Social constraints from an observer's perspective: Coordinated actions make an agent's position more predictable

CrossMark

Jun Yin [a,b], Haokui Xu [a], Xiaowei Ding [a], Junying Liang [c], Rende Shui [a], Mowei Shen [a,*]

[a] Department of Psychology and Behavioral Sciences, Zhejiang University, Hangzhou, PR China
[b] Department of Psychology, Ningbo University, Ningbo, PR China
[c] School of International Studies, Zhejiang University, Hangzhou, PR China

ABSTRACT

Action prediction, a crucial ability to support social activities, is sensitive to the individual goals of expected actions. This article reports a novel finding that the predictions of observed actions for a temporarily invisible agent are influenced, and even enhanced, when this agent has a joint/collective goal to implement coordinated actions with others (i.e., with coordination information). Specifically, we manipulated the coordination information by presenting two chasers and one common target to perform coordinated or individual chases, and subjects were required to predict the expected action (i.e., position) for one chaser after it became momentarily invisible. To control for possible low-level physical properties, we also established some intense paired controls for each type of chase, such as backward replay (Experiment 1), making the chasing target invisible (Experiment 2) and a direct manipulation of the goal-directedness of one chaser's movements to disrupt coordination information (Experiment 3). The results show that the prediction error for invisible chasers depends on whether the second chaser is coordinated with the first, and this effect vanishes when the chasers behaves with exactly the same motions, but without coordination information between them; furthermore, this influence results in enhancing the performance of action prediction. These findings extend the influential factors of action prediction to the level of observed coordination information, implying that the functional characteristic of mutual constraints of coordinated actions can be utilized by vision.

© 2016 Elsevier B.V. All rights reserved.

1. Introduction

The ability to predict and anticipate the actions of others is crucial for planning appropriate behaviors before engaging or intervening in observed actions (Csibra & Gergely, 2007; Hauser & Wood, 2010). Evidently, people are able to generate predictions even with limited information about agents' actions (Csibra, Bíró, Koós, & Gergely, 2003; Saunier et al., 2013). This sophisticated ability is thought to be sensitive to an individual's goals (or just the associative contingency between actions and outcomes) (Gergely & Csibra, 2003; Verschoor, Spapé, Biro, & Hommel, 2013). However, people's actions are not always framed as pursuing their own individual goals. Instead, they are often embedded in coordinated interactions to achieve a collective/shared goal, which are referred to coordinated or joint actions (Knoblich & Sebanz, 2008; Sebanz, Bekkering, & Knoblich, 2006). Less is known about whether this interpersonal coordination information, beyond individual goals, could influence action prediction.

Recently, some researchers have started to explore how the information conveyed by coordinated actions affects action processing/understanding. Observing coordinated interactions has been consistently found to have a tangible benefit for extracting information from actions or at least in detecting the actors. For instance, Neri et al. (2006) found the visual discrimination of a human agent is influenced by the second agent when their actions involving physical contact could be interpreted as meaningful coordination (i.e., fighting or dancing); Manera et al. (2011) confirmed this conclusion, showing that communicative gestures, even without contact, can increase the likelihood of perceiving a second agent. The above efforts notwithstanding, no direct evidence has illustrated the role of observed coordinated interaction in action prediction.

Interpersonal coordination is not only a mere summation of individual actions, but most importantly, it is also more than the individual elements, as its behaviors are interdependent and may sometimes be mutually complementary (Sebanz et al., 2006).

* Corresponding author at: Department of Psychology and Behavioral Sciences, Xixi Campus, Zhejiang University, Hangzhou 310028, PR China.
E-mail address: mwshen@zju.edu.cn (M. Shen).

Moreover, coordinated actions are thought to be constrained by each other within a coordinative structure (Shockley, Richardson, & Dale, 2009). For instance, Shockley, Santana, and Fowler (2003) found that mutual interpersonal postural constraints (i.e., sharing more locations in phase space) are involved during conversation in a coordinated manner. Although it is still under debate whether the emergence of this social constraint is supported by acting together with shared representation across persons or is due to spontaneous organization (Sebanz et al., 2006; Shockley et al., 2009), in any case, such a structured constraint ensures that the adjustment of one's actions could result in predictively aligned changes of other people' actions when the people interact in a coordinated fashion. Therefore, from the observer's perspective, the actions of one agent could serve as efficient predictors for the actions of other agents in a coordinated interaction. Thus, when observing a coordinated interaction, even when an agent temporarily disappears, the vision could use the characteristic of mutual constraints in coordinated actions to reduce possible hypothesis spaces when inferring or predicting the actions of the invisible agent. In this case, an observer should generate much better predictions for the temporarily invisible actions that are involved in interpersonal coordination, in comparison with those that are not involved in interpersonal coordination. Namely, the observed coordination information should influence, and even enhance, the predictive accuracy for the expected actions.

To test our hypothesis, the manipulation of the coordination information used two types of dynamic chase scenes, in which two agents acted as chasers running in a coordinated or individual manner, toward a common prey.[1] The different chase scenes were modelled after displays used by Heider and Simmel (1944) that presented geometric figures only in a chasing motion. One of the advantages of this method is that motion is the only action information that contributes to the understanding of semantic social meaning; thus, if we are interested in social information (e.g., chasing relation, coordination information), only the physical features of motion need to be controlled. Previous research has extensively used this type of chasing motion, but with only one chaser, to explore the perception of animacy, intention, and interaction (Dittrich & Lea, 1994; Gao, Newman, & Scholl, 2009). All of these studies documented that the motion sequences should not simply be treated as physical movement; they should be thought of meaningful actions with goals, which influences our other processes accordingly, such as visual searches and interactive behaviors (Gao, McCarthy, & Scholl, 2010; Meyerhoff, Schwan, & Huff, 2014). Usually, the chasing motion with one chaser and one target was generated with specific steering rules by referring to AI algorithms. With two chasers and one target of multi-agent chasing, the principles of movement have not been determined (Rawal, Rajagopalan, & Miikkulainen, 2010). Thus, it is better to rely on man-made trajectories than to use AI algorithms to describe multi-agent chasing. Indeed, our previous research successfully used the recorded motion of real people as they controlled their own avatars (chasers) in a coordinated or individual chase toward the same target (Yin et al., 2013). As well, the current research has adopted methods of using recordings of human motion to display coordinated and individual chases.

