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Modulating Action Duration to Establish Nonconventional Communication

Cordula Vesper
Central European University and Aarhus University

Laura Schmitz and Günther Knoblich
Central European University

In many joint actions, knowledge about the precise task to be performed is distributed asymmetrically such that one person has information that another person lacks. In such situations, interpersonal coordination can be achieved if the knowledgeable person modulates basic parameters of her goal-directed actions in a way that provides relevant information to the co-actor with incomplete task knowledge. Whereas such sensorimotor communication has frequently been shown for spatial parameters like movement amplitude, little is known about how co-actors use temporal parameters of their actions to establish communication. The current study investigated whether systematic modulations of action duration provide a sufficient basis for communication. The results of 3 experiments demonstrate that knowledgeable actors spontaneously and systematically adjusted the duration of their actions to communicate task-relevant information if the naïve co-actor could not access this information in other ways. The clearer the communicative signal was the higher was the benefit for the co-actor's performance. Moreover, we provide evidence that knowledgeable actors have a preference to separate instrumental from communicative aspects of their action. Together, our findings suggest that generating and perceiving systematic deviations from the predicted duration of a goal-directed action can establish nonconventionalized forms of communication during joint action.

Keywords: social cognition, joint action, cooperation, coordination strategy, sensorimotor communication

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When two or more people perform joint actions together, communication is often key to successful coordination. An obvious case is having a conversation (Clark, 1996), for instance, discussing the steps necessary to prepare dinner. However, communication can also occur nonverbally, such as when someone waves to inform another of her presence or when nodding to indicate approval. These gestures are, like spoken language, purely communicative—their exclusive purpose is to inform another person, request something or issue instructions. However, some actions can also serve an instrumental purpose *and* inform another person at the same time: If a passenger occupying the window seat on a train stands up in a demonstrative way, then the instrumental purpose of her action is to leave her seat. At the same time, she informs the person occupying the aisle about her intention to leave. Thus, there are actions that concurrently serve two goals: the instrumental (or pragmatic) goal of completing a specific motor act, and the communicative goal of making this motor act more easily predictable for an observer. This is referred to as sensorimotor communication or signaling actions (Pezzulo, Donnarumma, & Dindo, 2013).

Actions used for sensorimotor communication are an interesting class of actions for three main reasons. First, they do not rely on pre-established conventions in the way most of verbal language does. Whereas it is obvious that conventional language systems constitute extremely powerful coordination devices (Clark, 1996; Grice, 1957; Scott-Phillips, 2015), some situations actually prevent the use of conventional communication systems. For example, people might not share a common history or they might not be part of the same culture, so they cannot rely on a "common ground" (Clark, 1996; Stalnaker, 2002), or the interaction context and the available means of communication might be novel and, therefore, restrict the use of conventional communication (Galantucci, Garrod, & Roberts, 2012). In such cases, relying on sensorimotor communication can be a useful communication tool.

A second reason why sensorimotor communication is important is that it can generally support interpersonal coordination. For example, it can be used in addition to conventional forms of communication or in situations where communication is not necessary but helpful. In particular, redundant coding of information

Cordula Vesper, Department of Cognitive Science, Central European University, and School of Communication and Culture, Aarhus University; Laura Schmitz and Günther Knoblich, Department of Cognitive Science, Central European University.

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Correspondence concerning this article should be addressed to Cordula Vesper, School of Communication and Culture, Aarhus University, Jens Chr. Skous vej 2, 8000 Aarhus C, Denmark. E-mail: cvesper@cc.au.dk

can simplify coordination with another person (Vesper, Schmitz, Safra, Sebanz, & Knoblich, 2016), making relevant information salient and easily accessible. Thus, interaction partners might use sensorimotor communication irrespective of whether task success solely depends on it—just as many cospeech gestures are used by speakers to provide information in a redundant manner and thereby support the listener's understanding (Hilliard, O'Neal, Plumert, & Cook, 2015; Hostetter, 2011; Ozyurek, Kita, Allen, Furman, & Brown, 2005).

