Action-Effect Anticipation and Temporal Adaptation in Social Interactions

Jarosław R. Lelonkiewicz, Chiara Gambi, Lisa Weller, and Roland Pfister

Scuola Internazionale Superiore di Studi Avanzati (SISSA)

Cardiff University

University of Würzburg

Word Count: 10587

Correspondence concerning this article should be addressed to Jarosław R. Lelonkiewicz, Cognitive Neuroscience Area, Scuola Internazionale Superiore di Studi Avanzati (SISSA), via Bonomea, 265, 34136 Trieste, Italy.

E-mail: jlelonki@sissa.it

Abstract

Interacting agents may anticipate their partner's upcoming response and include it in their action plan. In turn, observing an overt response can trigger agents to adapt. But while anticipation and adaptation are known to shape action control, their interplay in social interactions remains largely unexplored. In four experiments, we asked how both of these mechanisms could contribute to one striking phenomenon: Agents initiate actions faster when they know their partner will produce a compatible rather than an incompatible response. In Experiment 1, we manipulated the compatibility between agents' actions and partners' responses, and investigated the interplay between adaptation and anticipation within the same dyadic interaction. In Experiments 2-4 we isolated the contribution of each of the two mechanisms by having agents interact with virtual partners whose responses could be experimentally controlled. We found that adaptation and anticipation exert parallel but independent effects on action execution: Participants initiated their actions more quickly when the upcoming partner response was compatible and, independently, when their partner had responded more quickly on the preceding trial. These findings elucidate models of action control in social interactions.

Keywords: anticipation, adaptation, entrainment, action-effect, imitation

Public Significance Statement

This study suggests that our behavior in social interactions is affected by a tendency to anticipate how our interaction partner will respond and, independently, by a tendency to adapt to the speed of their previous responses. These findings help shed light on the mechanisms that allow people to coordinate with each other in social interactions.

Action-Effect Anticipation and Temporal Adaptation in Social Interactions

Actions executed in social interactions can be shaped by several different mechanisms (Knoblich, Butterfill, & Sebanz, 2011). When interacting, agents may engage anticipatory mechanisms, i.e., they may represent the upcoming actions of their interaction partners. Such anticipation is known to influence action planning and execution across various contexts, from musical performances, to sports, dancing and conversations (Aglioti, Cesari, Romani, & Urgesi, 2008; Bläsing et al., 2012; Corps, Crossley, Gambi, & Pickering, 2018; Wolf, Sebanz, & Knoblich, 2018). In addition, actions in social interactions may be shaped by mechanisms of adaptation, such as the spontaneous tendency to adapt to the temporal characteristics of other people's behavior (Loehr, Large, & Palmer, 2011; Marsh, Richardson, & Schmidt, 2009; Schmidt & Richardson, 2008; Schmidt, Fitzpatrick, Caron, & Mergeche, 2011; Shockley, Richardson, & Dale, 2009; Varlet, Marin, Lagarde, & Bardy, 2011; Wilson & Wilson, 2005).

But while it is clear that both anticipation and adaptation play a role in social interactions, it is difficult to tease apart the contribution of each mechanism to specific interpersonal phenomena. Here, we focus on one striking finding, namely that agents perform actions faster if they know they are going to be imitated by their interaction partner, compared to when they know their interaction partner will respond with an action different from their own (Lelonkiewicz & Gambi, 2017; Pfister, Dignath, Hommel, & Kunde, 2013; Pfister, Weller, Dignath, & Kunde, 2017; Weller, Pfister, & Kunde, 2019). In four experiments, we investigated how adaptation and anticipation may contribute to this phenomenon. To this end, our participants interacted with a partner and performed a task that allowed for simultaneous anticipation and adaptation, or for anticipation only, and we tested how these mechanisms affected action planning and execution.

A growing body of research shows that social interactions often involve anticipation. In a landmark study by Knoblich and Jordan (2003), participants controlled an object moving

laterally across the screen by operating an acceleration and a deceleration key. Importantly, prior to reaching the edge of the screen (at which point the object should bounce back and change the direction of motion), they had to gradually stop accelerating and start decelerating. The study revealed that participants who performed the task in pairs (where each key was operated by a different person, and they had to coordinate) were similarly successful as solo participants (where one person operated both keys), suggesting that they were able to predict each other's keypresses. Indeed, many other studies showed that agents anticipate the actions of their interaction partners, both with respect to *what* actions will be performed and *when* they will be performed (Sebanz & Knoblich, 2009; for reviews, see also Keller, 2008; Keller, Novembre, & Hove, 2014; Meyer, Bekkering, Haartsen, Stapel, & Hunnius, 2015; Pickering & Gambi, 2018; Sebanz, Bekkering, & Knoblich, 2006).

But what allows for anticipation in social interactions? In a recent extension of ideomotor theory, i.e., the sociomotor framework, Kunde, Weller and Pfister (2018) proposed that anticipation results from a general mechanism of action planning: When an agent performs an action, bidirectional associations are automatically established between this action and its typical effect (i.e., the auditory, visual or proprioceptive event that appears to be contingent on this action). Critically, once these associations are formed, the action becomes represented in terms of the effect. Thus, according to ideomotor accounts of human action control, planning and executing an action involves the anticipation of its typical effect (Hommel, Müsseler, Aschersleben, & Prinz, 2001; Hommel, 2013; Pfister, 2019; Shin, Proctor, & Capaldi, 2010).

Evidence consistent with this proposition comes from research using the action-effect compatibility paradigm (Kunde, 2001, 2003; see also Badets, Pesenti, & Olivier, 2010; Földes, Philipp, Badets, & Koch, 2017). Studies in this paradigm involve action-contingent effects that are either compatible or incompatible with participants' actions on a dimension such as spatial position (e.g., left vs. right), duration (e.g., long vs. short) or intensity (e.g., high vs. low; see

Kornblum, Hasbroucq, & Osman, 1990, for details on the concepts of compatibility and dimensional overlap). If actions are indeed represented in terms of their effects, action execution should be facilitated when participants can expect their action to be followed by a compatible rather than incompatible effect. This prediction has been confirmed by several studies involving non-social action effects. For instance, participants are known to initiate a button-press more quickly when it is followed by a spatially compatible light effect (e.g., a right button-press followed by a light on the right side), as compared to an incompatible light effect (e.g., a right button-press followed by a light on the left side; Kunde, 2001; see also Horváth, Bíró, & Neszmélyi, 2018; Kunde, Koch, & Hoffmann, 2004; Pfister, Janczyk, Wirth, Dignath, & Kunde, 2014).

Importantly, the sociomotor framework (Kunde et al., 2018) holds that such mechanism of action planning can be extended to social interactions, i.e., an action can also become associated with the behavior that it typically evokes in others. Under this premise, agents may represent their action in terms of the expected response of their interaction partner, and therefore, in social contexts, action execution should come with an anticipation of the partner's upcoming response. In an early attempt to demonstrate this process, Pfister and colleagues (2013) asked participants to perform a button-pressing task, acting either as a leader or follower. The leader performed either a short or long button-press reacting to a color cue, and the follower responded with a button press of the same (in the compatible block) or different length (in the incompatible block). The study found that leaders initiated their actions more quickly when they were followed by a compatible rather than an incompatible response, even though the task did not require them to consider how the follower would respond. This was consistent with the possibility that leaders represented in their action plan the type of response that the follower was about to produce (for similar findings, see Müller, 2016).

However, actions executed during social interactions are also known to be affected by adaptation to previously observed behavior (Knoblich et al., 2011). One striking illustration of this phenomenon is the tendency to adapt to the temporal patterns present in the behavior of others, such as when audience members fall into a single clapping rhythm (Neda, Ravasz, Brechte, Vicsek, & Barabasi, 2000; see also Oullier, De Guzman, Jantzen, Lagarde, & Kelso, 2008; Keller et al., 2014; Levitin, Grahn, & London, 2018; Schmidt & O'Brien, 1997). Importantly, temporal adaptation appears to influence actions beyond intentional control. For instance, in a study by Okano, Shinya, and Kudo (2017) participants were asked to tap on an electronic drum set either in synchrony with a metronome (solo condition) or both with the metronome and with one another (joint condition). The results revealed that participants who performed the task with a partner departed from the metronome rhythm to a greater extent than solo participants, and that, crucially, this was caused by adaptation to the other person's tapping speed. This adaptation was captured by a positive correlation between agent's response speed and the response speed of the partner on the preceding trial (see also Konvalinka, Vuust, Roepstorff, & Frith, 2010).

Based on these findings, Lelonkiewicz and Gambi (2017) asked if the behavioral pattern obtained by Pfister and colleagues (2013) could be explained by adaptation to the follower's response speed, rather than anticipation of the upcoming response. Critically, in Pfister and colleagues' (2013) study, as in many previous studies on motor imitation, the follower responded faster in the compatible than in the incompatible block (e.g., Berthenthal, Longo, & Kosobud, 2006; Brass, Bekkering, Wohlschläger, & Prinz, 2000; Catmur & Heyes, 2011). Thus, the difference in leaders' action initiation speed between the compatible and incompatible blocks could be produced by leaders adapting to the speed with which the follower produced the response on the preceding trial, rather than by leaders anticipating the type of response the follower would produce next. To test this alternative explanation, Lelonkiewicz and Gambi

(2017) manipulated the follower's response speed, so that the follower was now faster producing incompatible than compatible responses: Under these conditions, they found that leaders were also faster in the incompatible than in the compatible block. Crucially, this behavioral pattern was contrary to what should occur if leaders were influenced only by anticipation of the follower's response type. Moreover, leaders' action initiation speed on the current trial was positively correlated with follower's speed on the preceding trial, which was consistent with the possibility that leaders adapted to the follower's observed timing (Experiment 2). Further, when leaders could not see or hear the follower (and thus could not adapt), their speed was uncorrelated with the follower's speed, and there was no effect of the follower's upcoming response type (Experiment 1).

While Lelonkiewicz and Gambi's (2017) findings confirmed that actions executed in a social context can be affected by spontaneous temporal adaptation, they did not demonstrate that adaptation was the sole factor driving the behavioral pattern observed by Pfister and colleagues (2013). Indeed, there is some indication that actions may be influenced by anticipation of the upcoming response even when the speed of this response is held constant. In a recent study by Pfister and colleagues (2017) participants acting as leaders performed the button-pressing task together with a virtual follower who, again depending on the experimental block, responded with a compatible or an incompatible press. Crucially, the virtual follower was programmed to initiate responses with constant speed across the compatible and incompatible blocks. The results revealed that leaders initiated their actions sooner in the compatible than incompatible block, suggesting they anticipated the type of the follower's upcoming response.

Taken together, these independent investigations suggest that action execution in social interactions is likely to be affected by both mechanisms - anticipation of the partner's response associated with one's own action and adaptation to the partner's observed response speed. However, no study has yet investigated the interplay between these mechanisms. We set out to

fill this gap using the same leader/follower button-pressing paradigm as in past research (Lelonkiewicz & Gambi, 2017; Pfister et al., 2013; 2017). In a set-up allowing for anticipation and adaptation alike (Experiments 1 and 4), or for anticipation only (Experiments 2 and 3), we tested how these mechanisms affected action planning and execution. In addition, while previous studies manipulated the follower's response between blocks, we used a design where the response varied trial-by-trial. This allowed us to address an important, and so far unanswered, question: How flexible is the anticipatory mechanism proposed by the sociomotor framework (Kunde et al., 2018)? Past research has demonstrated that agents anticipate a partner's behavior when the partner consistently produces this behavior, for example a compatible response, over many trials, but it is less certain whether anticipation would be engaged when the partner dynamically alternates between producing compatible and incompatible responses (a situation that is not uncommon in social interactions).