To examine the role of coordination information on action prediction, the recorded motions from both coordinated and individual chases were shown in a forward sequence to subjects who were required to predict the expected position (i.e., action) for

one chaser after it became momentarily invisible. To further isolate the effect of socially coordinated information from possible low-level physical properties, we also established some intense paired controls for each type of chase, such as backward replay (Experiment 1), making the chasing target invisible (Experiment 2), and a direct manipulation of the goal-directedness of one chaser's movements to disrupt coordination information (Experiment 3). If coordination information enhanced the prediction of actions, we should observe fewer prediction errors in coordinated chases compared with the controls, but not in individual chases.

2. Experiment 1a

Both the coordinated and individual chases were presented by forward replaying of recorded trajectories and were compared with their own controls, which consisted of backward replays of the same trajectories. In such settings, the physical features were the same in the two types of replay sequences, whereas in the backward replay, the chasers' intended actions became inverted and ambiguous, disturbing the processing of social meaning behind them (though it never disappeared completely). Accordingly, the distinction between the forward and backward trajectories was comprehensible to an observer who understood the interpersonal coordination between chasers. Therefore, the differences in action predictions between the forward- and backward-replayed stimuli should be attributed to the experienced social interaction between the two chasers.

2.1. Method

2.1.1. Participants

Fourteen naïve Zhejiang University students (7 males and 7 females; mean age: 21 years; range: 18–26 years) participated in the experiment for a financial reward. All of them had normal or corrected-to-normal vision. All participants provided written and informed consent before participating in the experiments and the procedures were approved by the Research Ethics Board of Zhejiang University and the granting agency.

2.1.2. Stimulus design

The movement trajectories were recorded according to the following steps. Three participants as a group were asked to finish a chasing game and sit without head restraint approximately 60 cm from a monitor (the measurements were computed based on this viewing distance; 28 pixels = 1° or 1 cm). In total, five groups were included (6 males and 9 females; age range: 18–26 years). Each of them in a group controlled an agent with a mouse on the screen: one played the role of prey by controlling a red square (1° × 1°), and the other two played the role of chasers by controlling green and blue disks of 1° diameter. The two chasers were required to chase the common prey, either in a coordinated manner (i.e., cooperatively) or individually (i.e., capturing the target on his or her own), and the prey tried to avoid being caught. If any chaser reached the prey, the trial ended. To prevent the prey from being caught at the beginning, the initial distances between each pair of agents were greater than 5°. Participants could move the agents less than 0.5°/frame and the controlled agents could not pass each other according to the algorithm that each agent cannot occupy the same space of the remaining agents on the screen; they controlled only their own agents within a common zone bounded by a visible gray square (25° × 25°), whereas the monitor subtended 36.6° × 27.6°. This chasing game was executed on PC monitors (resolution: 1024 × 768; refresh rate: 60 Hz) using custom software written in MATLAB with the Psychophysics Toolbox libraries (Brainard, 1997). Each group member manipulated a PC

---

[1] When more than one chaser is running, it is nearly impossible for an individual to be completely alone in a chase pursuing the same target. For instance, one agent occupies the possible positions of others, and to some extent, exhibits competitive chasing, which was observed in our study. Here, individual chasing means that the agents behave without coordination, or at least with less coordination, than found in coordinated chasing.

and saw the same online chasing motions on the screen; the online positions were transferred between PCs by the TCP/IP protocol. Their dynamic positions were recorded. Finally, five trajectories from five different groups were obtained for either the coordinated chases or the individual chases (i.e., one group generated one trajectory for coordinated chases and one trajectory for individual chases), whose durations ranged from 4 to 10 s; the last 1 s of each recording was discarded, because the three agents usually tangled before the prey was caught. To generate smoother trajectories with longer durations, we produced ten new trajectories by adding new positions between each pair of adjacent frames using the mean of the two positions (i.e., for each trajectory, the new length was twice as long as the original one). Given that the velocities of the new dynamic motion trajectories became slower, the motion trajectories were presented at a 70 Hz refresh rate in the replay stage. The replays consisted of a randomly segmented 3.5-s excerpts from the recorded trajectories. Moreover, the replayed positions were rotated randomly by 0°, 90°, 180°, or 270° around the center of the screen. (Demonstrations of the conditions used in the experiments can be seen in the Supplementary Materials.)

2.1.3. Procedure

For each trial (see Fig. 1a), a black (RGB: 0, 0, 0) dot subtending 0.5° of the visual angle and a restricted white wall (RGB: 255, 255, 255) identical to the one used during the generation of trajectories were first presented at the center of the screen for 0.4–0.5 s. This alerted the participants that the dynamic motion was about to begin. Subsequently, a 3.5-s segment from the trajectory was replayed. In the first 2.5 s, all agents were present, including two chasers and one target. Then, one of the agents (i.e., always one of chasers) was made invisible but still moved according to the segmented trajectory, and the remaining two agents moved visibly for 1 s. After these movements, the agents stopped while the restricted wall became black to alert the participants to respond. Before the experiment, the subjects were informed about the invisible agent and were asked to predict the expected position of the invisible agent, as if it still moved according to its planned motion for 1 s, by clicking the mouse at its predicted position on the screen (the initial position of the mouse was always at the center of the screen). No feedback about the prediction accuracy was provided. The remaining agents were present until a response was made, followed by the next trial with a 1.5–2.5-s inter-trial interval.

There were two types of 3.5-s segments (coordinated and individual). The segments were randomly sampled, without repetition, from the collected trajectories. To control for low-level differences, each of the segments was replayed twice in both the forward and backward sequences (see Fig. 1b), resulting in four classes of dynamic motion (Videos S1–S4). Each condition had 30 trials, resulting in a total of 120 trials that were run randomly with an equal probability of the invisible agent being blue or green. Finally, the prediction error for each trial was measured by calculating the distance between the clicked position and the true position of the invisible agent saved in the recorded trajectories (in pixels). If the response time exceeded 5 s, the trial was not considered in the subsequent analysis, as our pilot test showed that the time window of 5 s was sufficient for participants to move the mouse to the target position.