Finally, sensorimotor communication provides an opportunity to investigate a potentially relevant evolutionary process in the lab: If we can observe a graded transition from actions with both a communicative and an instrumental function to actions with only a communicative function this could provide valuable insights into the evolution of human language. In particular, it is possible that modern human communication systems might have evolved from sensorimotor communication such that informing others was initially only a secondary aspect to fulfilling a pragmatic action goal. It might have turned out then that separating instrumental and communicative goals might offer advantages for social interaction, for example by making it easier for observers to recognize a communicative intention, which in turn provided the basis for rich and stable communication systems (Scott-Phillips, 2015).

Previous research on sensorimotor communication has focused on joint actions where communication is needed because one person lacks information necessary to achieve a joint goal and, therefore, requires a knowledgeable partner to provide this information. Overall, these studies have shown that knowledgeable partners modulate kinematic aspects of their movements, such as grip aperture (Candidi, Curioni, Donnarumma, Sacheli, & Pezzulo, 2015; Sacheli, Tidoni, Pavone, Aglioti, & Candidi, 2013) and movement amplitude or direction (Goebl & Palmer, 2009; Vesper & Richardson, 2014), to convey information their naïve partners lack, for example, about the location of a movement target. Similar action modulations have been reported during interactions of caretakers with young infants ("motionese") where adults typically perform actions more slowly and in a more accentuated manner to facilitate the infants' learning (Brand, Baldwin, & Ashburn, 2002; Pitsch, Vollmer, Rohlfing, Fritsch, & Wrede, 2014). Moreover, it has recently been shown that movement amplitude exaggerations also occur if both co-actors have access to the same task information (Vesper et al., 2016). In these symmetric joint actions, co-actors communicate to support coordination under high timing pressure.

Successful communication also requires that (naïve) partners perceive action modulations. There is ample evidence that people are sensitive to deviations from the most efficient performance of another person's action. For instance, it has been demonstrated that observers detect subtle kinematic differences in others' movements (Becchio, Sartori, Bulgheroni, & Castiello, 2008; Stapel, Hunnius, & Bekkering, 2012) that allows them to distinguish between cooperative and competitive observed actions (Manera, Becchio, Cavallo, Sartori, & Castiello, 2011; Sartori, Becchio, & Castiello, 2011). To understand and use a communicative movement modulation, however, an observer needs to detect another's action modulation and, possibly, also interpret the intended meaning of the modulation (Sperber & Wilson, 1995). Whereas verbal language and most gestures are conventional and thus based on associations between an arbitrary (linguistic) code and its meaning (Scott-Phillips, 2015), this may not be required to understand communicative modulations of instrumental actions. Instead, observers may understand kinematic signals by making use of their own motor system to predict another's unfolding action (Wilson & Knoblich, 2005; Wolpert, Doya, & Kawato, 2003). Systematic deviations from these predictions may be taken as conveying particular meaning (Pezzulo et al., 2013). A recent account of verbal language production and comprehension similarly argues that prediction critically underlies both speaking and listening processes that cannot be treated separately but need to be understood as an integrated system (Pickering & Garrod, 2013).

Building on this previous research, the aim of the present study was to determine whether action duration provides a basis for establishing sensorimotor communication between co-actors. So far, action duration as a parameter in sensorimotor communication has been neglected, even though it is known that knowledgeable actors ("Leaders" in a joint action setting) tend to generally slow down their own performance to facilitate its recognition (Sacheli et al., 2013; Vesper & Richardson, 2014). Building on earlier work about sensorimotor communication, we hypothesized that Leaders would actively modulate the duration of their actions to provide information to naïve co-actors ("Followers") such that Followers would be able to perform their own part in the joint action. Such communication should be especially relevant in cases where visual access between co-actors is constrained or unavailable so that kinematic modulations affecting the spatial trajectory of a movement cannot be perceived and, thus, cannot provide any information (for an exception, see research using a "sonification technique" that makes movement aspects hearable; Effenberg, 2005). Motor simulation, which forms the basis for sensorimotor communication, can be used to predict movement duration even in the absence of visual input (Umiltà et al., 2001; Vesper, van der Wel, Knoblich, & Sebanz, 2013). For example, previous research demonstrated that observers can estimate the duration of (partially) hidden actions such as the time point at which someone will reappear behind an occluding object (Graf et al., 2007; Sparenberg, Springer, & Prinz, 2012; Stapel, Hunnius, Meyer, & Bekkering, 2016).

