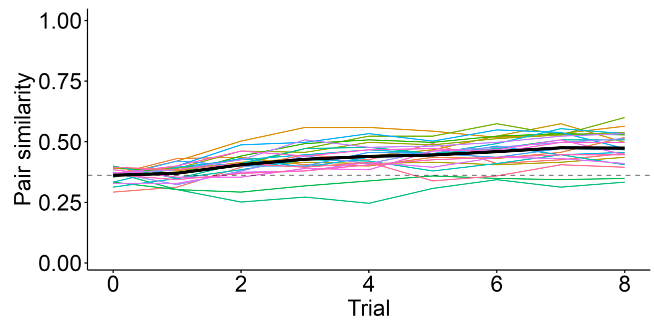

Figure 4. Change in pair similarity within an interaction block. Colored lines show the mean pair similarity in each trial. A black solid line shows the mean accuracy of all pairs in each trial. A black dashed line is the reference line, which is the mean similarity between randomly ordered sequences.

the LMM, with the other fixed and random variables being the same as in the previous analysis, the effect of the interaction block was not significant ($\beta = 0.00, SD = 0.00, t = -1.75, p = 0.08$). This indicates that the participants' memories did not improve during the experiment, nor did their accuracy increase as they became more familiar with the task. Thus, these results suggest that the participants gradually changed their sequences to make them easier to learn.

Pair similarity

We examined whether the sequences reproduced within a pair became increasingly similar through their interactions. Figure 4 shows the mean pair similarity for each of the 23 pairs (colored lines) and the overall mean (a solid black line) across the trials. The black dashed line represents the reference line, which is the mean similarity between randomly ordered sequences. Most pairs showed an increase in similarity across the trials. We constructed an LMM in which the independent variable was pair similarity, the dependent variable was trial, and the random intercept was pair ID. On the basis of this analysis, the effect of trial was significant ($\beta = 0.01, SD = 0.00, t = 15.09, p = 0.00$). However, Pairs 8 and 9 showed no coordination even after eight interaction trials (two green lines below the dashed line in Figure 4). A large variance of pair similarity in the last trial was observed: The minimum value of pair similarity in the last trial was 0.33 (Pair 9), and the maximum value was 0.60 (Pair 6). We found a difference in the similarity between the pairs in the last trial ($F\ (22, 322) = 2.36, p = 0.00$).

Relationship between consistency and pair similarity

To examine the effect of individual belief strength on coordination, we analyzed the consistency of individual outputs. Figure 5 shows the relationship between pair similarity and consistency (1) calculated using only the sequence data from the first trial for each interaction. Each dot represents one pair. Consistency (1) shows the variance between and within pairs. Overall, pair similarity was lower when both individuals in a pair had lower consistency. We constructed a linear regression model in which the independent variable was pair similarity, and the dependent variable was the within-pair sum of consistency (1). We found a significant effect of the within-pair sum of consistency (1) on pair similarity ($\beta = 0.84, SD = 0.22, t = 3.78, p = 0.00$).

Figure 6 shows the pair similarity and consistency (past) calculated using the similarity to the previously presented sequence data. In this analysis, consistency (past) between pairs had high variance, but low variance within pairs. The tendency of pair similarity to be lower when the consistency of both individuals was lower was also replicated. We constructed a linear regression model in which the independent variable was pair similarity, and the dependent variable was the within-pair sum of consistency (1). We found a significant effect of the within-pair sum of consistency (1) on pair similarity ($\beta = 0.77, SD = 0.14, t = 5.29, p = 0.00$). When both participants in the pairs produced inconsistent sequences, coordination was unlikely to occur. Note that the current data do not include the case where both beliefs are strong: the largest value of consistency in the current data is about 0.5 (the maximum value is 1.0). That is, our analysis does not show that coordination was likely to occur if both participants in the pairs produced consistent sequences.