2.1.4. Data analysis

For the statistical analyses, we first checked whether the social content from coordinated chases actually exerted an influence on action prediction compared with individual chases. This inspection was based on examining the interaction effect using a 2×2 analysis of variance (ANOVA) with segment type (coordinated vs. individual) and replay sequence (forward vs. backward) as the two factors. If the interaction effect was significant, to further examine the details of this interaction effect, we conducted paired t-tests with replay sequence (forward vs. backward) as a factor for both segment types (i.e., coordinated chase vs. individual chase), and reported Cohen's d as the effect size.

2.2. Results & discussion

Overall, 0.94% of trials were rejected because the response time exceeded the criteria. A 2×2 ANOVA with segment type and replay sequence as factors revealed that both the main effect of segment type ($F(1,13) = 14.52$, $p = 0.002$, $\eta_p^2 = 0.53$), showing that the prediction error for observed coordinated chases was lower than that of observed individual chases, and the interaction effect between the two factors ($F(1,13) = 14.49$, $p = 0.002$, $\eta_p^2 = 0.53$) were significant. The significant main effect of segment type may be due to that agents were moving faster in individual chases (mean speed approximately 25°/s) than in coordinated chases (mean speed approximately 18°/s). In individual chases, the two predators tried to accelerate continuously to surpass one another and approach the target (for all four experiments, we found that the main effect of segment type was significant. The reason for this may be the same as is being described here. For simplicity, we only reported the statistical results below). Regarding the interaction effect, paired t-tests revealed that the prediction error for forward replay was lower than that for backward replay in the coordinated chase condition (Fig. 2a; $t(13) = 3.34$, $p = 0.005$, $d = 0.89$, 95% CI = $[-46, -10]$). No significant difference was found in the individual chase condition (Fig. 2b; $t(13) = 0.32$, $p = 0.751$, $d = 0.09$, 95% CI = $[-13, 18]$).[2] These results suggest that the coordinated information modulates the prediction regarding the actions of the invisible partner.

3. Experiment 1b

Although we kept the whole segments identical between forward and backward replay in Experiment 1a, the trajectories of the predicted agent were different when the agent's motion was invisible. Therefore, the effects observed may still be explained by physical differences. In this experiment, the invisible trajectories of predicted agents were matched between backward and forward replays to determine whether the same results found in Experiment 1a would be observed.
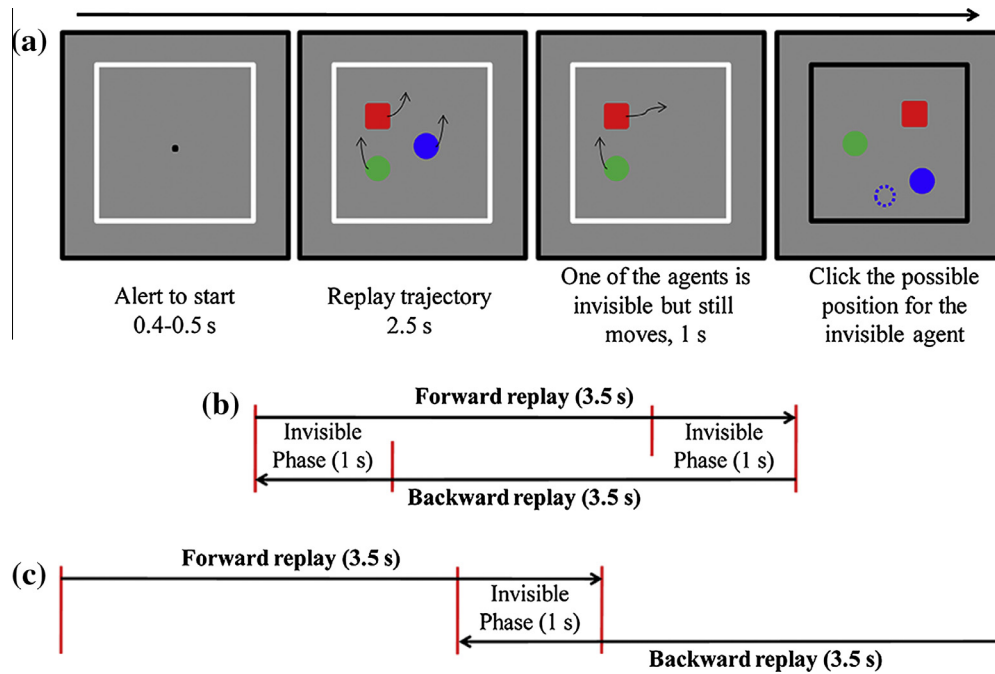
3.1. Methods

The experimental methods were identical with those of Experiment 1a, except as noted below. Another fourteen naïve Zhejiang University students (7 males and 7 females; mean age: 21 years; range: 18–26 years) participated in this experiment. To control non-social differences when one of the chasers was invisible, we set the offset and overlapped the trajectories in the invisible windows between the two replay conditions (see Fig. 1c).

3.2. Results & discussion

In total, only 2.2% of the trials exceeded the 5-s criteria. Paired t-tests showed almost the same results as those found in the previous experiment. Similar to Experiment 1a, the ANOVA with segment types and replay sequence as factors also yielded a significant interaction effect ($F(1,13) = 9.35$, $p = 0.009$, $\eta_p^2 = 0.42$) and a significant main effect of segment type ($F(1,13) = 10.16$, $p = 0.007$, $\eta_p^2 = 0.44$).

---

[2] The prediction error for each condition seems high. This pattern may be due to some systematic factors for each condition, such as clicking or memorizing.