Thus, a first aim of our study was to investigate whether Leaders, who have access to relevant task information that Followers lack, would use action duration to establish a communication system when other channels for information transmission are unavailable (Galantucci, 2005; Misyak, Noguchi, & Chater, 2016). A second aim was to examine whether Leaders would show a preference for combining communicative and instrumental action goals as in sensorimotor communication contexts or whether they would rather attempt to separate those if given the opportunity. Arguably, this latter form is easier to recognize as a communicative act (Csibra & Gergely, 2009; Scott-Phillips, 2015; Sperber & Wilson, 1995). Experiments 1 and 2 investigated these questions in an interactive two-person setting where co-actors' task was to perform aiming movements toward matching target locations under conditions of different kinds and amounts of shared information. The aim of Experiment 3 was to apply the communication systems developed in Experiments 1 and 2 in an offline task setting, thereby further exploring whether the previously established communication systems would be generalizable beyond the dyadic interaction in which they were created.

Experiment 1

Experiment 1 investigated whether and how people would communicatively modulate action duration in a joint setting. We hypothesized that actors would convey distance information by systematically modulating the duration of their action performance. To this end, pairs of participants were instructed to perform goal-directed hand movements from a start location to one of three target locations on a table (see Figure 1). One member of the dyad, who we will refer to as Leader, knew the target location; the other member, referred to as Follower, did not know the target location. Targets were positioned such that Target 1 was closest to the start location and Target 3 was farthest away. There was one set of targets for Leaders and a corresponding set for Followers, located on opposite sides of a shared work table.

The co-actors' joint goal was to match target locations, that is, Followers were instructed to move to the same target as the Leaders. In contrast to previous experiments on sensorimotor communication, the task was performed sequentially. The Leader moved first, after a short tone had marked the start of a new trial. A second short tone was triggered when the Leader arrived at a target location. Thus, the Leader's action duration was perceivable as the time interval between start and arrival tones even in the absence of visual information. Followers performed their movement after the Leader had reached a target.

There were three different joint conditions: In "Informative Vision," Leaders and Followers could see each other, so this condition directly links to previous research in which information was exchanged through the visual channel (e.g., Sacheli et al., 2013; Vesper & Richardson, 2014). In "Informative Pitch," co-actors could not see each other but the Leaders' arrival on a particular target location triggered a tone that differed in pitch from the tones triggered at the other locations. We included this second baseline to account for the novelty of using the auditory domain for information exchange in a nonconventional communication task. In "Uninformative," our critical condition, no immediate source of information about the target was available as Followers could not see the Leaders and the Leaders' target hits always produced tones with the same pitch.

For the Uninformative condition, we predicted that Leaders would communicatively modulate action duration (i.e., the interval between start and arrival tone) to create a source of information that would help Followers identify the matching target. For the two baseline conditions Informative Vision and Informative Pitch, we did not expect Leaders to communicatively modulate action duration since both conditions contained other forms of target information (visual or auditory based on different pitches) to be picked up by Followers, making additional communication less relevant (Wilson & Sperber, 2004).