In Experiment 1, we investigated whether adaptation and anticipation affect leader's action execution in such interactions. We hypothesized that, if action-effect anticipation is engaged, leaders should be quicker to initiate their actions on trials where the upcoming follower's response would be compatible (as compared to trials where it would be incompatible). Further, if action execution is shaped by spontaneous temporal adaptation, leaders' speed on the current trial should be positively correlated with follower's speed on the preceding trial.

Experiments 2 and 3 used the same task as Experiment 1 but with pre-programmed virtual followers replacing human followers. The main purpose of adopting this design was to allow full control over the timing of responses, while retaining the manipulation of response compatibility (as in Pfister et al., 2017). Specifically, we held the speed with which the followers initiated their responses constant, so we could investigate whether anticipation of the follower's response type affected leaders' actions independently from any phenomena related to response speed.

Finally, in Experiment 4, we used a variant of the virtual follower paradigm to address another important question related to the sociomotor account of action planning (Kunde et al., 2018): What features of the upcoming response are captured by action-effect anticipation? Whereas previous research showed that this mechanism contributes to the ability to anticipate what type of response will be produced, it is unclear whether it may also underlie the ability to anticipate when the response will occur. Although there is some evidence that agents represent the delay between their actions and upcoming non-social effects (Dignath & Janczyk, 2017; see also Dignath, Pfister, Eder, Kiesel, & Kunde, 2014; Thomaschke & Dreisbach, 2015), a test of whether agents use this mechanism to anticipate the timing of their partner's responses is currently lacking. Thus, in Experiment 4, we varied the speed of the virtual followers' responses while keeping the relationship between the leaders' actions and followers' responses constant (i.e., responses were always compatible), and we tested if leaders anticipated the speed with which the follower would initiate the response.

Experiment 1

Experiment 1 tested whether anticipation and adaptation shaped leaders' action execution in an interaction where the compatibility between leader and follower actions varied from trial to trial. Crucially, the engagement of action-effect anticipation in such contexts is not trivial. Recall that the mechanism proposed by the sociomotor framework (Kunde et al., 2018) requires a stable associative binding between the action and the partner's response. It is plausible that agents exploit such associations when their partner consistently produces the same type of response (e.g., tossing a ball to one another). However, in many interactions the partner produces different responses to one and the same agent's action (e.g., in tandem canoeing, the person in the back paddles on the right side while the person in the front corrects the course by varying between the left or right side), making it potentially difficult for the agent to acquire and update the action-response associations. Although there is some suggestion that agents can anticipate non-social

effects when the action-effect mapping changes between trials (Gaschler & Nattkemper, 2012; Pfister, Kiesel, & Melcher, 2010; Zwosta, Ruge, & Wolfensteller, 2013), current evidence for anticipation of social effects is confined to paradigms where the mapping changes between experimental blocks (Müller, 2016; Pfister et al., 2013; 2017; Weller et al., 2019).

Thus, in Experiment 1 we tested if leaders anticipated the follower's response in an interaction where the type of the upcoming response was randomly determined at the beginning of each trial. We hypothesized that if anticipation is automatically engaged in such circumstances, leaders should initiate their actions more quickly on trials where the follower would produce a compatible (vs. an incompatible) response. Moreover, we tested if leaders' engaged in temporal adaptation. Consistently with the evidence that such adaptation occurs on trial-by-trial basis (e.g., Konvalinka et al., 2010; Lelonkiewicz & Gambi, 2017; Okano et al., 2017), we expected to observe a positive correlation between leaders' speed on the current trial and follower's speed on the preceding trial.

Methods

Raw data, analysis scripts, experiment scripts, stimulus materials, pre-registered protocols, and additional details about the project are available at Open Science Framework (https://osf.io/532qr/).

Participants. We recruited 40 participants (i.e., 20 pairs; mean age: 27.6 years, range: 20-65 years; 27 females, 6 left-handed; tested at University of Würzburg). A power analysis based on the effect size for response anticipation suggested a sample size of at least 12 participants (effect size: $d_z = \frac{t}{\sqrt{n}} = \frac{3.52}{\sqrt{24}} = 0.89$; desired power: $1 - \beta = 0.80$; data taken from Pfister et al., 2013). We opted to recruit a somewhat larger sample, however, to account for possible reductions of the effect size due to the trial-wise design. All participants gave informed consent prior to the experiment and received course credit for participation. The study followed the guidelines of the ethics committee of the Institute of Psychology at the University of

Würzburg and the ethical regulations of the German Society for Psychology (Deutsche Gesellschaft für Psychologie).

Stimuli, apparatus, and procedure. The methods were a close replication of previous work (Experiment 1 in Pfister et al., 2013), with the exception that the compatibility between the leader's action and the follower's response was manipulated on a trial-by-trial basis (rather than between blocks). Leader and follower sat across the table from each other, controlling one external response key each, and the leader observed a 17'' monitor which was placed at the edge of the table (for a photograph of the set-up, see Pfister et al., 2013, Supplement).

In the beginning of each trial, participants heard an auditory cue indicating whether on the current trial the follower would produce a compatible or an incompatible response (either a synthesizer chord or a whistle sound played back via speakers, each 900 ms long; the mapping of sound to response type was counterbalanced across participant pairs). Next, 1000 ms after the end of the auditory cue, the screen changed from black to either red or green, prompting the leader to produce a short (1–150 ms) or a long (200–600 ms) keypress (color to keypress mapping was counterbalanced across participant pairs). To measure keypress durations, the external keys fed back onset (i.e., keypress) and offset (i.e., key release) events to the computer's parallel port. Leaders were instructed to lift the finger visibly from the key when finishing their keypress action so that the end of the leader action would be clearly detectable for the follower. Depending on the upcoming response condition, the follower would then respond with either the same or the other type of keypress. The follower was instructed to initiate their keypress immediately after the leader had finished his or her action (i.e., lifted the finger from the key). In case of errors (wrong leader or follower response, indeterminate responses with 150 ms < duration < 200 ms or durations > 600 ms, premature response of the follower, or no action), the computer played a buzzer sound and displayed an error message for 1000 ms. The screen went

black at the end of each trial and the program waited for another 500 ms until the next trial started.

Participants were acquainted with the auditory and color cues at the beginning of the session: The experimenter repeatedly played the sounds until both participants indicated to have memorized the mapping; they then had the opportunity to practice short and long keypresses before commencing the experiment proper. Participants completed 20 blocks consisting of 32 trials. Each block comprised 8 repetitions of each possible mapping of the leader's action (short, long) and the follower's response (compatible, incompatible; Figure 1), which were presented in random order. After 10 blocks, the participants swapped roles so that the leader of the first half of the experiment became the follower in the second half and vice versa.

Statistical analyses. As per our experimental design, we tested whether leader's action initiation time (i.e., the time between the color cue and when the leader starts pressing on their key; henceforth, *Leader RT*) would differ between trials where the follower was expected to produce a compatible versus an incompatible response (*Upcoming Response: compatible vs. incompatible*). For completeness, we also checked whether such an effect was modulated by the type of response produced by the follower on the preceding trial (*Preceding Response: compatible vs. incompatible*), as there may be sequential effects when the follower's response varies on each trial (e.g., participants might be biased to anticipate the same effect type as in the previous trial; cf. Liepelt, Wenke, Fischer, & Prinz, 2011). Thus, we conducted a 2X2 within-subjects Analysis of Variance (ANOVA) followed up by two-tailed paired-sample *t*-tests. An analogous analysis was conducted for follower's action initiation time.

Moreover, to determine whether Leader RT was affected by the speed with which the follower initiated their response on the preceding trial (i.e., the time between when the leader lifts the finger from their key and when the follower starts pressing on their key, calculated for the preceding trial; *Preceding Follower RT*), we carried out a Linear Mixed Effect (LME) model

involving Preceding Follower RT, Upcoming Response, and Preceding Response (and all

interactions) as fixed effects, and by-subjects random intercepts and slopes for all fixed effects

and interactions (we scaled and centered Preceding Follower RT and applied contrast effect-

coding to Upcoming Response and Preceding Response). Full model structure and results, as

well as error rate analysis can be found in the Supplement.

Results

Prior to the Leader RT analysis, we excluded four participants whose error rate exceeded

33% in at least one design cell (leaving n = 36). We also discarded the first block from each half

of the experiment as training, error trials (9%), and outlier trials (i.e., RT > 2.5 SD from the

participant's condition mean; further 2%).

To investigate if leaders engaged in anticipation, we tested if leaders' actions were

affected by the type of the upcoming response of the follower, and whether this effect would be

modulated by the type of response produced by the follower in the preceding trial. The results

are illustrated in Figures 2 and 3. The ANOVA revealed two main effects qualified by an

interaction (Upcoming Response: $F(1,35) = 13.76$, $p < .001$, $\eta_G^2 < .01$; Preceding Response:

$F(1,35) = 7.76$, $p < .001$, $\eta_G^2 < .01$; interaction: $F(1,35) = 58.06$, $p < .001$, $\eta_G^2 = .02$). Follow-up t-

tests showed that leaders initiated their actions more quickly before compatible than

incompatible responses, but only if on the preceding trial the follower had produced a compatible

response ($t(35) = 6.58$, $p < .001$, $d_z = 1.10$); if, however, on the preceding trial the follower had

produced an incompatible response, leaders' actions were not reliably affected by the upcoming

response ($t(35) = -1.74$, $p = .090$, $d_z = -0.29$).

We conducted a corresponding analysis on Follower RT, after treating it the same way as

we did for Leader RT (leaving n = 28). The results are illustrated in Figure 2. There was a main

effect of Upcoming Response ($F(1,27) = 32.73$, $p < .001$, $\eta_G^2 = .04$), but no effect of Preceding

Response ($F(1,27) = .51$, $p = .483$, $\eta_G^2 < .01$). Importantly, just as in the Leader RT data, the

analysis revealed an interaction ($F(1,27) = 30.53$, $p < .001$, $\eta_G^2 = .02$), and the follow-up

comparisons detected a large and robust effect of the upcoming response for trials occurring after

a compatible response trial ($t(27) = 7.21$, $p < .001$, $d_z = 1.36$) and a small, non-reliable effect for

trials occurring after an incompatible response trial ($t(27) = 1.65$, $p = .110$, $d_z = 0.31$).

To determine if leaders engaged in temporal adaptation, we tested whether leaders' action

initiation speed on a given trial was affected by the speed with which the follower initiated their

response on the preceding trial (Figure 4). The LME model confirmed the findings from the

ANOVA, i.e. the main effects of Upcoming Response ($B = -12.45$, $SE = 3.43$, $t = -3.63$, $p < .001$)

and Preceding Response ($B = -5.17$, $SE = 2.43$, $t = -2.13$, $p = .041$) and their interaction ($B = -$

36.14, $SE = 5.10$, $t = -7.08$, $p < .001$). Critically, it also revealed a main effect of Preceding

Follower RT, such that the longer the follower RT on the preceding trial, the longer the leader

RT on the current trial ($B = 7.83$, $SE = 1.60$, $t = 4.88$, $p < .001$). Interestingly, there were no

reliable interactions involving this effect (ps > .098), suggesting that it was independent from the

effects related to the follower's response type (either preceding or upcoming).

Discussion

In Experiment 1, leaders interacted with a follower who produced either a compatible or

an incompatible response, varying compatibility on a trial-by-trial basis. Consistently with

previous studies, the speed with which leaders initiated their action on the current trial was

positively correlated with the follower's speed on the preceding trial, indicating that leaders

engaged in temporal adaptation (Konvalinka et al., 2010; 2014; Loehr & Palmer, 2011; Okano et

al., 2017; Wu, Chapman, Walker, Bischof, & Kingstone, 2013). Moreover, our analysis

suggested that adaptation impacted leaders' actions independently from any effects of response

type (as in Experiment 2 of Lelonkiewicz & Gambi, 2017).