Fig. 1. Experimental methods. (a) An illustration of the experimental procedure. The red square is the prey and the other two disks are chasers. The arrow depicts the direction of movement for the three agents. In this trial, the subject had to predict the expected position of the blue chaser after it moved invisibly for 1 s. The dashed blue circle (which does not appear in the formal experiments) and the solid blue disk represent the real position saved in the recorded trajectory and the position predicted by the participants, respectively. See the main text for details. (b) The manipulation of matching the motion features between the forward and backward replays in Experiment 1a. (c) The manipulation of matching the motion features during the invisible phase between the forward and backward replays in Experiment 1b. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
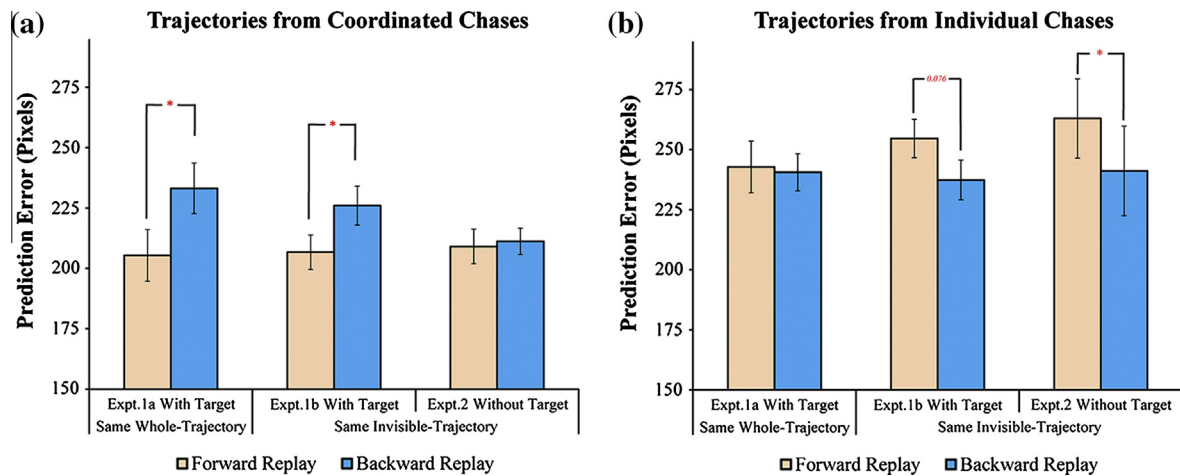
Fig. 2. Results of Experiments 1 & 2. The panels depict the mean prediction error of the expected position for replaying (a) coordinated and (b) individual chase trajectories. The prediction error varies as a function of replay sequence and control method of matching motion features. Error bars indicate standard errors.

In coordinated interactions (Fig. 2a), subjects predicted the position of the invisible chaser more accurately after watching forward-replayed motions than after watching backward-replayed motions ($t(13) = 4.17$, $p = 0.001$, $d = 1.11$, 95% CI = [−29, −9]). Thus, the difference between forward and backward replay in the coordinated chases in Experiment 1a could not be explained by physical differences. Even the invisible motions, whose prediction was required, were kept identical and we still obtained the same modulation effect.

Interestingly, in contrast to Experiment 1a, the prediction error between forward and backward replay approached significance for individual chases, but showed a contrasting pattern with coordinated chases (Fig. 2b; $t(13) = 1.93$, $p = 0.076$, $d = 0.52$, 95% CI =

[−2, 37]). This effect at least indicated that the pattern of prediction errors for individual chases was sensitive to the physical manipulations. Thus, it is possible that the motion features of agents, such as speed, direction of movement, and relative position between agents, led to the current results for individual chases (we will discuss this more in Experiment 2).

4. Experiment 2

To ensure that the effects in Experiment 1 were indeed caused by the coordination information and not by the low-level motion features, in this experiment, only two chasers for both forward and backward replay were presented, and the prey was invisible.

Because the chasers' behaviors respond continuously to those of the prey, if the prey becomes invisible, it is difficult for the observer to determine the intent of the chasers, even though they are still moving in exactly the same way as when the prey was present (Lima, 2002; Yin et al., 2013). Therefore, if the results in Experiment 1 were due to its social information, the manipulation of making the prey invisible should eliminate the difference between the forward- and backward-replay conditions for coordinated chases and display a similar result pattern for individual chases, as the impression of the social relationship vanishes or weakens; otherwise, the effects should be attributed to the unique low-level motion patterns.

4.1. Methods

Fourteen new participants (7 males and 7 females; mean age: 22 years; range: 18–27 years) were tested in this experiment. They were all naïve Zhejiang University students and received financial rewards. The stimuli, procedure, and design were almost identical as used in Experiment 1b, except that the target was set to be absent (Videos S5–S8).

4.2. Results & discussion

In total, 2.7% of trials were rejected because they failed to meet the reaction time criteria. By conducting an ANOVA with segment type and replay sequence as the two factors, we found a significant main effect of segment type ($F(1,13) = 6.72$, $p = 0.022$, $\eta_p^2 = 0.34$) and a significant interaction effect between segment type and replay sequence ($F(1,13) = 4.77$, $p = 0.048$, $\eta_p^2 = 0.27$). Thus, the pattern of simple effects was very different from that in Experiment 1. Specifically, in contrast to Experiment 1, we did not find a significant difference in prediction error between forward and backward replay when the replayed segments of predators were kept identical with Experiment 1b, but the common target was invisible (Fig. 2a; $t(13) = 0.45$, $p = 0.660$, $d = 0.12$, 95% CI = $[-12, 8]$). Nevertheless, a lower prediction error for backward replay of individual chasing segments was also observed (Fig. 2b; $t(13) = 3.03$, $p = 0.010$, $d = 0.81$, 95% CI = $[6, 38]$), than for forward replay. We performed a repeated-measure an Analysis of Variance (ANOVA) for each type of chase by setting experiment type (Experiment 1b and Experiment 2) as a between-subject factor and replay sequence (forward and backward) as a within-subject factor. These comparisons revealed that for coordinated chases, the interaction effect was significant ($F(1,13) = 5.65$, $p = 0.034$, $\eta_p^2 = 0.30$), although the overall prediction error in the current experiment was lower than in Experiment 1, as shown in Fig. 2 (perhaps because this experiment had only two agents with less distraction). However, no significant interaction effect for individual chases ($F(1,13) = 0.13$, $p = 0.728$, $\eta_p^2 = 0.01$) was found. These results indicate that the difference between the two replays with coordinated chases was indeed caused by the coordinated information that subjects experienced from dynamic motions, and individual chase information could not assist (or hinder) subjects' predictions, at least in the current settings. To some extent, these findings suggest that, when observing individual chase scenes, subjects may use non-social information from the two chasers to infer possible positions, such as the relative position of the two predators, as discussed below.