Qualitative analysis of pairs with the highest and lowest pair similarity

To further explore the relationship between consistency and pair similarity, we examined the actual sample data for each interaction block: Pair 6, which had the highest mean pair similarity in the last trial, and Pair 9, which had the lowest. First, we examined Pair 6 (Figure 7). We observed a typical pattern of low accuracy at the beginning of the trial and large changes in the reproduced sequences. In subsequent trials, accuracy increased, the change in sequence became smaller, and the participants seemed to remember the two sequence patterns accurately. However, in the sixth trial, one participant (the right column: Individual 1) changed the sequence significantly and reproduced the same pattern as the

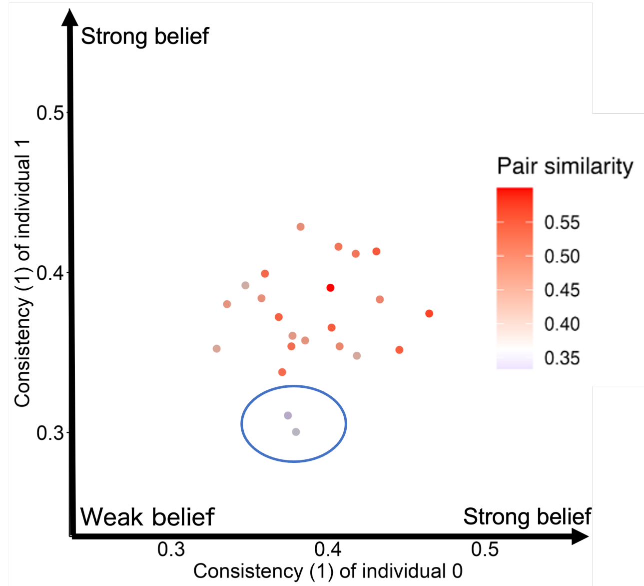

Figure 5. Relationship between consistency (1) and pair similarity. Each dot indicates the pair similarity of each pair and individual consistency. Consistency (1) is calculated using only the sequence data from the first trial in each interaction.

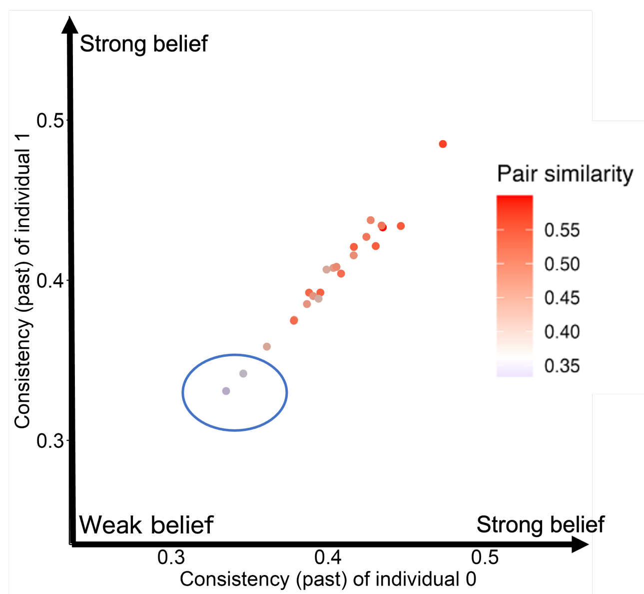

Figure 6. Relationship between consistency (past) and pair similarity. Each dot indicates the pair similarity of each pair and individual consistency. Consistency (past) is calculated using the similarity to previously presented sequence data.

sequence in the previous trial: The first seven items (“ggyybbr”) are identical. Owing to the partner (the left column: Individual 0) following the change, the sequences reproduced by the two participants in Trials 6–8 were very similar, that is, they achieved high pair similarity.