To measure whether and how Leaders would strategically modulate their action performance to create distinguishable time intervals for Followers, we designed the task such that any timing differences between the three target locations could be attributed to the active modulation of Leaders' actions. In particular, the distances from start to target locations and the sizes of the targets were chosen so that the duration of Leaders' efficient movements was expected to be equal for all three target locations according to Fitts' law (Fitts, 1954). Fitts' law describes how the duration of a movement lawfully depends on the relation between the distance covered from the start to the end point of a movement (with larger movement distances requiring more time) and the precision needed at the end of the movement (captured by the target size where smaller targets require higher precision and, therefore, more time). Fitts' law, therefore, allows to quantify movements in terms of their overall difficulty and to predict the duration of movements to targets of particular distances and sizes. In particular, we expected that efficient movement performance in our task would lead to

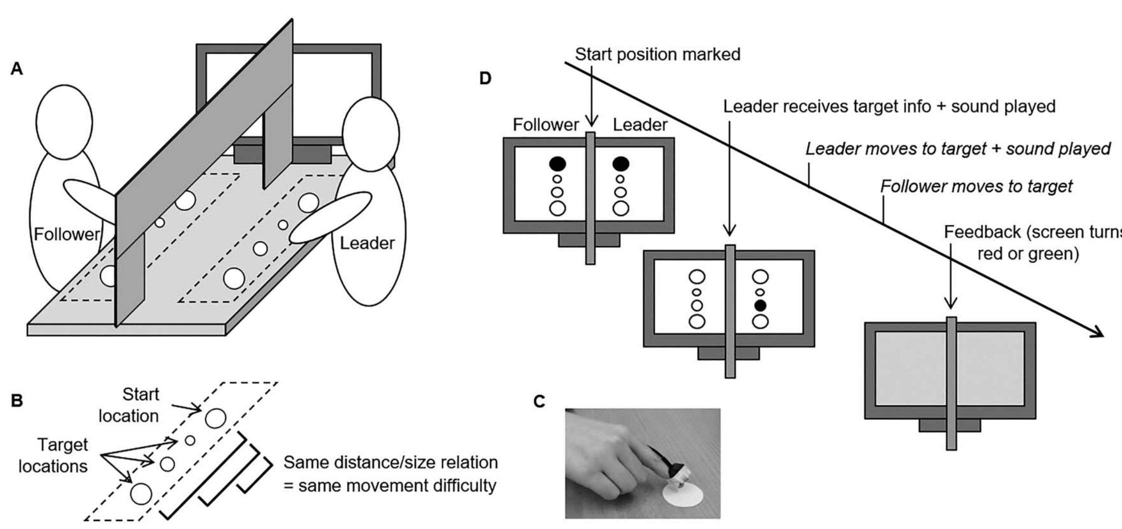

Figure 1. (A) Schematic drawing of the experimental setup. (B) According to Fitts' law, movement times are the same for targets with the same movement difficulty because of the lawful relation of movement distance and target width. We expected Leaders to actively modulate movement duration to make it perceivably different for the three targets. (C) Placement of the motion capture sensor. (D) Trial procedure. Only Leaders received target information on the computer screen, whereas Followers had to infer this information from the Leaders' actions.

equal movement times to each target, whereas deviations from efficient movement performance would be a way to distinguish between targets. Previous research has shown the generality of Fitts' law that holds both in individual action performance and motor imagery (Decety & Jeannerod, 1995) and also in observation of others' actions (Grosjean, Shiffrar, & Knoblich, 2007). Applying this basic movement law to our task design allowed us to quantify Leaders' communication as systematic violations of Fitts' law, based on sensorimotor communication accounts that define communication as deviations from efficient action performance (e.g., Pezzulo et al., 2013). We expected that such violations would occur in the Uninformative condition but not in the other two conditions.

Modulating action duration for communication in the Uninformative condition could be achieved in two different ways. Either Leaders could adjust the duration of the movement itself, for example, by actively modulating movement velocity. Alternatively, Leaders could delay the initiation of their movements and keep movement duration unchanged. To tease apart these two possibilities, we analyzed the movement onset time (interval between the external start tone and the start of the movement) separately from the movement execution time (interval between the initiation of Leaders' movement and arrival at the target). If participants modulated movement execution time rather than movement onset time this would imply that they chose to convey communicative information via the same channel used for the instrumental action, in line with a sensorimotor communication account.