4.3. Further discussion about results of individual chases

Here, we provided a possible explanation of the different prediction errors between forward and backward replay on individual chase trajectories. Specific to our generated trajectories, when the two chasers chased the target individually, each of them planned

his or her actions according to the movement trend of the target. Thus, if the actions of the two chasers, which were used by the subjects to catch the target, were more similar, the actions of the invisible chaser could be more accurately predicted according to the correlated information with the visible chaser. The further the individual chase went, the greater the similarity between the actions of the two chasers, because they learned more about the common target and gradually converged toward the best way of approaching the target. That is to say, if the segments were from later parts of the trajectories, the position of the invisible chaser would be more accurately predicted according to the correlated information with the visible chaser. Such speculation was consistent with the settings, because the segments for backward replay should be much later than those for forward replay in order to overlap the invisible part.

For example, the relative position between two chasers, which can be measured by the distance, may be important information to use. When one of the chasers was invisible (time point 2, short for T2), participants still used the relative position in visible parts (time point 1, short for T1) to approximate the distance between two chasers and then computed the possible position by referring to the position of the visible chaser. Namely, if the information at T1 is more correlated with the information at T2 (as measured by the serial correlation), the missed elements at T2 could be more accurately predicted or inferred based on the information at T1. This correlated information of the relative position in a time series is termed serial correlation and can be quantified by the Durbin–Watson statistic (see Appendix A). Thus, the higher the serial correlation on the relative position computed from the whole segments is (i.e., the lower the Durbin–Watson statistic), the more the invisible chaser will be accurately predicted. These are the results that we found using the Durbin–Watson statistic. Specifically, using computers, we simulated Experiment 1b with the same settings and sample size as the original experiment, and we saved all information about the segments, without behavioral responses. This analysis revealed that the Durbin–Watson statistic was lower (i.e., higher serial correlation) for backward replay ($M = 1.40 \times 10^{-3}$) than that for forward replay ($M = 1.78 \times 10^{-3}$) when the trajectories were from individual chases ($t(13) = 9.62$, $p < 0.001$, $d = 2.57$, 95% CI = $[-4.6 \times 10^{-4}, -2.9 \times 10^{-4}]$). There was no difference between them when the trajectories were from coordinated chases (forward replay: $M = 2.4 \times 10^{-4}$; backward replay: $M = 2.5 \times 10^{-4}$; $t(13) = 0.74$, $p = 0.474$, $d = 0.20$, 95% CI = $[-1.6 \times 10^{-5}, 3.3 \times 10^{-5}]$).

Even after re-running the simulated experiment an additional five times, we obtained the same results. These serial correlation patterns were consistent with the findings in which the prediction error for backward replay was lower than for forward replay in the individual chases (both Experiments 1b and 2), and if no social interaction information could be experienced on coordinated trajectories, the prediction errors did not differ from each other (Experiment 2). Moreover, the results in Experiment 1a may also imply that subjects used the relative distance to make predictions regarding the invisible chaser during individual chases. Because the trajectory was the same between forward and backward replays, the serial correlation was not affected by the time sequence. This indicates that a non-effect should be observed between the two replay conditions, which is consistent with the findings of Experiment 1a.

Surely, there are many other factors influencing the prediction of the chaser from the individual chases, such as speed and direction of movement. Here, we only aimed to give a possible explanation of how physical features are used to predict positions. In any case, in contrast to the coordinated chase, information about individual actions did not facilitate the prediction of another agent's actions, even with a common target, which clearly supports our conclusion.

5. Experiment 3

The above experiments clearly indicate that action prediction is modulated by coordination information, even though agents in both coordinated and individual chases are directed toward the target. Such modulation could be caused either by disruption from backward replay as the control condition or by enhancement from coordination information transmitted by the forward-replayed trajectories. To examine these possibilities, we introduced a direct intervention for coordination information in which the motion of one of the chasers in the coordinated chase was replaced with random motion (modified chasing with no coordination information), and the prediction for the remaining chaser was compared with the same chaser from the recorded chase with coordinated interaction. If the results of Experiments 1 and 2 are due to the enhancement of coordination information (or the disruption of control conditions), lower (or higher) prediction errors should be observed when the chaser is from the recorded chase than when it comes from the modified chase. The same manipulation was also applied to the individual chases, but a null effect was expected because there was no coordination information in either condition.

5.1. Methods

5.1.1. Participants

Fourteen participants (7 males and 7 females; mean age: 21 years; range: 18–26 years) were tested in this experiment. They were all naïve Zhejiang University students and received financial rewards. All of them had normal or corrected-to-normal vision. All participants provided written and informed consent before the experiments and the procedures were approved by the Research Ethics Board of Zhejiang University and the granting agency.

5.1.2. Procedure and design

This experiment still used the segments from the coordinated and individual chase trajectories. In addition, based on the collected trajectories, we created new chase trajectories by replacing either of the predators with a non-chasing agent. The non-chasing agent was steered by algorithms to avoid collision and pass the "wall." Specifically, we computed the mean speed for each coordinated or individual chase trajectory for each agent (human speed) and then restricted the replaced trajectories to the same requirements as human steering; the speed and direction of the replaced agent were determined by the force from the wall and the un-replaced agents, with the speed centered on the human mean and a ±5°/s limitation of movement. We selected new trajectories with the same average distance between the un-replaced chaser and the replaced agent as the corresponding trajectories recorded from humans. Finally, three types of trajectories for each chase were obtained, including trajectories with two chasing agents (i.e., original trajectories; referred to as a non-replaced setting), and trajectories with the blue chaser replaced by a non-chasing agent (i.e., blue-chaser replaced trajectories; referred to as a replaced setting) and the green chaser replaced by a non-chasing agent (i.e., green-chaser replaced trajectories; also termed as a replaced setting). There were five trajectories for each type.