We also found evidence that leaders anticipated the follower's response type: Leaders

initiated their actions sooner prior to a compatible than incompatible response, suggesting they

represented the upcoming response in their motor plan. Importantly, this implies that agents are able to anticipate another person's response, and incorporate it in their motor plan "on the fly", and not just on the basis of observing repeated and consistent associations over many trials, as in previous blocked designs (Pfister et al., 2013; 2017). But whereas this effect was large and statistically robust for trials occurring after a compatible response from the follower, it was considerably smaller and failed to reach statistical significance for trials occurring after an incompatible response. There are a number of possible explanations for this striking interaction.

One interpretation of this result is that leaders did in fact anticipate the partner's behavior following both compatible and incompatible responses, but after observing an incompatible response anticipation was attenuated by conflict adaptation, a processing mode that has been shown to hamper effects related to stimulus representation after experiencing conflict (e.g., the Simon effect; Wühr & Ansorge, 2005; see Gratton, Coles, & Donchin, 1992; we return to this in General Discussion). Alternatively, this result could be due to leaders anticipating the speed rather than the type of the upcoming response. Although it is currently unclear whether agents use action-effect anticipation to predict the timing of their partner's responses, there is evidence that they do so with regards to non-social action effects (i.e., they represent the delay between the action and its non-social effect; Dignath & Janczyk, 2017; Dignath et al., 2014; Thomaschke & Dreisbach, 2015). Importantly, while in Experiment 1 followers initiated their response sooner if it was compatible rather than incompatible (the well-known automatic imitation effect; Heyes, 2011), this effect was considerably larger for trials occurring after a compatible than an incompatible response. Thus, it is possible that leaders anticipated the different speed of compatible and incompatible responses particularly after a compatible trial, when the difference between these response types was salient. In contrast, leaders' action execution was not affected by response compatibility after an incompatible trial, when the follower's speed did not reliably differ depending on compatibility. Experiment 2 was conducted to tease apart these alternative

explanations (i.e., response type anticipation modulated by conflict adaptation versus response speed anticipation).

Experiment 2

To study response type anticipation without possible confounding influences of response speed, in Experiment 2 the role of the human follower was taken by two virtual followers who produced their responses with constant speed. One follower always produced compatible, while the other follower always produced incompatible responses; since the identity of the follower was announced at the beginning of each trial, participants (who now only acted as leaders) could anticipate the upcoming response based on the virtual follower's identity. We hypothesized that if the critical anticipation finding from Experiment 1 (i.e., leaders' actions were affected by the upcoming response after compatible, but not after incompatible trials) can be attributed to anticipation of response type (modulated by conflict adaptation), we should observe it also in Experiment 2. Alternatively, if it was solely due to anticipation of response speed, leaders' actions should now be unaffected by the manipulation of response compatibility.

Methods

Participants. Thirty-two participants took part in the experiment (mean age: 22.6 years, range: 18-37 years; 26 females, 4 left-handed; tested at University of Würzburg), again allowing sufficient power for testing the effect of response anticipation. Ethical approval, informed consent and participant compensation were arranged as per Experiment 1.

Stimuli and apparatus. Participants sat in front of a 17'' CRT monitor and operated a standard German QWERTZ keyboard. They used the M key for long and short keypresses and K to react to the catch trials (see Design and Procedure for details). The virtual followers were presented in the middle of the screen against a black background. Either follower appeared seated at a table in front of a laptop, with their upper body visible to the participant. Stimuli prompting participants' reactions were displayed at the bottom of the screen.

The videos showing the follower were implemented in E-Prime, by presenting still frames of successive phases of the movements at 30Hz. The videos showing the follower producing a long or a short keypress had the same structure for both followers: The movement started 33 ms (i.e., 1 video frame) after the video onset and the follower's hand reached the laptop to press a key after a further 264 ms (8 frames); the hand then remained on the key for 66 ms (2 frames) in the short keypress video and 825 ms (25 frames) in the long keypress video, after which it returned to the starting position. The short keypress video had a total duration of 627 ms (19 frames) and the long keypress video of 1386 ms (42 frames). The video frames were created with Poser 10 (Smith Micro Software Inc., Aliso Viejo, CA) and are available online (https://osf.io/532qr/).

Design and Procedure. At the beginning of the experiment, the virtual followers were introduced as characters with distinct names and identities (one male, Tim, and one female, Sophie). Participants were told that one follower would always produce a compatible response to their action (e.g., after a short keypress of the participant the follower would also perform a short keypress), while the other follower would always produce an incompatible response (e.g., after a short keypress of the participant the follower would perform a long keypress). Thus, the follower's identity determined whether the upcoming response would be compatible or incompatible (the mapping of follower to response type was counterbalanced across participants). Participants then practiced long (200-600 ms) and short keypresses (1-150 ms) and completed six practice trials in which they were familiarized with the structure of standard trials and catch trials (see below).

In each trial, a picture of one of the two followers and a white fixation cross appeared for 1000 ms (Figure 5). Then, a color cue was presented for 200 ms prompting participants to produce either a short or long keypress (blue or red rectangle; color to keypress mapping was counterbalanced across participants). Participants were expected to produce a keypress within

1500 ms from the cue onset. If they produced a correct action, the video of the follower's long or short keypress started after further 300 ms. Next, the picture of the follower stayed on the screen for another 300 ms, after which the screen went black and the next trial started after 1500 ms. If participants produced an incorrect action, no action at all, or initiated the action before the presentation of the cue, an error message was displayed for 1000 ms, the follower remained still and a new trial was started after 1800 ms. Participants completed ten experimental blocks with 40 trials each. The identity of the follower was randomized within blocks, but both followers appeared equally often in each block.

To ensure that participants paid attention to the followers' movements, we implemented catch trials (see Pfister et al., 2017); we deemed these necessary in this experiment because participants were now performing only the role of leaders and interacting with a virtual follower, and were thus potentially more likely to ignore the follower's responses entirely. In catch trials, the time between the participant's keypress and the follower's movement was prolonged from 300 ms to 1000 ms. Participants were asked to press the K key whenever they noticed such a catch trial. Each trial had a one in twenty chance to be a catch trial (determined randomly at the beginning of each trial), but the first five trials of each block were never catch trials to allow participants to get used to standard trials first. If participants detected a catch trial correctly, a reassuring message was displayed (*Well done!*), and if they missed a catch trial, a warning message was displayed (*Pay attention to your partner's reactions!*).

Statistical analyses. Leader RT was analyzed with a 2X2 within-subjects ANOVA followed by paired-sample *t*-tests, as per Experiment 1. However, since now leaders interacted with a follower who initiated responses with constant speed, in Experiment 2 we did not test for the effects of temporally adapting to the follower.

Results

Prior to the analysis, we discarded data as per Experiment 1 (block one, error trials 9%, outliers further 2%; no participant had an error rate qualifying for exclusion). We also discarded observations following catch trials (4%) and excluded one participant who did not respond on any of the catch trials (leaving n = 31). The results are illustrated in Figure 3. A 2X2 within-subjects ANOVA on Leader RT found a reliable main effect of Upcoming Response, a marginal, but not reliable effect of Preceding Response, and a marginal interaction (Upcoming Response: $F(1,30) = 11.62$, $p = .002$, $\eta^2_G < .01$; Preceding Response: $F(1,30) = 4.06$, $p = .053$, $\eta^2_G < .01$; interaction: $F(1,30) = 3.04$, $p = .092$, $\eta^2_G < .01$). Critically, just as in Experiment 1, follow-up comparisons showed that leaders initiated their actions more quickly prior to compatible than incompatible responses, but this effect was robust after compatible trials ($t(30) = 3.23$, $p = 0.003$, $d_z = 0.58$) and not after incompatible trials ($t(30) = -0.24$, $p = .812$, $d_z = -0.04$) (means in Table S1).

Discussion

Experiment 2 replicated the critical finding of action-effect anticipation from Experiment 1: Leaders' actions were affected by the upcoming response, but this effect was statistically reliable only for trials occurring after the follower had performed a compatible response (and not for trials after an incompatible response). Importantly, this pattern now occurred in a setting where the followers initiated their responses with constant speed, suggesting that it can be attributed to anticipation of response type rather than response speed (see also Pfister et al., 2017). Note, however, that the relevant statistical effect (i.e., the effect of upcoming response type for trials after compatible responses) was considerably smaller than in Experiment 1 ($d_z = 0.58$ vs. $d_z = 1.10$). Thus, to assess its robustness, we conducted Experiment 3.

Experiment 3

Experiment 3 was a conceptual replication of Experiment 2. Again, participants acted as leaders and two virtual followers performed compatible or incompatible responses with constant speed. However, we made two important changes: First, to minimize any effect of task-unrelated information about the follower, we displayed only the follower's hand; second, we changed the timing of the responses so that it more closely resembled the typical follower's performance from Experiment 1. We tested if the interaction of Upcoming Response and Preceding Response would replicate in this carefully controlled context and, crucially, whether following a compatible trial, leaders would be quicker when they could anticipate the upcoming response to be compatible. Positive evidence would further corroborate the hypothesis that leaders' actions can be affected by response type anticipation. Experiment 3 was pre-registered (https://osf.io/532qr/).

Methods

Participants. As per our pre-registration, we halted data collection after reaching the desired sample size of 32 participants (mean age: 21.6 years, range: 18-33 years; 20 females, none left-handed; tested at University of Edinburgh). We estimated the sample size based on the effect size for the Upcoming Response*Preceding Response interaction from Experiment 1 (we used package *simr* in R with 10 simulations, and the *compare* "lr" method). This showed that a sample size of 32 achieves close to 100% power. Thirteen additional participants were tested but their data were discarded prior to response speed analyses because of a technical problem (4) or because they failed to meet one of the criteria set in our pre-registration (9): They were either left-handed (5), or made errors on more than 33% of trials in at least one design cell (4). Participants gave informed consent and received £7; all experimental procedures were approved by the Ethics Committee at the Department of Psychology, University of Edinburgh.

Stimuli and apparatus. Participants sat in front of an LCD monitor and operated a

custom-made button box (similar to the one depicted in front of the virtual follower; see Figure

5) with their right-hand. Their left hand rested on a standard English QWERTY keyboard, which

they used to respond to catch trials by pressing the K key. The follower's response began with a

still frame (33 ms) of the neutral position, then the index finger began moving from the neutral

position to reach the button (movement duration: 165 ms, or 5 frames); note that this stage (i.e.,

165 ms) was shorter than in Experiment 2 (i.e., 264 ms) – this was to ensure that followers

responded with speed resembling the one typically produced by human followers; next, the

finger remained on the button for either 66 ms (2 frames, short press) or 825 ms (25 frames, long

press; as in Experiment 2), after which it returned to the neutral position during 363 ms (11

frames).[1] A "click-on" sound played when the hand pressed the button, and a "click-off" sound

played on release (both sounds 60 ms long). The virtual hands were created in Blender (v2.78;

open source, The Blender Foundation); video frames used for presentation to participants are

available online (https://osf.io/532qr/).

Design and Procedure. As in Experiment 2, participants (acting as leaders) interacted

with two virtual followers, who were introduced using a male (Tim) and a female name (Sophie).