Method

Participants. Eleven women and 13 men participated in randomly matched pairs (3 women only pairs, 4 men only pairs). Participants were between 21 and 33 years old (M = 26.4 years, SD = 3.0 years), right-handed and had normal or corrected-to-normal vision. They gave prior written informed consent, received monetary compensation, and were debriefed about the study purpose at the end of the experiment. In each pair, one participant was randomly assigned to the experimental role of Leader and the other to the role of Follower. The experiment was performed in accordance with the Declaration of Helsinki.

Apparatus. An interactive real-time motion-capture setup was created for the purpose of the present experiment. It consisted of a table with a row of four circles on each long side (Figure 1A). The circle diameters were 4.8 cm for the start locations and 1.6, 3.2, and 4.8 cm for targets 1, 2, and 3, respectively. All circles were centrally aligned with a center-to-center distance of 20 cm. The index of difficulty (ID) was 4.64 for all three targets (Figure 1B) as calculated according to Fitts' law (Fitts, 1954). Fitts' law captures the relation of movement difficulty (measured as movement duration) movement amplitude (A) and target width (W), according to the following equation:

$$ID = log_2 \frac{2A}{W} \quad (1)$$

The two participants were seated opposite of each other at the table's long sides. A cardboard partition was set up between participants on the table. The partition had an opening in the middle (85 cm long, 35 cm high) that could be covered with a black opaque cloth to prevent visual contact between participants. The partition also separated the stimulus display on a 24" Asus computer screen (resolution 1,920 × 1,080 pixels, refresh rate 60 Hz) such that Leaders and Followers could be presented with different information on each side of the screen. The interactive setup was controlled online with a Polhemus G4 electro-magnetic motion capture system (www.polhemus.com) that recorded participants' movement data with a constant sampling rate of 120 Hz. Movement sensors were taped centrally onto the nail of each participant's right index finger (Figure 1C). The experimental procedure and data recording was controlled by Matlab (2015), using the Psychophysics Toolbox extension (Brainard, 1997).

Procedure. Participants received written instructions, which were verbally repeated by the experimenter before each block of the experiment. The first block was an individual training and was completed only by the Leader, while the Follower waited in a separated part of the room. Afterward, both participants performed three blocks of trials together with short breaks in between. In the Informative Vision block, co-actors could see each other's hand movements (but not each other's faces). In the Informative Pitch block, visual access was prevented but Leaders' target arrival triggered differently pitched tones. In the Uninformative block, neither visual access nor pitch information was available. The order of the three joint blocks was counterbalanced across participant pairs.

Each block began with a short calibration procedure to acquire the spatial coordinates of participants' finger positions at start and targets to guide the online control of the experiment via the motion capture system. Then, after three training trials to allow participants to get acquainted with the block's specific procedure, 72 experimental trials were performed (24 trials per target, in random order). The experiment took about 1 hr in total.

All trials followed the same procedure (Figure 1D): Participants first moved with their index finger to the start location as prompted on the computer screen. Once the Leader (individual training) or both Leader and Follower (joint conditions) were in the start location, the Leader's side of the computer screen displayed the target location and a short tone was played (80 ms, 659 Hz). The Leader now moved to the target at her own speed. Upon target arrival, which was detected by online evaluation of the motion tracking data, a second short tone was played. Its frequency depended on the respective condition: In the individual training, Informative Vision and Uninformative, the same tone was played for all targets (659 Hz). In Informative Pitch, the frequency varied for the three targets (1109 Hz for Target 1, 1319 Hz for Target 2, 1661 Hz for Target 3). The Follower's task was to then perform a speeded hand movement from her own start location to the same target as the Leader. Subsequently, the screen would turn green or red (for 300 ms), indicating whether Leader and Follower had moved to matching or nonmatching targets, respectively. After an intertrial interval of 700 ms, the next trial began.