According to the predicted agent (i.e., agent type), three conditions for both coordinated and individual chases were included: prediction of chasing agent in the non-replaced setting, prediction of chasing agent in the replaced setting, and prediction of non-chasing agent in the replaced setting (Videos S9–S12). Each condition had 40 trials, resulting in 120 trials for each chase type, and the trials were randomly presented. To be specific, (1) we cut 40 3.5-s segments from the pool of the original trajectories, without overlap. These 40 segments were set to be required to either pre-

dict the blue disk or the green disk (i.e., either of the chasers could be used), with equal probability, thus forming 40 trials for the condition of prediction of chasing agent in the non-replaced setting. (2) We cut 40 segments from the pool of the blue-chaser replaced trajectories, with the same segmenting time as the condition of prediction of chasing agent in the non-replaced setting. Again, the probabilities of predicting the blue disk (non-chaser) and predicting the green disk (chaser) were equal, resulting in 20 trials for the condition of prediction of chasing agent in the replaced setting and 20 trials for prediction of the non-chasing agent in the replaced setting. Importantly, the segments of predicting the green disk in this replaced setting were the same as those in the condition of prediction of chasing agent in the non-replaced setting before they were modified. Namely, the physical features of the green chaser in the non-replaced setting were the same as those in the replaced setting. (3) The same logic of (2) was extended to the green-chaser replaced trajectories. Finally we obtained 40 trials for the condition of prediction of the chasing agent in the replaced setting and 40 trials for the condition of prediction of the non-chasing agent in the replaced setting. The only difference between these two conditions was whether the unpredicted agent was coordinated with the predicted one. Additionally, the condition of prediction of the non-chasing agent in the replaced setting was not closely related to our conclusion, because it was set to balance the probabilities of the predicted agents, and the predictability of a non-chasing agent was dependent upon the algorithm. Therefore, the main comparison was made between the first two conditions using paired *t*-tests, but the results for all conditions can be seen at Fig. 3.

The experimental procedure was the same as in the previous experiments.

5.2. Results

According to our criteria, 1.3% of trials were rejected (0.6% in the coordinated chase condition; 0.7% in the individual chase condition). A significant interaction effect was revealed by an ANOVA with segment type and agent type as factors. This showed that the prediction error of the observed individual chases was higher than that of observed coordinated chases ($F(1,13) = 22.17$, $p < 0.001$, $\eta_p^2 = 0.63$), and the social relationship between the two chasers actually modulated the action prediction ($F(1,13) = 5.16$, $p = 0.04$, $\eta_p^2 = 0.28$; see Fig. 3). *T*-paired comparisons when the predicted agent was part of a coordinated chase revealed that the prediction error for the chasing agent in the replaced setting was higher than in the non-replaced setting ($t(13) = 4.16$, $p = 0.001$, $d = 1.11$, 95% CI = [9, 29]), even though the motion features were identical. However, we did not find any significant difference between the replaced and non-replaced trajectories when the predicted chaser came from an individual chase ($t(13) = 0.26$, $p = 0.801$, $d = 0.07$, 95% CI = [−17, 22]). These results confirmed that the influence of the coordinated chase on action prediction was indeed due to the coordination information and further suggest that this influence was due to the beneficial effect from the coordination information rather than the disruption effect from the control.

6. General discussion

The primary purpose of this study was to explore the role of coordination information beyond individual goals on action prediction. We found that the prediction error for an agent's position decreased when coordinated chasers were presented. The nature of this discovered influence on action prediction should stem from the experienced social coordination behind the actions instead of
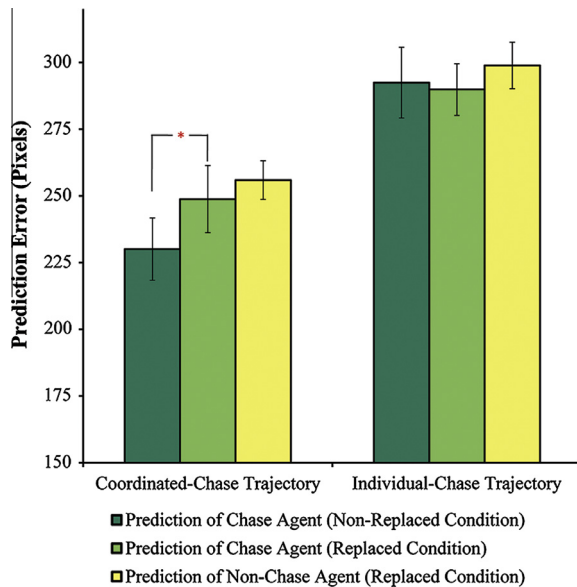
Fig. 3. Results of Experiment 3. Prediction errors are presented with types of chase trajectories and predicted agents. Error bars indicate standard errors.

from physical factors or individual actions in multi-agents chases, exhibiting an enhancement effect. Specifically, (1) the manipulation of changing the replay sequence on coordinated chase trajectories or the availability of social interaction influences prediction errors for actions of the invisible agent, though both forward and backward replay of recorded motions has almost identical physical features (Experiment 1); (2) the effect in (1) vanishes in Experiment 2, in which the chasers behaves with exactly the same motions as in Experiment 1 but without interaction meaning; (3) the action prediction for the chaser depends on whether the second agent coordinates with it to pursue the common goal (individual chase and Experiment 3); (4) the difference on action prediction between two replay sequences in coordinated chase trajectories is due to enhancing action prediction by the coordination information in forward-replay conditions instead of disrupting action prediction from the control of backward-replay conditions (Experiment 3).

Nevertheless, someone may argue that the current findings are due to memory bias, in which the predicted position is attracted to the memorized position at the time point as when the agents became invisible (i.e., the disappearing position), but subjects actually performed equally well when predicting actions in all cases. This possibility would imply that the predicted position in the controls should be closer to the disappearing position, compared with conditions with coordination information. However, we found that the distance to the disappearing position in the forward-replay condition was even closer than that in the backward-replay condition in Experiment 1a ($t(13) = 6.10$, $p < 0.001$, $d = 1.63$, 95% CI = $[-83, -40]$); no significant result was found in Experiment 1b ($t(13) = 1.03$, $p = 0.323$, $d = 0.27$, 95% CI = $[-23, 8]$); the distance between the predicted position and the disappearing point did not differ between the replaced and non-replaced trajectories ($t(13) = 1.46$, $p = 0.167$, $d = 0.39$, 95% CI = $[-23, 4]$). Therefore, our results cannot be explained by memory bias, supporting our hypothesis that the observed coordination information can enhance action prediction.