Importantly, in the present design participants only saw the followers' hands, i.e., one follower

was represented by a right hand wearing a white ring on the index finger, while the other was

represented by an identical hand wearing a black ring; the hands were shown resting on a

---

[1] In Experiment 3, both followers responded with a speed that was as close as possible to the

average Follower RT observed in Experiment 1 (i.e., Experiment 3: 498 ms = 300 ms idle

period + 33 ms still frame + 165 ms finger down; Experiment 1: 484 ms). The finger up

period was prolonged relative to Experiment 2 so as to maintain the total duration of the

follower's response in Experiments 2-3, i.e., short response 627 ms, long response 1386 ms.

white/black surface to make it easier for participants to identify the follower. Further, we set the

inter-trial interval to 500 ms (to replicate the interval used in Experiment 1). Apart from that, the

trial structure was equivalent to the one of Experiment 2.

Statistical analyses. Leader RT was analyzed as in Experiment 2.

Results

Prior to the analysis, data was treated as in Experiment 2 (excluded error trials 11%, trials

after catch trials 5%, outliers 2%). The results are shown in Figure 3. The analysis replicated the

critical Upcoming Response*Preceding Response interaction ($F(1,31) = 7.32$, $p = .011$, $\eta_G^2 < .01$)

from Experiment 1, and follow-up t-tests confirmed that leaders initiated their action more

quickly prior to compatible than incompatible responses, but only after trials where the follower

had produced a compatible response ($t(31) = 2.91$, $p = .006$, $d_z = 0.52$; response compatibility did

not reliably affect leaders action execution after incompatible trials: $t(31) = -1.70$, $p = .098$, $d_z = -$

0.30). The two main effects were not reliable (Upcoming Response: $F(1,31) = 1.50$, $p = .230$, η_G^2

$< .01$; Preceding Response: $F(1,31) = 1.29$, $p = .265$, $\eta_G^2 < .01$).

Discussion

In Experiment 3 we found further evidence for the hypothesis that action execution can

be affected by response type anticipation, and that such mechanism can act independently of any

processes involving follower's speed. These results, and results from Experiment 2, imply that

the behavioral pattern observed in Experiment 1 was caused at least in part by response type

anticipation. Notwithstanding, the critical effect in Experiments 2 and 3 was considerably

smaller than in Experiment 1 ($d_z = 0.58/0.52$ vs $d_z = 1.10$). The smaller effect size in

Experiments 2-3 could be due to a number of differences between these experiments and

Experiment 1. Most notably, in Experiment 1 leaders (participants) interacted with a human

follower (another participant), while in Experiment 2 they interacted with a virtual follower, and

just a virtual hand in Experiment 3. There is evidence that others' actions are less strongly

represented when the other is a non-human agent (Müller et al., 2011; Press, Bird, Flach, &

Heyes, 2005; Stenzel et al., 2012; Tsai, Kuo, Hung, & Tzeng, 2008; Weller et al., 2019).

However, another possibility is that anticipation of followers' response speed did play

some role in leaders' action execution in Experiment 1 (see Experiment 1, Discussion). Since

agents readily anticipate the delay between actions and their non-social effects during action

planning (e.g., Dignath & Janczyk, 2017), it is plausible that the timing of partner's responses

may be anticipated in a similar manner. Recall that followers in Experiment 1 initiated

compatible responses more quickly than incompatible responses, and that this difference was

particularly pronounced on trials occurring after a compatible trial (for an illustration of this

finding, see Figure 2). Thus, in Experiment 1, leaders could have anticipated the speed of the

upcoming response based on this pattern, which in turn resulted in a greater effect size in this

experiment as compared to Experiments 2-3 (where response speed was constant and such

anticipation could not have an effect). We ran Experiment 4 to investigate this possibility.

Experiment 4

Experiment 4 tested if agents represent the timing of the partner's upcoming response in

their action plan. There is some evidence that this might be the case: In a recent study by Dignath

and Janczyk (2017), keypresses were initiated sooner when they would be followed by a tone

occurring after a short, rather than long delay, suggesting that the anticipated delay length

affected action execution (see also Dignath et al., 2014; Thomaschke & Dreisbach, 2015).

However, it is unclear whether these findings can be extended to social action effects. Whereas

several studies demonstrated that some form of temporal anticipation is present in social

interactions, most of these demonstrations involved tasks that required agents to anticipate, or at

least to coordinate with each other (e.g., Wolf et al., 2018; for reviews, see Harry & Keller, 2019;

Keller et al., 2014; van der Steen & Keller, 2013). Thus, it is currently unclear whether agents

would anticipate the timing of their partner's responses when the task does not require them to do so.

To investigate this, in Experiment 4 we once again used the button-pressing paradigm which does not require leaders to anticipate or to coordinate. Specifically, we used a design similar to Experiment 3 where leaders (participants) interacted with two virtual followers (animated hands). Now, however, the followers produced only compatible responses and instead we manipulated their response speed: One follower initiated responses with constant speed, whereas the other increased their speed across the experimental session. Consequently, particularly towards the end of the session, one follower was quicker to respond than the other. Thus, follower's identity could help anticipate whether the upcoming response would be fast or slow. We hypothesized that, if leaders anticipate the timing of the follower's responses based on action-effect associations, they should initiate actions more quickly where they interact with the quicker follower (i.e., where they could anticipate a faster response), as compared to trials where they interact with the slower follower (i.e., where they could anticipate a slower response). Experiment 4 was pre-registered (https://osf.io/532qr/).

Methods

Participants. We recruited 32 participants (mean age: 20.9 years, range: 18-27 years; 24 females, none left-handed; tested at Cardiff University). A further 8 participants were tested but their data was discarded (7 because their error rate was greater than 33% in at least one design cell, and 1 due to technical failure). Participants gave informed consent and received £8 compensation. All experimental procedures were approved by the Ethics Committee at the School of Psychology, Cardiff University.

Stimuli and apparatus. Like in Experiment 3, participants were seated in front of a LCD monitor, they operated the custom-made button box with their right hand, while their left hand

rested on an English QWERTY keyboard to respond to catch trials (using the K key). The

stimuli representing the virtual followers were the same as in Experiment 3.

Design and Procedure. Experiment 4 followed the design and procedure of Experiment

3, but with a few modifications. Specifically, the virtual followers now produced only

compatible responses and we manipulated their response speed: The experimental session was

divided into four parts, across which for one follower we incrementally increased their response

initiation speed while keeping it constant for the other follower (Table 1). Recall that follower's

response speed was the time between the moment when the leader lifts the finger from their key

and the moment when the follower starts pressing on their key. For the virtual followers in

Experiments 2-4, response speed comprised the pre-presentation interval, with the addition of the

time to display one still frame of the video and the time to complete the finger down movement.

Thus, to manipulate response speed in Experiment 4, we modulated the length of the idle period

before the presentation of the response (see Figure 5).

To help relate Experiment 4 to the findings of Experiment 1, we modelled the responses

based on those of human followers in Experiment 1: In Part 1, response speed of both virtual

followers was identical to the mean Follower RT in Experiment 1; In Part 2, one follower

responded more quickly than the other, and the difference between their speeds corresponded to

the difference in Follower RT between compatible and incompatible responses on trials after an

incompatible trial; In Part 3, this difference further increased and now corresponded to the

Follower RT difference between compatible and incompatible responses after a compatible trial;

Finally, in Part 4, the difference between followers increased once again (this time it was

estimated with a linear function fitting the difference values from preceding parts). All response

speeds were presented with the addition of random jitter across trials (+/-25 ms). There were five

blocks of 32 trials in each part of the experiment. The instructions never mentioned the

followers' speed. Catch trials were also modified: they were now trials in which the follower responded incompatibly. Every other aspect of the procedure was the same as in Experiment 3.

Statistical analyses. We investigated if Leader RT would vary depending on whether the leader expected a fast or slow response (*Upcoming Speed: fast vs. slow*). Importantly, since the speed difference between the fast and slow responses increased across the experimental session, we expected this effect to be modulated by the factor coding for the progression of the session (*Part: 1 vs. 2 vs. 3 vs. 4*). Thus, we conducted a 2X4 within-subject ANOVA. Further, we tested if Leader RT was affected by the Preceding Follower RT (i.e., speed with which the follower initiated their response on the preceding trial). To this end, we analyzed the subset of trials following those trials where the follower speed varied (i.e., quick follower in parts 2-4): We ran a LME model regressing Leader RT against Preceding Follower RT (scaled and centered), with by-subjects random intercepts and slopes.

Table 1. Experiment 4: Average response speed of the followers across parts of the experimental session.

	Part 1	Part 2	Part 3	Part 4
constant follower	460 ms	460 ms	460 ms	460 ms
quick follower	460 ms	444 ms	394 ms	344 ms

Results

As per our pre-registration, we discarded the first block from each part of the experiment (as leaders may take time to learn to anticipate the fast followers' speed after a speed change), error trials (10%), observations following catch trials (4%), and outliers (2%). The ANOVA revealed a main effect of Part, but no effect of Upcoming Speed and no interaction, suggesting a

practice effect – leaders became faster as the experiment progressed, regardless of whether the upcoming follower's response would be fast or slow (Part: $F(3,93) = 4.42$, $p = .017$, $\eta_G^2 = .01$; Upcoming Speed: $F(1,31) = 2.32$, $p = .138$, $\eta_G^2 < .01$; interaction: $F(3,93) = 0.87$, $p = .462$, $\eta_G^2 < .01$). Consistently, follow-up comparisons conducted on data from each part found little evidence for the Upcoming Speed effect (uncorrected ps > .033; full results in Supplement).

In addition, we investigated if leaders temporally adapted (see Figure 4). The analysis revealed a main effect of Preceding Follower RT indicating that leaders adapted to the follower's response speed on the preceding trial ($B = 3.76$, $SE = 1.70$, $t = 2.21$, $p = .035$; see Supplement for the details about the LME model and for additional analyses confirming this finding).

Discussion

Experiment 4 tested if participants spontaneously anticipated the follower's response speed. Although they adapted to the speed of follower's response on the preceding trial, they did not show evidence of anticipating the speed of the upcoming response. This suggests that such anticipation did not contribute to the critical behavioral pattern in Experiment 1 nor to the difference in effect sizes observed between Experiment 1 and Experiments 2-3.

General Discussion

Both anticipation and adaptation are important for action planning and execution, but the exact contribution of each mechanism to social interactions remains poorly understood. We addressed this gap in four experiments involving a leader/follower paradigm. Our results suggest that agents *anticipate* the type of their partner's upcoming response action motor planning and execution, even in interactions where the mapping between their action and the response changes on a trial-by-trial basis (Experiments 1, 2, 3). In contrast, we found no evidence that anticipation involves a representation of partner's speed in such interactions (Experiment 4). In addition, we observed that agents *adapt* to the speed of their partner's past responses, and our data suggested that such adaptation is engaged independently from anticipation (Experiments 1, 4). These

findings have several implications, both for accounts of social interactions and for our understanding of the mechanisms through which anticipation and adaptation are realized.

Anticipation. The sociomotor framework (Kunde et al., 2018) postulated that much of the anticipation observed in social interactions can be attributed to a general mechanism that governs actions in individual and social contexts alike. In this view, actions are represented in terms of their effects, so executing an action in a social context involves anticipating the response that this action typically evokes in others. The critical prediction of this account is that action execution should be facilitated when the upcoming response is similar to one's own action. Consistently, we found that leaders initiated their actions sooner prior to compatible than incompatible follower's responses (at least on trials occurring after a compatible response; Experiments 1-3). Importantly, we demonstrated this in a social context where the follower produced both compatible and incompatible responses, switching randomly between these response types on a trial-by-trial basis. Thus, together with previous research that used blocked designs (e.g., Pfister et al., 2017), our study suggests that the mechanism proposed by the sociomotor framework is a plausible candidate for explaining anticipation across various kinds of social interactions.