For practical reasons, Leaders were instructed not to touch the target locations directly and instead end their movements at a point slightly above the table. This was done to prevent any noise when Leaders hit a target on the table which could have potentially provided directional auditory cues to Followers. Followers were instructed to touch the targets directly so as not to interfere with their instruction to move to the target as fast as possible. In all the instructions for the joint conditions it was stressed that Leader and

Follower should "work together" to jointly achieve the goal of choosing matching targets. That this would require communication between partners was never explicitly mentioned. Demo videos of the three conditions can be found in the supplementary online material.

Data preparation and analysis. From Leaders' movement time series, two time intervals were extracted. "Movement onset time" (MO) was defined as the interval between the computer-generated start sound and the Leaders' movement onset (onset criterion based on the measured calibration points: horizontally outside of a 2.4 cm radius or vertically above 1 cm), while "movement execution time" (MT) was defined as the interval between Leaders' movement onset and offset, that is, the moment of reaching a target location (offset criterion based on the measured calibration points: horizontally inside a radius of 0.8 cm/1.6 cm/2.4 cm and vertically below 1 cm, corresponding to the three different target sizes). For the analysis of Followers' performance, we also calculated the overall time to target (MO + MT) as the interval between the two tones that, therefore, equaled the sum of MO and MT. All trials in which Leaders moved to the wrong target or in which the overall time to target exceeded 2 *SD*s around the mean were excluded per Leader and condition from further analysis (2.7% of all data, $SD = 1.5\%$).

From the remaining trials, we calculated signal-to-noise ratios (SNR) as measures for Leaders' signal clarity. Specifically, the SNR of, for example, MT combines the difference between the mean MTs for the three different targets and the variability of these MTs. Thereby, it captures in one measure how distinct Leaders' timing (= signal) is in relation to its variability (= noise). SNR was calculated for each participant, each condition and each parameter as the averaged difference between the mean (*M*) time to adjacent targets, divided by the mean of the *SD* of the time to all targets, as described by the following equation:

$$SNR = \frac{M((M_{target\,2} - M_{target\,1}),\ \ (M_{target\,3} - M_{target\,2}))}{M\ \ (SD_{target\,1},\ \ SD_{target\,2},\ \ SD_{target\,3})} \tag{2}$$

Larger SNR values indicate a clearer signal. To test which part of the movement was modulated, we calculated SNR for MO (SNR_{MO}) and MT (SNR_{MT}). For reference purposes, we also report the absolute means and *SD*s for all these movement phases separately per joint condition and target in Table 1.

For the analysis of movement velocity, we first filtered all raw trajectories using a 4th-order Butterworth digital filter with cut-off at 10 Hz and then calculated Leaders' mean velocity along the horizontal axis on which the targets were aligned. Finally, to assess joint task performance, trials in which Followers moved to the same target as the Leaders were classified as a match and trials in which they moved to a different target as a mismatch. Based on this, a percentage of target matches per total number of trials was calculated. Signal-to-noise ratios and accuracy were analyzed with within-subjects analyses of variance (ANOVAs) with the factor condition (Informative Vision, Uninformative, and Informative Pitch). Significant ANOVA results were followed up by Bonferroni-corrected *t* tests comparing Uninformative with Informative Vision and Uninformative with Informative Pitch. All data preparation was done with Matlab, 2015 and significance testing with IBM SPSS 22.