To our knowledge, this research is the first to reveal that a new type of visual information—coordination information transmitted by coordinated actions, at least by coordinated chasing—has been used to predict actions. The current advancement is consistent with recent findings that observed coordination facilitates the

extraction of information from actions (Manera et al., 2011; Neri et al., 2006). Nevertheless, our study extended its role to a further mechanism of action understanding: action prediction. More than helping someone to anticipate future behaviors while taking part in an interaction, as previously emphasized (Sebanz & Knoblich, 2009), the current research suggests that interpersonal coordination is also used to facilitate the prediction of observed coordinated actions.

Generally, the prediction benefit due to coordination information is directly implied by the crucial characteristic that actors are mutually constrained and conditioned, because this characteristic signifies that one's actions function as the predictor of the actions of others. Interestingly, the constraint experienced for coordinated actions seems to be based on the intentional or goal-directed level in our settings; otherwise, there would be no difference between the action prediction for forward- and backward-replayed motions, and the action prediction would not be modulated by the visibility of the target, given that they have the same conditional information between chasers on the physical level. As suggested, goal-directed behavior is computed through the rational principle that actions function to realize goal-states by the most efficient means available, in both individual and coordinated actions (Gergely & Csibra, 2003; Mascaro & Csibra, 2014). Therefore, we speculate that the constraint in coordinated actions is partly computed as the expectation of co-efficiently approaching the goal. Namely, when obtaining information in a coordinated chase, observers could predict the scope of the invisible-chaser's position by maximizing the possibility of catching the target via rational principles. All of these computations may be built on the fact that the representation of individuals within an interaction is structured into a unit and, accordingly, constrains them, considering that the coordinated agents are treated visually as a whole (Mascaro & Csibra, 2012; Yin et al., 2013).

Concerning the process of predicting action (i.e., position), one more interesting question is about the updating mechanism. It could be that participants predicted actions by either dynamically computing the actions with the inherent sampling rate of the brain (i.e., not necessarily always the case) during the entire invisible segment, or by simply performing computations at the time point when required to infer, or both. The question of which strategy was adopted by participants is beyond the scope of our study and could probably be further examined by eye-tracking or EEG/ERP methods. Nevertheless, there are at least three reasons supporting the first updating strategy. (1) Computing the action when needed means that our brain has to store all (or most) of the past information to achieve higher prediction accuracy, and this exerts a heavy load on the memory; even the stored information could seriously interfere with each other. (2) However, if participants update the action dynamically, in theory they only need to keep the information of the position for the latest sampled epoch/point (or few epochs/points), which could save the memory space. (3) Numerous studies have shown that people, even infants, predict others' actions continuously (Southgate, Johnson, El Karoui, & Csibra, 2010; Stapel, Hunnius, & Bekkering, 2012), which are usually used as the feedback for the future available actions, similar to the Bayesian inference (Kilner, Friston, & Frith, 2007).

Besides the possible cognitive interpretations, the current work fits well into the popular Bayesian framework at the computational level (Tenenbaum, Kemp, Griffiths, & Goodman, 2011; Ullman et al., 2009). In the Bayesian framework, the computation for the predicted invisible actions can be divided into two steps: (1) inferring a constraint structure when both chasers are invisible based on observed actions (i.e., P(Structure|Data) ∝ P(Structure) × P(Data|Structure); here just for simplicity; actually observers have to infer the goal of each agent): observers could assume that the prior P(Structure) is equal between coordinated and individual

chases, but when accumulating more data, they prefer that coordinated chases have the social structure of mutual constraint between the chasers, but not for individual chases; (2) generating predictions for invisible actions from the possible hypothesis space (i.e., likelihood P(Data|Structure, Other Factors); other factors at least include the possible goals of each agent). We could assume both coordinated and individual chases have almost identical other factors; however, the structure of mutual constraints only happens in the coordinated chases and introduces more information to reduce the hypothesis spaces for generating the observed data. Thus, the likelihood for predicting actions within a coordinated interaction becomes less deviant from the true value and, accordingly, the possible actions (i.e., data or position) are also more accurately predicted. In the future, it would be interesting to construct a model regarding how this proposed framework is implemented.

In any case, the current research has indicated that observing coordination information facilitates action prediction, implying that the functional characteristic of mutual constraints in coordinated actions can be utilized by our vision.

Author contributions

J. Yin, H. Xu, and M. Shen conceived and designed the experiments. J. Yin, H. Xu, X. Ding, J. Liang, and R. Shui performed the experiments and analyzed the data. J. Yin and M. Shen wrote the manuscript.

Acknowledgement

Appendix A. Durbin–Watson statistic (DW)

The Durbin–Watson statistic (DW) was originally used to measure the serial correlation of the error in a time series. Here, we assigned the error value to the distance between chasers to compute the statistic.

$$Durbin-Watson\ statistic = \frac{\sum_{t=2}^{T}(X_t - X_{t-1})^2}{\sum_{t=1}^{T} X_t^2}$$

X_t is the variable measured in the time series (i.e., the distance between the chasers in our analysis). T is the number of time periods. The DW statistic will fall in the 0–4 range, with a value near 2 indicating no serial correlation. Positive serial correlation is associated with DW values below 2 and negative serial correlation is associated with DW values above 2. When successive values of X are close to each other, the DW statistic will be low, indicating the presence of positive serial correlation. Importantly, the same statistic will be obtained whether the computation is performed from the end time to the start time or from the start time to the end time.

Appendix B. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.cognition.2016.02.009.

References

Brainard, D. H. (1997). The psychophysics toolbox. *Spatial Vision, 10*(4), 433–436.

Csibra, G., Bíró, S., Koós, O., & Gergely, G. (2003). One-year-old infants use teleological representations of actions productively. *Cognitive Science, 27*(1), 111–133.

Csibra, G., & Gergely, G. (2007). "Obsessed with goals": Functions and mechanisms of teleological interpretation of actions in humans. *Acta Psychologica, 124*(1), 60–78.