Further, our findings inform the discussion of what features of the partner's responses are represented through this mechanism. Although the sociomotor framework does not make specific predictions in this regard, the underlying process of associative learning (on which this account relies) would suggest that associations should be formed on all the dimensions shared between the action and response (Shin, et al., 2010; cf. Weller et al., 2019). Thus, in our experiments, agents should represent both the type and the speed of the upcoming response. However, whereas we observed response type anticipation (Experiments 1-3), we found little evidence that agents represent the speed of the upcoming response: Leaders' initiated their actions just as quickly when they were about to interact with a follower who was consistently slow or a

follower who was fast (Experiment 4). This is difficult to reconcile with the vast evidence for

anticipation of other people's timing in social interactions (e.g., Knoblich & Jordan, 2003;

Pecenka & Keller, 2011; Wolf et al., 2018).

One possible explanation for the lack of speed anticipation in our experiments is that,

unlike anticipating the timing of non-social effects (Dignath & Janczyk, 2017; Dignath et al.,

2014; Thomaschke & Dreisbach, 2015), anticipation of partner's timing is realized through a

different mechanism, perhaps one driven by task goals. This would be consistent both with

earlier studies showing such anticipation in tasks that explicitly require participants to coordinate

in time, and with theoretical accounts viewing anticipation as a voluntary process (Harry &

Keller, 2019; Keller et al., 2014; van der Steen & Keller, 2013). Another possibility is that the

incorporation of effect delays into action planning is less likely for social than for non-social

effects, since effect delays might be more variable in social interactions (Kunde et al., 2018).

However, neither of these explanations conforms to a strong formulation of the ideomotor

theory, which would expect anticipation to be engaged automatically and irrespectively of the

nature of the action effect. That said, null results should be interpreted with caution.

While generally underscoring the role played by action-effect anticipation in social

interactions, our findings are also informative about the conditions under which the involvement

of such mechanism is reduced. Consistently across our experiments, a difference between

compatible and incompatible responses for leaders' action initiation occurred on trials following

a compatible follower response, but was much reduced on trials following an incompatible

response. This pattern of results is likely related to conflict adaptation (Gratton et al., 1992;

Grosjean & Mordkoff, 2001; Wühr & Ansorge, 2005), a processing mode engaged after

experiencing a cognitive conflict, and involving active inhibition of stimulus or response features

that might induce further conflict (Fanini, Nobre, & Chelazzi, 2006; Melcher et al., 2015; Nobre,

Rao, & Chelazzi, 2006; for a review, see Egner, 2007). For our experiments, such an account

would suggest that leaders formed a representation of the upcoming follower's response (e.g., "the follower will move the finger downwards to press the button"), but after incompatible trials they inhibited the features of this representation that conflicted with their action plan (e.g., "the follower will perform a different type of press than me"), thus reducing the effect related to anticipating compatible vs. incompatible responses.

However, an alternative view would hold that, after experiencing conflict on incompatible trials, agents transiently switched to a mode of action representation where anticipated social effects were no longer included in the action plan at all. Such alternative action representation could for example include only body-related effects, such as visual and proprioceptive effects of the planned finger movement, but not a representation of the follower's action as being compatible or incompatible with the leader's own action (Pfister, Janczyk, Gressmann, Fournier, & Kunde, 2014; Thébault, Michalland, Derozier, Chabrier, & Brouillet, 2018; Wirth, Pfister, Brandes, & Kunde, 2016; see Pfister, 2019, for a review). If correct, this view would suggest that anticipation of the follower's response type only occurred after compatible trials but not after incompatible trials. Even though both accounts might explain the reduced compatibility effect following incompatible trials, one aspect of our findings favors the interpretation that anticipation of social effects did not occur after incompatible trials - we did not find evidence for a residual compatibility effect following such trials.[2] Thus, we propose that experiencing conflict due to incompatibility between their action and the partner's response cause agents to transiently switch to a different mode of action representation, one that does not incorporate anticipated social action effects into the action plan.

---

[2] Although one could also assume a residual compatibility effect to be overshadowed by post-conflict slowing, post-conflict slowing is typically only observed in simple, univalent tasks (Verguts, Notebaert, Kunde, & Wühr, 2011), which are unlike those used in the current study.

Finally, a third possible interpretation of our results pattern is that agents might have been slowed by the need to represent a distinct action for the partner (e.g., short keypress) in addition to representing one's own (e.g., long keypress).[3] This could be caused either by observing an incompatible past response or anticipating an incompatible upcoming response. In either case, the processing burden would be greater than when agents' actions were both preceded and followed by a compatible response (and so the representation of partner's action was identical to one's own). Note that this interpretation is compatible with the hypothesis that agents automatically represent the type of their partner's upcoming response (Kunde et al., 2018).

Adaptation. Our study demonstrates that agents spontaneously engage in temporal adaptation: When interacting with a follower whose response speed varied between trials, leaders adapted their action initiation speed to the follower's speed on the preceding trial. They did so even if they were not explicitly tasked with coordinating their actions in time, and even though they performed discrete actions. This is consistent with evidence suggesting that adaptation is ubiquitous in social interactions, occurring when agents perform continuous (e.g., Konvalinka et al., 2010) or discrete actions (e.g., van der Wel & Fu, 2015), and when they do (e.g., Okano et al., 2017) or do not have a goal to coordinate (e.g., Schmidt & O'Brien, 1997).

Importantly, we showed that spontaneous temporal adaptation can act independently from anticipation: Our analyses suggested that, in an interaction where both mechanisms were at play, adaptation and anticipation exerted independent effects on the speed with which leaders initiated their actions (Experiment 1). Moreover, we found evidence for temporal adaptation also in an interaction where anticipation was not engaged (Experiment 4). Consistently with recent studies, this implies adaptation is a distinct mechanism (Konvalinka et al., 2010; 2014; Koban, Ramamoorthy, & Konvalinka, 2019; Lelonkiewicz & Gambi, 2017; Okano et al., 2017).

---

[3] We thank an anonymous reviewer for suggesting this additional interpretation.

Since our study did not aim to test any particular account of temporal adaptation, we can only speculate on what is the exact nature of this mechanism. According to nonlinear dynamic models of synchronization, motor activity of one agent becomes synchronized with the activity of another through perceptual coupling, similarly to two metronomes synchronizing via a mechanical connection. In this view, adaptation stems from the general tendency of coupled systems to self-organize (Dumas et al., 2014; Fairhurst, Janata, & Keller, 2012; 2014; Kelso, de Guzman, Reveley, & Tognoli, 2009; Schmidt & O'Brien, 1997). Alternatively, temporal adaptation can be viewed through the lens of linear event-based models, which propose that motor activity is organized by an internal time-keeping system (Harry & Keller, 2019; Keller et al., 2014; van der Steen & Keller, 2013). In this perspective, adaptation results from automatic correction mechanisms that adjust the timing of the time-keeper in response to the temporal patterns observed in the environment (Repp, 2005; Repp & Su, 2013). While these models have been developed to explain behavior in continuous synchronization tasks, and have not been applied to discrete reaction tasks akin to the one used here, participants in our study may have fallen into a semi-rhythmic pattern of performance due to the regular temporal structure of the task, which used constant and relatively short inter-trial intervals. In sum, while at this time we cannot ascertain which group of models better captures the adaptation observed in our study, our findings are compatible with accounts postulating that interacting agents engage in spontaneous temporal adaptation.

The Role of Anticipation and Adaptation in Social Interactions. Consistently with the proposition that social interactions rely both on anticipatory and adaptive mechanisms (Keller, et al., 2014; Knoblich et al., 2011; Loehr & Palmer, 2011; Pickering & Garrod, 2007; Schmidt et al., 2011), we found that agents engaged action-effect anticipation and temporal adaptation in an interaction where their partner alternated between producing compatible and incompatible responses. Together with the studies that attested these mechanisms for tasks where response

compatibility varied between blocks (Lelonkiewicz & Gambi, 2017; Pfister et al., 2013; 2017),

our findings suggest that anticipation and adaptation might be involved in social interactions

more generally. Interestingly, despite both mechanisms being primarily related to action

planning and execution in the individual, it is plausible that their involvement in interactions can

also have the function of increasing coordination between agents. Specifically, anticipating the

upcoming response can be seen as a form of task co-representation, a process allowing agents to

infer the goals of their interaction partner (Knoblich et al., 2011; Sebanz et al., 2006; Sebanz,

Knoblich, & Prinz, 2003; 2005). Further, temporal adaptation often leads the agents to converge

on a common temporal structure, which in turn makes their actions more predictable and easier

to coordinate with (Vesper, Butterfill, Knoblich, & Sebanz, 2010; Vesper, van der Wel,

Knoblich, & Sebanz, 2011). In this sense, our findings point to an interesting possibility that the

same cognitive mechanisms that govern actions in the individual context, in the social context

may help transform an interaction with no explicit coordination goal into a joint action.

   This is compatible with recent theoretical accounts. According to the Associative

Sequence Learning (ASL) model of action planning, the associative learning mechanism

underlying anticipation is also responsible for the phenomenon of social imitation (Heyes, 2001;

2011; Brass & Heyes, 2005). In this view, much like in the ideomotor view of action planning,

excitatory connections are established between an action plan and the perceptual consequences

of this action, and it is because of these connections that observing an action induces a tendency

to imitate it. Thus, imitation, which has been dubbed "social glue" due to its ability to increase

cooperation (for reviews, Chartrand & Lakin, 2013; Hamilton, 2015; Heyes, 2013), may serve as

an example of how a basic learning mechanism, operating both inside and outside the social

domain, in social contexts helps to bring the interacting agents together.

   Another illustration of this process comes from research on sensorimotor

synchronization. According to the Adaptation and Anticipation Model (ADAM) of sensorimotor

synchronization, much of the ability to temporally coordinate with others is achieved through an automatic adaptation mechanism that adjusts the timing of an internal time-keeping system to external temporal patterns (Harry & Keller, 2019; Keller et al., 2014; van der Steen & Keller, 2013). This mechanism has been shown to operate irrespective of whether or not the patterns are produced by human agents (for reviews, Repp, 2005; Repp & Su, 2013). However, when occurring in social contexts, such temporal adaptation contributes to coordination and to feelings of connectedness between agents (Marsh et al., 2009).

In sum, these data converge with the possibility that social interactions benefit from the engagement of adaptation and anticipation. But how widely can this be applied? On one hand, it is plausible that the effects of anticipation and adaptation are limited in certain contexts. Specifically, the use of anticipation may be constrained when interacting with a partner who often changes their response (e.g., in a competitive game of tennis), because these situations may pose a challenge for establishing reliable action-response associations. Temporal adaptation, in contrast, is likely to prevail in interactions with variable partners since agents are known to adapt to perturbed rhythms (Repp & Su, 2013), but it might be hampered in interactions that do not have a discernable temporal structure (e.g., carrying a couch up the stairs). Arguably, however, many social contexts involve temporally regularized and highly predictive behavior (e.g., dancing, turn-taking in conversations, rowing), and in such contexts both the anticipatory and adaptive mechanisms would be expected to support efficient interactions.