Next, we focused on Pair 9 (Figure 8). Both participants in Pair 9 changed their sequences dramatically in the first trial, strongly favoring the repeated color pattern. These participants likely gave up trying to remember, but the patterns that emerged when they were not engaged can be a clear indication of their prior tendency; therefore, we needed to look at these data more closely. Although the repeated patterns occupied a large part of the sequence and appeared to be very easy to remember, the participants' accuracy was not always perfect, and the sequence was often changed. Overall, pair similarity in the final trial was low because the two sequences with different repetition patterns (repeated blue and red) were maintained within the interaction block. An interesting feature of this pair of interactions is the change observed in the sequences with many blue repetitions in Trials 5–8. When we looked at the four parts at the head of these sequences, Individual 0 was trying to maintain the blue-blue-red-red pattern and Individual 1 was maintaining the blue-blue-red-blue pattern. There seemed to be a tendency to always return to the preferred pattern even when the partner changed the sequence. Based on the current analysis, although both individuals showed a lower consistency than the other pairs (consistency (1): [Individual 0: Individual 1] = [0.37, 0.31]; consistency (past): [Individual 0: Individual 1] = [0.33, 0.33]), these participants may have strong beliefs in certain structural patterns.

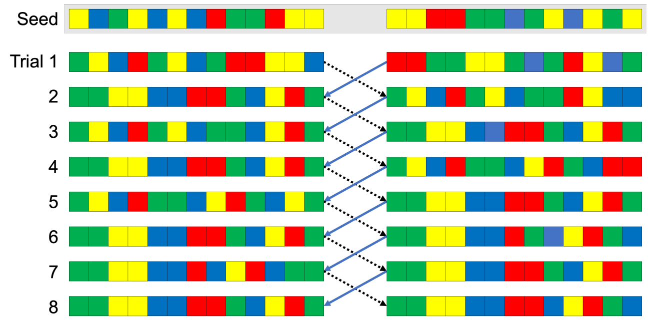

Figure 7. Sequences from an interaction of Pair 6 (with the highest pair similarity on average) in the third interaction block. The left column shows the seed sequence shown to Individual 0 and the sequence reproduced by them. The right column shows corresponding data from Individual 1.

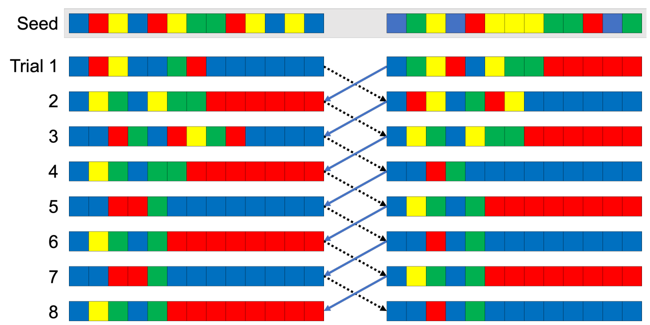

Figure 8. Sequences from an interaction of Pair 9 (with the lowest pair similarity on average) in the fourth interaction block. The left column shows the seed sequence shown to Individual 0 and the sequence reproduced by them. The right column shows corresponding data from Individual 1.

Discussion

In this study, we investigated the relationship between coordination and belief strength in human interaction experiments from the perspective of predictive processing. Computational studies on dyadic imitation suggest that the success or failure of interpersonal coordination depends on the combination of belief strengths held by the two individuals. We designed an experiment in which stimuli were learned and exchanged by applying the Simon game task to an unintended interaction experiment, to investigate whether a similar phenomenon in computational research is observed in humans.

Accuracy increased gradually in the interaction block, which is consistent with previous studies showing that participants unconsciously modified the sequences to make them easier to remember (Cornish et al., 2013; Nakata & Takezawa, 2023). In addition, most participant pairs showed gradual coordination through interactions, as many psychological experiments have demonstrated. The finding that interpersonal coordination occurs through learning by exchanging stimuli, rather than with the intention of coordinating with each other, is consistent with the results of computational and robotic studies (Mostafaoui et al., 2022). However, the degree of coordination varied between pairs, with some pairs showing little coordination, even after eight interaction trials. We examined the consistency of the sequences reproduced by the participants to measure the strength of their individual beliefs. The results of the analysis suggested that pairs with little coordination both had weak beliefs. This finding is consistent with the results of a robotics study that directly controlled for the belief strength of neural networks (e.g., Wirkuttis & Tani, 2021).