Dittrich, W. H., & Lea, S. E. (1994). Visual perception of intentional motion. *Perception, 23*(3), 253–268.

Gao, T., McCarthy, G., & Scholl, B. J. (2010). The wolfpack effect: Perception of animacy irresistibly influences interactive behavior. *Psychological Science, 21*(12), 1845–1853.

Gao, T., Newman, G. E., & Scholl, B. J. (2009). The psychophysics of chasing: A case study in the perception of animacy. *Cognitive Psychology, 59*(2), 154–179.

Gergely, G., & Csibra, G. (2003). Teleological reasoning in infancy: The naïve theory of rational action. *Trends in Cognitive Sciences, 7*(7), 287–292.

Hauser, M., & Wood, J. (2010). Evolving the capacity to understand actions, intentions, and goals. *Annual Review of Psychology, 61*, 303–324.

Heider, F., & Simmel, M. (1944). An experimental study of apparent behavior. *The American Journal of Psychology, 57*(2), 243–259.

Kilner, J. M., Friston, K. J., & Frith, C. D. (2007). The mirror-neuron system: A Bayesian perspective. *NeuroReport, 18*(6), 619–623.

Knoblich, G., & Sebanz, N. (2008). Evolving intentions for social interaction: From entrainment to joint action. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences, 363*(1499), 2021–2031.

Lima, S. L. (2002). Putting predators back into behavioral predator–prey interactions. *Trends in Ecology & Evolution, 17*(2), 70–75.

Manera, V., Del Giudice, M., Bara, B. G., Verfaillie, K., & Becchio, C. (2011). The second-agent effect: Communicative gestures increase the likelihood of perceiving a second agent. *PLoS ONE, 6*(7), e22650.

Mascaro, O., & Csibra, G. (2012). Representation of stable social dominance relations by human infants. *Proceedings of the National Academy of Sciences of the United States of America, 109*(18), 6862–6867.

Mascaro, O., & Csibra, G. (2014). Infants compute the efficiency of joint actions. *Poster presented at the fourth annual Budapest CEU conference on cognitive development, Budapest, Hungary*. Abstract retrieved from <http://www.bcccd.org/down/bcccd_final_program_2014.pdf>.

Meyerhoff, H. S., Schwan, S., & Huff, M. (2014). Perceptual animacy: Visual search for chasing objects among distractors. *Journal of Experimental Psychology: Human Perception and Performance, 40*(2), 702–717.

Neri, P., Luu, J. Y., & Levi, D. M. (2006). Meaningful interactions can enhance visual discrimination of human agents. *Nature Neuroscience, 9*(9), 1186–1192.

Rawal, A., Rajagopalan, P., & Miikkulainen, R. (2010). Constructing competitive and cooperative agent behavior using coevolution. In *Proceedings of the 2010 IEEE conference on computational intelligence and games, CIG2010* (pp. 107–114).

Saunier, G., Martins, E. F., Dias, E. C., de Oliveira, J. M., Pozzo, T., & Vargas, C. D. (2013). Electrophysiological correlates of biological motion permanence in humans. *Behavioural Brain Research, 236*(1), 166–174.

Sebanz, N., Bekkering, H., & Knoblich, G. (2006). Joint action: Bodies and minds moving together. *Trends in Cognitive Sciences, 10*(2), 70–76.

Sebanz, N., & Knoblich, G. (2009). Prediction in joint action: What, when, and where. *Topics in Cognitive Science, 1*(2), 353–367.

Shockley, K., Richardson, D. C., & Dale, R. (2009). Conversation and coordinative structures. *Topics in Cognitive Science, 1*(2), 305–319.

Shockley, K., Santana, M. V., & Fowler, C. A. (2003). Mutual interpersonal postural constraints are involved in cooperative conversation. *Journal of Experimental Psychology: Human Perception and Performance, 29*(2), 326–332.

Southgate, V., Johnson, M. H., El Karoui, I., & Csibra, G. (2010). Motor system activation reveals infants' on-line prediction of others' goals. *Psychological Science, 21*(3), 355–359.

Stapel, J. C., Hunnius, S., & Bekkering, H. (2012). Online prediction of others' actions: The contribution of the target object, action context and movement kinematics. *Psychological Research Psychologische Forschung, 76*(4), 434–445.

Tenenbaum, J. B., Kemp, C., Griffiths, T. L., & Goodman, N. D. (2011). How to grow a mind: Statistics, structure, and abstraction. *Science, 331*(6022), 1279–1285.

Ullman, T., Baker, C., Macindoe, O., Evans, O., Goodman, N., & Tenenbaum, J. (2009). Help or hinder: Bayesian models of social goal inference. In Y. Bengio, D. Schuurmans, J. Lafferty, C. K. I. Williams, & A. Culotta (Eds.). *Advances in neural information processing systems* (Vol. 22, pp. 1874–1882). La Jolla, CA: The NIPS Foundation.

Verschoor, S. A., Spapé, M., Biro, S., & Hommel, B. (2013). From outcome prediction to action selection: Developmental change in the role of action-effect bindings. *Developmental Science, 16*(6), 801–814.

Yin, J., Ding, X., Zhou, J., Shui, R., Li, X., & Shen, M. (2013). Social grouping: Perceptual grouping of objects by cooperative but not competitive relationships in dynamic chase. *Cognition, 129*(1), 194–204.

Update

Cognition

Corrigendum

Corrigendum to "Social constraints from an observer's perspective: Coordinated actions make an agent's position more predictable" [Cognition 151 (2016) 10–17]

Jun Yin [a,b], Haokui Xu [a], Xiaowei Ding [a], Junying Liang [c], Rende Shui [a], Mowei Shen [a,*]

[a] Department of Psychology and Behavioral Sciences, Zhejiang University, Hangzhou, PR China
[b] Department of Psychology, Ningbo University, Ningbo, PR China
[c] School of International Studies, Zhejiang University, Hangzhou, PR China

The authors regret that an error occurred on the last but two paragraph in the discussion section [besides the possible cognitive interpretations, the current work fits well into the popular Bayesian framework at the computational level...]. P(StructureData) should be P(Structure|Data). Namely, '|' was missed.

The authors would like to apologise for any inconvenience caused.