Conclusions. To conclude, across four experiments we investigated the contribution of response anticipation and temporal adaptation to social interactions. We demonstrated that agents can spontaneously anticipate partner's responses in interactions where action-response mapping changes dynamically. However, we observed anticipation only of response type but not of response speed, and we found no evidence for anticipation occurring after trials where agents might have experienced a cognitive conflict. Further, we showed that agents' actions can be

affected by spontaneous adaptation to the observed timing of the partner's responses, and that

this mechanism can be engaged independently of response anticipation. Our results are in

agreement with models proposing that social interactions are shaped by multiple cognitive and

perceptual mechanisms, including anticipation and temporal adaptation, and that these

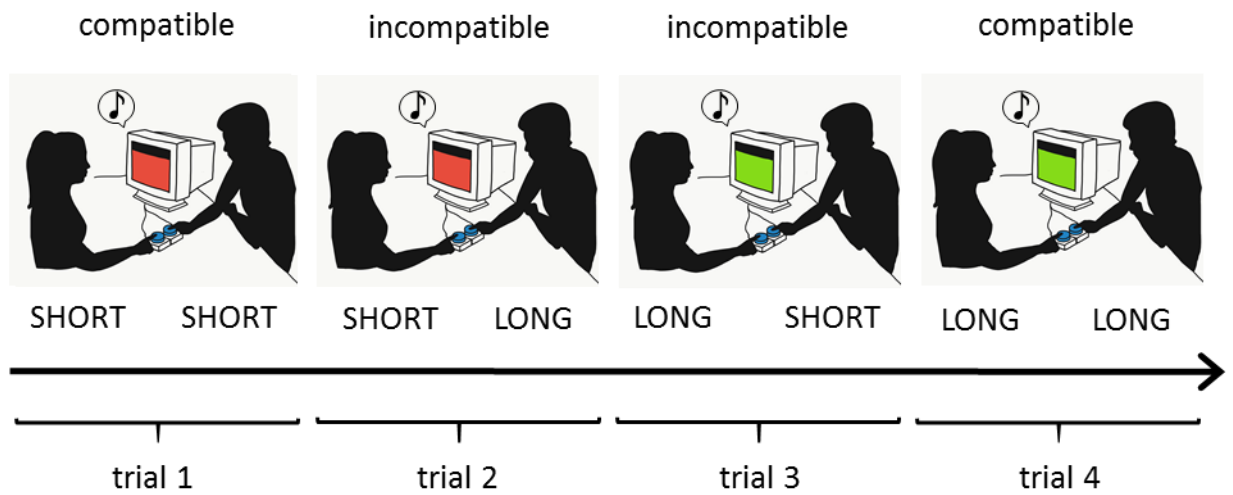mechanisms might help agents to achieve coordination.

Figure 1. Experiment 1: Exemplary trial sequence. On each trial, the leader (female silhouette) reacted to a color cue and produced either a short or a long keypress. Once the leader lifted the finger from her key, the follower (male silhouette) responded with a compatible or an incompatible keypress. An auditory cue at the beginning of each trial announced the type of the upcoming response.
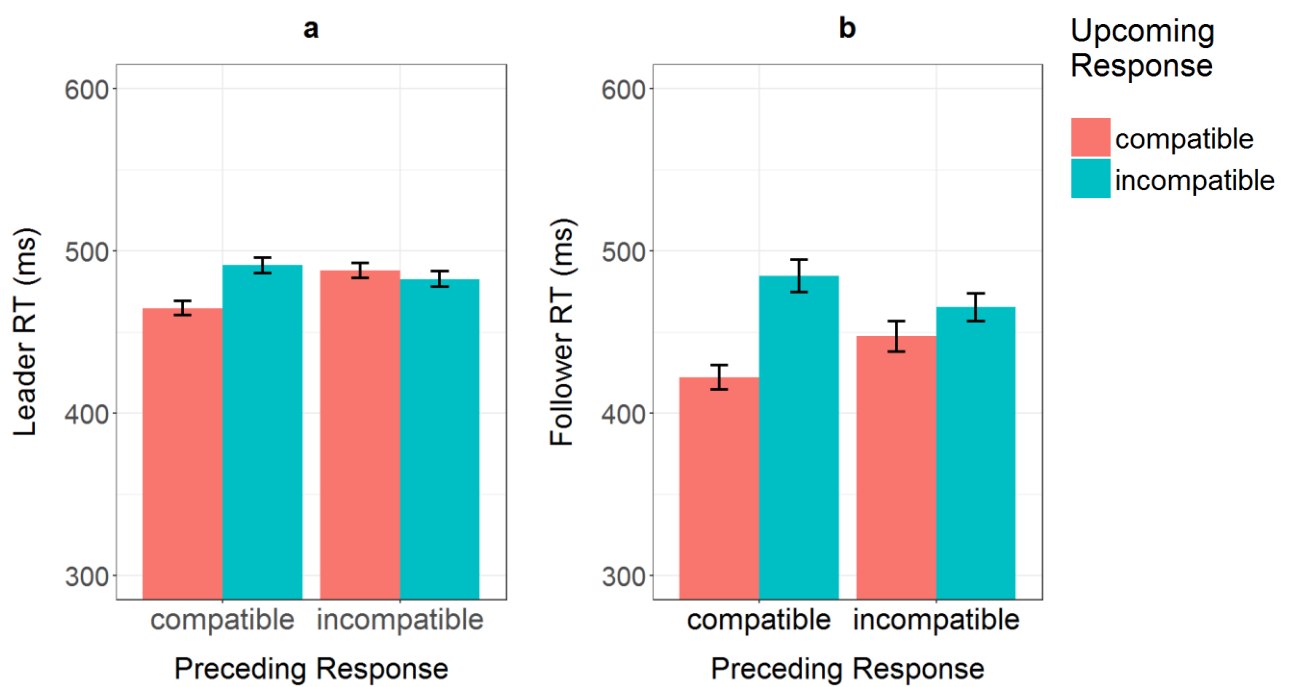
Figure 2. Experiment 1: Reaction times (RT) of the leader (panel a) and the follower (panel b) as a function of Preceding Response and Upcoming Response of the follower. Error bars represent 95% CIs of the mean.
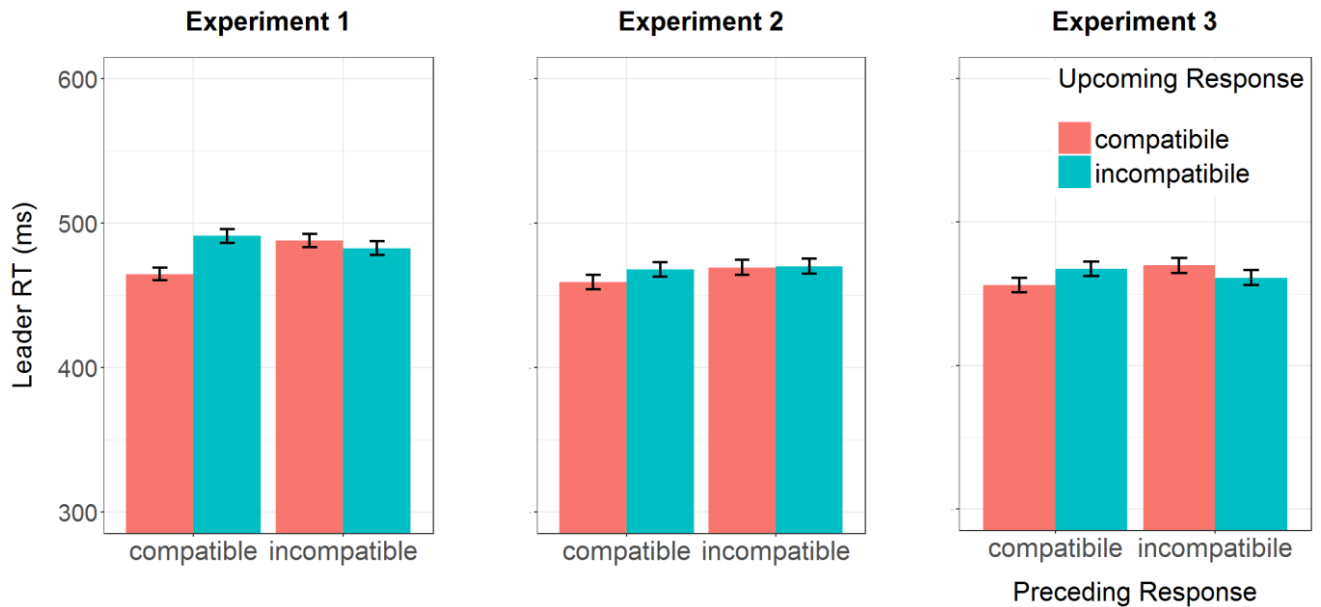