Results

Modulation of action duration. To investigate whether Leaders adapted their action performance to inform Followers about the target location and whether they chose to wait before moving or to slow down their movement execution, we compared the signal-to-noise ratios of the MO (SNR_{MO}) and the MT (SNR_{MT}) in the three conditions. For SNR_{MO} (Figure 2A), the ANOVA revealed no main effect of condition, $F(2, 22) = .87$, $p > .4$, $\eta_p^2 < .07$. In contrast, for SNR_{MT} (Figure 2B), there was a main effect of condition, $F(2, 22) = 16.87$, $p < .001$, $\eta_p^2 = .61$, such that Uninformative was significantly larger than Informative Vision, $p < .001$, and also than Informative Pitch, $p < .01$.[1] Thus, Leaders adapted the execution part of their movements when neither visual nor pitch information was available to provide a communicative signal to Followers but they did not modulate the time before initiating their movement.

Violation of Fitts' law. Given that Leaders chose to provide a communicative signal by changing their MT, we tested whether this effectively created a violation of Fitts' law (Fitts, 1954). Therefore, we examined Leaders' MT for each target, expecting that, compared with Informative Vision and Informative Pitch, the time to each target would be shorter for Target 1 and longer for Target 3. A within-subjects ANOVAs of MT with the factors condition (Informative Vision, Uninformative, and Informative Pitch) and target (1–3) showed that Leaders indeed specifically modulated their MT in the Uninformative condition (Figure 3A). There was a significant interaction effect of condition and target, $F(4, 44) = 11.23$, $p < .001$, $\eta_p^2 = .51$. Follow-up one-factorial ANOVAs revealed that only in Uninformative the factor target had an impact on MT, $F(2, 22) = 14.29$, $p < .01$, $\eta_p^2 = .57$, but not for Informative Vision, $F(2, 22) = 2.52$, $p > .1$, $\eta_p^2 < .1$, or Informative Pitch, $F(2, 22) = 2.62$, $p > .1$, $\eta_p^2 < .1$. There were also main effects for condition, $F(2, 22) = 5.19$, $p < .05$, $\eta_p^2 = .32$, and target, $F(2, 22) = 9.92$, $p < .01$, $\eta_p^2 = .47$. Thus, the analysis of MT showed that Fitts' law was specifically violated in the Uninformative condition.

To further investigate how Leaders adjusted MT, we performed the same analysis with mean velocity (Figure 3B). We hypothesized that Leaders would have more similar mean velocities for each target in Uninformative than in the two other conditions. In line with this prediction, there was a significant interaction effect of condition and target, $F(4, 44) = 17.58$, $p < .001$, $\eta_p^2 = .62$. Follow-up one-factorial ANOVAs revealed main effects of condition for Informative Vision, $F(2, 22) = 46.79$, $p < .001$, $\eta_p^2 = .81$, and Informative Pitch, $F(2, 22) = 30$, $p < .001$, $\eta_p^2 = .73$. In contrast, in Uninformative, velocity was not significantly influenced by the factor target, $F(2, 22) = 3.07$, $p > .09$, $\eta_p^2 = .22$. There were also main effects for condition, $F(2, 22) = 5.9$, $p < .05$, $\eta_p^2 = .35$, and target, $F(2, 22) = 31.99$, $p < .001$, $\eta_p^2 = .74$. Taken together, this analysis suggests that Leaders modulated MT by adjusting their mean velocity, making it more equal across targets in the Uninformative condition.

Target match accuracy. Finally, we analyzed the effects that Leaders' communication had on joint match accuracy, that is, on

[1] A discriminant analysis showed that movement execution time had the highest discriminatory power in the "Uninformative" condition.