We took a closer look at each interaction block within the high- and low-coordination pairs. In a high-coordination pair, we found that high pair similarity could be achieved by having one participant merge two sequence patterns into one similar pattern and having the other participant follow it. In a low-coordination pair, we found that they could not achieve high pair similarity by maintaining two different sequences and their preferred ordering patterns. Individuals in the pair showed high consistency in the two types of analyses, which is consistent with the hypothesis of predictive processing.

Limitations and future directions

While computational studies can directly manipulate the strength of agents' beliefs, experimental psychological studies in humans need to attempt to measure the strength of individual beliefs. We analyzed the consistency of participants' reproductions, which reflected the degree to which their posterior beliefs remained unchanged in the Bayesian model, in two ways to measure individual belief strength. First, we calculated the consistency (1) using only the sequence data from the first trial in each interaction block.

This focuses on the beliefs about the order of the color sequences that the participants had before participating in the experiment. It does not consider the effect of 120 trials on the participants' beliefs, although it has the advantage of being able to exclude the effect of seed sequences and modifications by the other participant. For example, when we calculated the consistency with all sequences, the reproduced sequences from Trials 1 and 3 were likely to be similar because they came from the same seed sequence. Second, we calculated the consistency using the similarity to previously presented sequence data. This considers that the participants' beliefs were formed in the experiment, although it does not exclude the effect of seed sequences and modifications by the other participant. For example, when the sequences reproduced from Trials 7 and 8 were similar, we could not judge whether the individual made consistent patterns or the partner individual did, and these sequences were accurately reproduced. The problem with the influence of the other participant is reflected in the fact that the consistency of the two participants in a pair was strongly correlated (Figure 6). As can be seen in Figures 7 and 8, later in the interaction block, the order pattern of the sequences was fairly well shared within the pair, so that the consistency measures of the two individuals in the pair were correlated. To accurately estimate the strength of an individual's beliefs, it is necessary to pursue more valid methods. For instance, consistency based on the structural level similarity is needed rather than Levenshtein distance because the least coordination pair may have strong beliefs in the structural pattern (e.g., repetition is also considered as structure). In this case, our data suggest that a pair is unlikely to coordinate when both individuals have strong beliefs. It is also supporting our hypothesis derived from the predictive processing theory.

It is necessary to consider whether the participants' interactions were leader-follower or of other types (Takamizawa & Kawasaki, 2019). We analyzed the degree of coordination by analyzing pair similarity. Although we discussed the possibility that leader-follower interactions could produce coordination, this was only a qualitative analysis. It is possible that some pairs with high similarity had moderate belief strength and averaged their beliefs through interactions, resulting in coordination. To test the hypothesis of interpersonal coordination based on predictive processing, it is necessary to analyze the extent to which pairs of interactions are of the leader-follower type. Once this is possible, we can systematically investigate questions such as how large a gap in belief strength causes leader-follower emergence, and how strong or weak is the belief that interpersonal coordination will fail.

Although we studied people based on the assumption that there would be diversity in the strength of their beliefs, it was unclear whether the included participants were sufficiently diverse. Computational studies suggest that interpersonal coordination does not occur even when both beliefs are weak, but we did not find such pairs in our experiments. Only adult participants were recruited for this study; however, this hypothesis must be tested using a more diverse group of participants. For example, children have different belief strengths for grammatical rules than adults (Hudson Kam & Newport, 2005). In addition, individuals with autism spectrum disorder may have different belief strengths than typically developing individuals (Philippsen et al., 2022).

Conclusion

In summary, we found that how interaction varied between pairs of individuals could be explained by the different combinations of belief strengths. Our research demonstrates the potential contribution of predictive processing theory not only to individual cognition but also to social interaction.

Acknowledgements

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