Figure 3. Experiments 1-3: Reaction times (RT) of the leader presented by Preceding Response and Upcoming Response of the follower. Error bars represent 95% CIs of the mean. Note that the panel for Experiment 1 is the same as panel *a* in Figure 2.
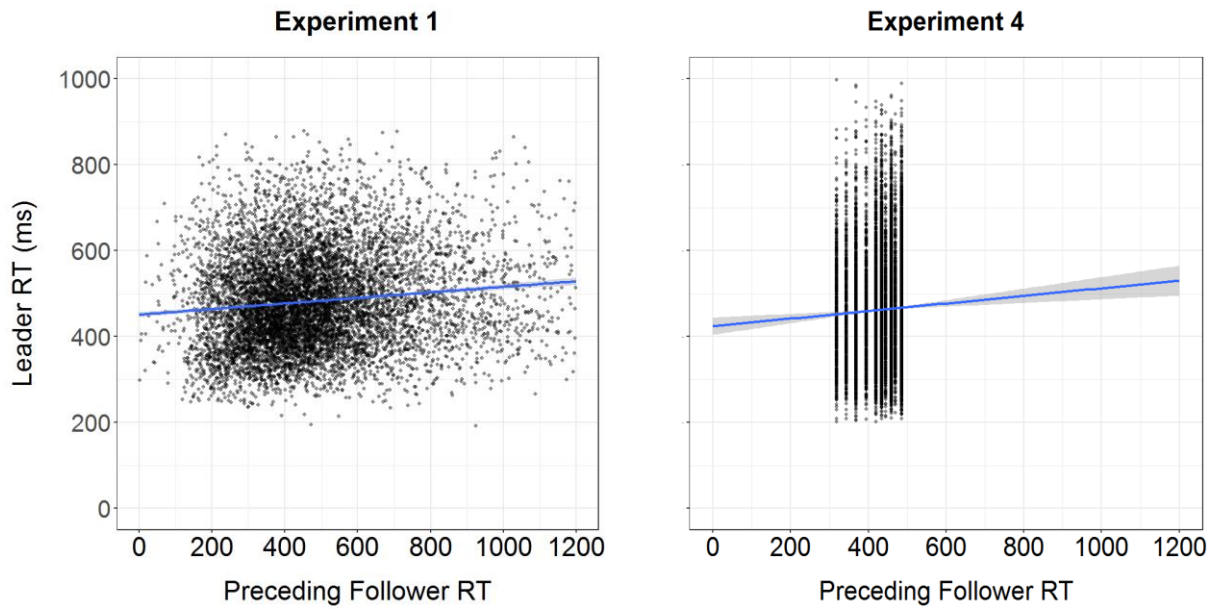
Figure 4. Experiments 1 and 4: The relation between Leader RT and Preceding Follower RT. The difference in range of Preceding Follower RT stems from the fact that response speed of human followers in Experiment 1 was considerably more variable than of virtual followers in Experiment 4. The shaded area around the regression line represents 95% CI on the fitted values.
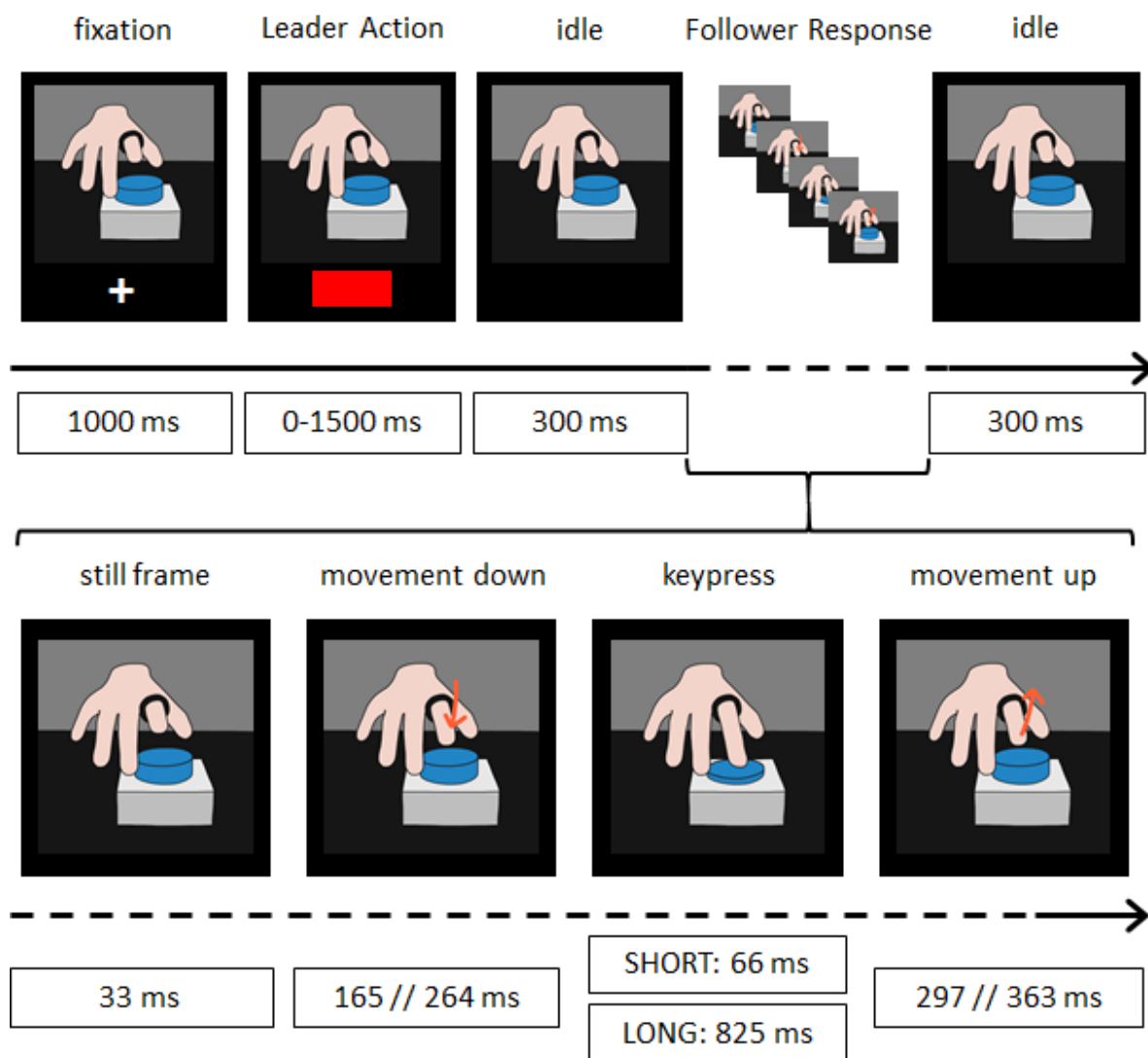
Figure 5. Experiments 2-3: The trial structure (upper panel) was identical in both experiments, but the exact timing of the follower's response (lower panel) differed as specified below (these differences were implemented to make Experiment 3 directly comparable with Experiment 1; see Experiment 3, Methods). For illustration purposes, the figure depicts only the hand of the virtual follower. The exact stimuli used in the experiments can be found online (https://osf.io/532qr/). Trial structure: For 1000 ms, leader observed a fixation cross, while the virtual follower remained still in the neutral position. Next, the leader reacted to a color cue and produced an action. After 1500 ms or after the leader's key release (whichever occurred first), the idle period started where the follower remained still for another 300 ms. Subsequently, the follower produced a response comprising of a still frame (33 ms), movement down (165 ms in Experiment

2 or 264 ms in Experiment 3), keypress (66 ms for short and 825 ms for long presses, both in

Experiment 2 and 3), and movement up (297 ms in Experiment 2 or 363 ms in Experiment 3).

The trial finished after another 300 ms of idle period.

References

Aglioti, S. M., Cesari, P., Romani, M., & Urgesi, C. (2008). Action anticipation and motor resonance in elite basketball players. *Nature Neuroscience, 11*(9), 1109–1116.

Badets, A., Pesenti, M., & Olivier, E. (2010). Response–effect compatibility of finger–numeral configurations in arithmetical context. *Quarterly Journal of Experimental Psychology*, *63*(1), 16-22.

Bates, D., Maechler, M., Bolker, B., & Walker, S. (2019). lme4: Linear mixed-effects models using Eigen and S4. http://CRAN.R-project.org/package=lme4

Bertenthal, B. I., Longo, M. R., & Kosobud, A. (2006). Imitative response tendencies following observation of intransitive actions. *Journal of Experimental Psychology: Human Perception and Performance, 32*, 210–225.

Bläsing, B., Calvo-Merino, B., Cross, E. S., Jola, C., Honisch, J., & Stevens, C. J. (2012). Neurocognitive control in dance perception and performance. *Acta Psychologica, 139*(2), 300-308.

Brass, M., Bekkering, H., Wohlschläger, A., & Prinz, W. (2000). Compatibility between observed and executed finger movements: Comparing symbolic, spatial, and imitative cues. *Brain and Cognition, 44*(2), 124–143.

Brass, M., & Heyes, C. (2005). Imitation: is cognitive neuroscience solving the correspondence problem? *Trends in Cognitive Sciences, 9*(10), 489-495.

Catmur, C., & Heyes, C. (2011). Time course analyses confirm independence of imitative and spatial compatibility. *Journal of Experimental Psychology: Human Perception and Performance, 37*(2), 409–421.

Chartrand, T. L., & Lakin, J. L. (2013). The antecedents and consequences of human behavioral mimicry. *Annual Review of Psychology, 64*, 285-308.

Corps, R. E., Crossley, A., Gambi, C., & Pickering, M. J. (2018). Early preparation during turn-taking: Listeners use content predictions to determine what to say but not when to say it. *Cognition, 175*, 77-95.

Dignath, D. & Janczyk, M. (2017). Anticipation of delayed action-effects: Learning when an effect occurs, without knowing what this effect will be. *Psychological Research, 81*(5), 1072-1083.

Dignath, D., Pfister, R., Eder, A. B., Kiesel, A., & Kunde, W. (2014). Representing the hyphen in action–effect associations: Automatic acquisition and bidirectional retrieval of action–effect intervals. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 40*(6), 1701–1712.

Dumas, G., de Guzman, G. C., Tognoli, E., & Kelso, J. S. (2014). The human dynamic clamp as a paradigm for social interaction. *Proceedings of the National Academy of Sciences, 111*(35), E3726-E3734.

Egner, T. (2007). Congruency sequence effects and cognitive control. *Cognitive, Affective, & Behavioral Neuroscience, 7*(4), 380-390.

Fairhurst, M. T., Janata, P., & Keller, P. E. (2012). Being and feeling in sync with an adaptive virtual partner: Brain mechanisms underlying dynamic cooperativity. *Cerebral Cortex, 23*(11), 2592-2600.

Fairhurst, M. T., Janata, P., & Keller, P. E. (2014). Leading the follower: An fMRI investigation of dynamic cooperativity and leader–follower strategies in synchronization with an adaptive virtual partner. *Neuroimage, 84*, 688-697.

Fanini, A., Nobre, A. C., & Chelazzi, L. (2006). Selecting and ignoring the component features of a visual object: A negative priming paradigm. *Visual Cognition, 14*, 584–618.

Flach, R., Press, C., Badets, A., & Heyes, C. (2010). Shaking hands: Priming by social action effects. *British Journal of Psychology, 101*(4), 739-749.

Földes, N., Philipp, A. M., Badets, A., & Koch, I. (2017). Exploring modality compatibility in the response-effect compatibility paradigm. *Advances in Cognitive Psychology*, *13*, 97-104.

Gaschler, R., & Nattkemper, D. (2012). Instructed task demands and utilization of action effect anticipation. *Frontiers in Cognition, 3*, 578.

Gratton, G., Coles, M. G., & Donchin, E. (1992). Optimizing the use of information: Strategic control of activation of responses. *Journal of Experimental Psychology: General, 121*(4), 480-506.

Grosjean, M., & Mordkoff, J. T. (2001). Temporal stimulus–response compatibility. *Journal of Experimental Psychology: Human Perception and Performance, 27*(4), 870-878.

Hamilton, A. F. (2015). EPS Prize Lecture: Cognitive underpinnings of social interaction. *Quarterly Journal of Experimental Psychology, 68*(3), 417-432.

Harry, B., & Keller, P. E. (2019). Tutorial and simulations with ADAM: An adaptation and anticipation model of sensorimotor synchronization. *Biological cybernetics*.

Heyes, C. M. (2001). Causes and consequences of imitation. *Trends in Cognitive Sciences, 5*, 253-260.

Heyes, C. (2011). Automatic imitation. *Psychological Bulletin, 137*, 463–483.

Heyes, C. (2013). What Can Imitation Do for Cooperation? In K. Sterelny, R. Joyce, B. Calcott, & B. Fraser (Eds.), *Cooperation and Its Evolution* (pp. 313-332). Cambridge: MIT Press.

Hommel, B. (2013). Ideomotor action control: On the perceptual grounding of voluntary actions and agents. In W. Prinz, M. Beisert, & A. Herwig (Eds.), *Action Science: Foundations of an Emerging Discipline* (pp. 113–136). Cambridge: MIT Press.

Hommel, B., Müsseler, J., Aschersleben, G., & Prinz, W. (2001). The theory of event coding: A framework for perception and action. *Behavioral and Brain Sciences, 24*, 849–878.

Horváth, J., Bíró, B., & Neszmélyi, B. (2018). Action-effect related motor adaptation in interactions with everyday devices. *Scientific Reports, 8*, 6592-6592.

Keller, P. E. (2008). Joint action in music performance. In F. Morganti, A. Carassa, & G. Riva (Eds.),

    Enacting intersubjectivity: A cognitive and Social Perspective to the Study of Interactions (pp.

    205-221). Amsterdam: IOS Press.

Keller, P. E., Novembre, G., & Hove, M. J. (2014). Rhythm in joint action: Psychological and

    neurophysiological mechanisms for real-time interpersonal coordination. *Philosophical*

    Transactions of the Royal Society of London B: Biological Sciences, 369, 20130394.

Kelso, J. S., de Guzman, G. C., Reveley, C., & Tognoli, E. (2009). Virtual partner interaction (VPI):

    Exploring novel behaviors via coordination dynamics. *PloS ONE, 4*(6):e5749.

Knoblich, G., Butterfill, S., & Sebanz, N. (2011). Psychological research on joint action: Theory and

    data. Psychology of Learning and Motivation. *Advances in Research and Theory, 54*, 59-101.

Knoblich, G., & Jordan, J. S. (2003). Action coordination in groups and individuals: Learning

    anticipatory control. *Journal of Experimental Psychology: Learning, Memory, and Cognition,*

    29, 1006-1016.

Koban, L., Ramamoorthy, A., & Konvalinka, I. (2019). Why do we fall into sync with others?

    Interpersonal synchronization and the brain's optimization principle. *Social Neuroscience, 14*(1),

    1-9.

Konvalinka, I., Bauer, M., Stahlhut, C., Hansen, L. K., Roepstorff, A., & Frith, C. D. (2014). Frontal

    alpha oscillations distinguish leaders from followers: Multivariate decoding of mutually

    interacting brains. *Neuroimage, 94*, 79-88.

Konvalinka, I., Vuust, P., Roepstorff, A., & Frith, C. D. (2010). Follow you, follow me: Continuous

    mutual prediction and adaptation in joint tapping. *Quarterly journal of experimental psychology,*

    63(11), 2220-2230.

Kornblum, S., Hasbroucq, T., & Osman, A. (1990). Dimensional overlap: Cognitive basis for stimulus-

    response compatibility - A model and taxonomy. *Psychological Review*, *97*(2), 253-270.

Kunde, W. (2001). Response-effect compatibility in manual choice reaction tasks. *Journal of Experimental Psychology: Human Perception and Performance, 27*(2), 387-394.

Kunde, W. (2003). Temporal response-effect compatibility. *Psychological Research, 67*(3), 153-159.

Kunde, W., Koch, I., & Hoffmann, J. (2004). Anticipated action effects affect the selection, initiation, and execution of actions. *The Quarterly Journal of Experimental Psychology. Section A: Human Experimental Psychology, 57*, 87-106.

Kunde, W., Weller, L., & Pfister, R. (2018). Sociomotor action control. *Psychonomic Bulletin & Review, 25*(3), 917-931.

Kuznetsova, A., Brockhoff, P. B., & Christensen, R. H. B. (2017). lmerTest Package: Tests in Linear Mixed Effects Models. *Journal of Statistical Software, 82*(13), 1–26.

Lelonkiewicz, J. R., & Gambi, C. (2017). Spontaneous adaptation explains why people act faster when being imitated. *Psychonomic Bulletin & Review, 24*(3), 842-848.

Levitin, D. J., Grahn, J. A., & London, J. (2018). The psychology of music: Rhythm and movement. *Annual Review of Psychology, 69*, 51-75.

Liepelt, R., Wenke, D., Fischer, R., & Prinz, W. (2011). Trial-to-trial sequential dependencies in a social and non-social Simon task. *Psychological Research, 75*(5), 366-375.

Loehr, J. D., Large, E. W., & Palmer, C. (2011). Temporal coordination and adaptation to rate change in music performance. *Journal of Experimental Psychology: Human Perception and Performance, 37*(4), 1292-1309.

Loehr, J. D., & Palmer, C. (2011). Temporal coordination between performing musicians. *The Quarterly Journal of Experimental Psychology, 64*(11), 2153-2167.

Marsh, K. L., Richardson, M. J., & Schmidt, R. C. (2009). Social connection through joint action and interpersonal coordination. *Topics in Cognitive Science, 1*(2), 320-339.

Melcher, T., Pfister, R., Busmann, M., Schlüter, M. C., Leyhe, T., & Gruber, O. (2015). Functional characteristics of control adaptation in intermodal sensory processing. *Brain and Cognition, 9*, 43-55.

Meyer, M., Bekkering, H., Haartsen, R., Stapel, J. C., & Hunnius, S. (2015). The role of action prediction and inhibitory control for joint action coordination in toddlers. *Journal of Experimental Child Psychology, 139*, 203-220.

Müller, B. C., Brass, M., Kühn, S., Tsai, C. C., Nieuwboer, W., Dijksterhuis, A., & van Baaren, R. B. (2011). When Pinocchio acts like a human, a wooden hand becomes embodied. Action co-representation for non-biological agents. *Neuropsychologia, 49*(5), 1373-1377.

Müller, R. (2016). Does the anticipation of compatible partner reactions facilitate action planning in joint tasks? *Psychological Research, 80*(4), 464–486.

Neda, Z., Ravasz, E., Brechte, Y., Vicsek, T., & Barabasi, A.-L. (2000). The sound of many hands clapping. *Nature, 403*, 849–850.

Nobre, A. C., Rao, A., & Chelazzi, L. (2006). Selective attention to specific features within objects: Behavioral and electrophysiological evidence. *Journal of Cognitive Neuroscience, 18*, 539–561.

Okano, M., Shinya, M., & Kudo, K. (2017). Paired synchronous rhythmic finger tapping without an external timing cue shows greater speed increases relative to those for solo tapping. *Scientific Reports, 7*, 43987.

Oullier, O., De Guzman, G. C., Jantzen, K. J., Lagarde, J., & Kelso, J. A. S. (2008). Social coordination dynamics: Measuring human bonding. *Social Neuroscience, 3*(2), 178-192.

Pecenka, N., & Keller, P. E. (2011). The role of temporal prediction abilities in interpersonal sensorimotor synchronization. *Experimental Brain Research*, *211*(3-4), 505-515.

Pfister, R. (2019). Effect-based action control with body-related effects: Implications for empirical approaches to ideomotor action control. *Psychological Review, 126*(1), 153-161.

Pfister, R., Dignath, D., Hommel, B., & Kunde, W. (2013). It takes two to imitate: Anticipation and imitation in social interaction. *Psychological Science, 24*(10), 2117-2121.

Pfister, R., Janczyk, M., Gressmann, M., Fournier, L. R., & Kunde, W. (2014). Good vibrations? Vibrotactile self-stimulation reveals anticipation of body-related action effects in motor control. *Experimental Brain Research, 232*(3), 847-854.

Pfister, R., Janczyk, M., Wirth, R., Dignath, D., & Kunde, W. (2014). Thinking with portals: Revisiting kinematic cues to intention. *Cogniton, 133*(2), 464-473.

Pfister, R., Kiesel, A., & Melcher, T. (2010). Adaptive control of ideomotor effect anticipations. *Acta Psychologica, 135*(3), 316-322.

Pfister, R., Weller, L., Dignath, D., & Kunde, W. (2017). What or when? The impact of anticipated social action effects is driven by action-effect compatibility, not delay. *Attention, Perception, & Psychophysics, 79*(7), 2132-2142.

Pickering, M. J., & Garrod, S. (2007). Do people use language production to make predictions during comprehension? *Trends in Cognitive Sciences, 11*(3), 105-110.

Pickering, M. J., & Gambi, C. (2018). Predicting while comprehending language: A theory and review. *Psychological Bulletin, 144*(10), 1002-1044.

Press, C., Bird, G., Flach, R., & Heyes, C. (2005). Robotic movement elicits automatic imitation. *Cognitive Brain Research, 25*(3), 632-640.

Repp, B. H. (2005). Sensorimotor synchronization: A review of the tapping literature. *Psychonomic Bulletin & Review, 12*(6), 969-992.

Repp, B. H., & Su, Y. H. (2013). Sensorimotor synchronization: A review of recent research (2006–2012). *Psychonomic Bulletin & Review, 20*(3), 403-452.

Schmidt, R. C., & O'Brien, B. (1997). Evaluating the dynamics of unintended interpersonal coordination. *Ecological Psychology, 9*(3), 189-206.

Schmidt, R. C., & Richardson, M. J. (2008). Dynamics of interpersonal coordination. In A. Fuchs & V.

Jirsa (Eds.), *Coordination: Neural, behavioral and social dynamics* (pp. 281-308). Heidelberg,

Germany: Springer.

Schmidt, R. C., Fitzpatrick, P., Caron, R., & Mergeche, J. (2011). Understanding social motor

coordination. *Human Movement Science, 30*, 834-845.

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., & Prinz, W. (2003). Representing others' actions: Just like one's own?

Cognition, 88(3), B11-B21.

Sebanz, N., Knoblich, G., & Prinz, W. (2005). How Two Share a Task: Corepresenting Stimulus-

Response Mappings. *Journal of Experimental Psychology, 31*(6), 1234-1246.

Sebanz, N., & Knoblich, G. (2009). Prediction in joint action: What, when, and where. *Topics in

Cognitive Science, 1*(2), 353-367.

Shin, Y. K., Proctor, R.W., & Capaldi, E. J. (2010). A review of contemporary ideomotor theory.

Psychological Bulletin, 136, 943–974.

Shockley, K., Richardson, D. C., & Dale, R. (2009). Conversation and coordinative structures. *Topics in

Cognitive Science, 1*(2), 305-319.

Stenzel, A., Chinellato, E., Bou, M., del Pobil, Á., Lappe, M., & Liepelt, R. (2012). When humanoid

robots become human-like interaction partners: Corepresentation of robotic actions. *Journal of

Experimental Psychology: Human Perception and Performance, 38*(5), 1073-1077.

Thébault, G., Michalland, A. H., Derozier, V., Chabrier, S., & Brouillet, D. (2018). When the vibrations

allow for anticipating the force to be produced: An extend to Pfister et al. (2014). *Experimental

Brain Research, 236*(4), 1219-1223.

Thomaschke, R., & Dreisbach, G. (2015). The time-event correlation effect is due to temporal expectancy, not to partial transition costs. *Journal of Experimental Psychology: Human Perception and Performance, 41*(1), 196-218.

Tsai, C. C., Kuo, W. J., Hung, D. L., & Tzeng, O. J. (2008). Action co-representation is tuned to other humans. *Journal of Cognitive Neuroscience, 20*(11), 2015-2024.

van der Steen, M. M., & Keller, P. E. (2013). The ADaptation and Anticipation Model (ADAM) of sensorimotor synchronization. *Frontiers in Human Neuroscience, 7*, 253.

van der Wel, R. P., & Fu, E. (2015). Entrainment and task co-representation effects for discrete and continuous action sequences. *Psychonomic Bulletin & Review*, *22*(6), 1685-1691.

Varlet, M., Marin, L., Lagarde, J., & Bardy, B. G. (2011). Social postural coordination. *Journal of Experimental Psychology: Human Perception and Performance, 37*(2), 473-483.

Verguts, T., Notebaert, W., Kunde, W., & Wühr, P. (2011). Post-conflict slowing: Cognitive adaptation after conflict processing. *Psychonomic Bulletin & Review, 18*, 76-82.

Vesper, C., Schmitz, L., Safra, L., Sebanz, N., & Knoblich, G. (2016). The role of shared visual information for joint action coordination. *Cognition, 153*, 118-123.

Vesper, C., van der Wel, R. P., Knoblich, G., & Sebanz, N. (2013). Are you ready to jump? Predictive mechanisms in interpersonal coordination. *Journal of Experimental Psychology: Human Perception and Performance, 39*(1), 48-61.

Weller, L., Pfister, R., & Kunde, W. (2019). Sociomotor actions: Anticipated partner responses are primarily represented in terms of spatial, not anatomical features. *Journal of Experimental Psychology: Human Perception and Performance.*

Wilson, M., & Wilson, T. P. (2005). An oscillator model of the timing of turn-taking. *Psychonomic Bulletin & Review, 12*(6), 957-968.

Wirth, R., Pfister, R., Brandes, J., & Kunde, W. (2016). Stroking me softly: Body-related effects in effect-based action control. *Attention, Perception, & Psychophysics, 78*(6), 1755-1770.

Wolf, T., Sebanz, N., & Knoblich, G. (2018). Joint action coordination in expert-novice pairs: Can experts predict novices' suboptimal timing? *Cognition, 178*, 103-108.

Wu, D. W. L., Chapman, C. S., Walker, E., Bischof, W. F., & Kingstone, A. (2013). Isolating the perceptual from the social: Tapping in shared space results in improved synchrony. *Journal of Experimental Psychology: Human Perception and Performance, 39*(5), 1218-1223.

Wühr, P., & Ansorge, U. (2005). Exploring trial-by-trial modulations of the Simon effect. *The Quarterly Journal of Experimental Psychology, 58*(4), 705-731.

Zwosta, K., Ruge, H., & Wolfensteller, U. (2013). No anticipation without intention: Response–effect compatibility in effect-based and stimulus-based actions. *Acta Psychologica*, *144*(3), 628-634.