Table 1
Means (and SDs) of Leaders' Performance for Each Condition and Target

Movement phase	Informative vision			Uninformative			Informative pitch		
	target 1	target 2	target 3	target 1	target 2	target 3	target 1	target 2	target 3
Experiment 1									
MO (ms)	258 (152)	444 (163)	444 (158)	300 (129)	503 (170)	609 (236)	249 (140)	412 (171)	401 (152)
MT (ms)	706 (260)	664 (255)	758 (247)	586 (136)	905 (265)	1,414 (760)	702 (175)	738 (182)	917 (412)
Experiment 2									
MT (ms)	560 (215)	571 (139)	670 (155)	581 (103)	605 (104)	760 (165)	625 (251)	619 (128)	700 (143)
DT (ms)	2,124 (119)	2,302 (177)	2,418 (280)	2,016 (95)	2,374 (142)	3,074 (295)	2,280 (260)	2,537 (235)	2,751 (390)

Note. MO = movement onset time; MT = movement execution time; DT = dwell time.

how well Followers understood the communicative signal and moved to the correct target location. An analysis of the percentage of target matches, $F(2, 22) = 27.99$, $p < .001$, $\eta_p^2 = .72$, showed that dyads' performance suffered from the lack of immediately available perceptual information: Dyads had significantly fewer target matches in Uninformative (63.1%) than in Informative Vision (94.1%), $p < .001$, and Informative Pitch (80.4%), $p < .01$.

Still, performance in Uninformative was significantly higher than chance performance of 33.3% that would be expected if Followers had only guessed the target, $t(11) = 6.25$, $p < .001$. Therefore, we investigated whether Followers' matching performance in Uninformative depended on Leaders' signal quality such that those dyads whose Leader provided a better signal also more often moved to matching target locations. To this end, we correlated pairs' percentage of target match with Leaders' signal-to-noise ratios of the whole time to the target ($SNR_{(MO\ +\ MT)}$, calculated also according to Equation 2), expecting a positive correlation of the two. Although the correlation (Figure 2C) did not reach significance, $r = .521$, $p = .08$, it was numerically rather high suggesting that our small sample provides insufficient statistical power to establish the predicted relationship between the quality of a Leader's communication system and how well a Follower understands and uses the given information.[2]

Discussion

Experiment 1 supported our hypothesis that Leaders would modulate action duration to provide information to a joint action partner if no direct visual or pitch information about the joint goal was available to the partner. The signal-to-noise ratio of Uninformative was significantly higher than in the other two conditions where communication was not needed or needed to a lesser degree. This finding demonstrates the specificity of Leaders' communication to contexts in which receiving information was relevant for the joint action partner (Wilson & Sperber, 2004).

Moreover, Experiment 1 showed that Leaders modulated the duration of moving toward the target instead of modulating the time before initiating the movement, although both options would have constituted a feasible strategy to adjust overall action duration for Followers (cf. Vesper et al., 2013). By modulating the duration of movement execution, Leaders deviated from the most efficient performance, thereby incurring a motor cost. This deviation from efficiency is what makes the action communicative, according to sensorimotor communication accounts (Pezzulo et al., 2013). Our particular experimental setting allowed us to measure deviations from efficient action performance as deviations from Fitts' law (Fitts, 1954), a motor law describing the relation between movement duration, movement distance and movement precision. Violations were assessed by comparing MTs to the three targets, which all had the same index of difficulty: Based on Fitts' law, it is expected that efficient movement performance would lead to equal movement times to each target. Confirming our prediction, Leaders' MTs were different for each target in the Uninformative condition, indicating a violation of Fitts' law, whereas they were similar in the other conditions. Additionally, an analysis of Leaders' movement velocity profiles indicated that they modulated action duration in Uninformative by keeping a similar mean movement velocity irrespective of the target distance. This effectively resulted in shorter action durations for near targets and longer action durations for farther targets and thereby provided the communicative signal that Followers needed to solve their part of the task.

However, was incurring motor costs useful for interpersonal coordination? As predicted, Followers were indeed able to detect Leaders' deviations from efficient action performance and successfully used them to achieve the joint action goal of matching targets. This was shown by a higher-than-chance matching performance between Leaders' and Followers' target choices in the Uninformative condition. Furthermore, a substantial numerical correlation between Leaders' signal-to-noise ratio of overall time to target and Followers' matching performance provided a first indication that better communicative signals result in better performance of the Followers. Previous studies have shown that people have an intrinsic expectation about the temporal requirements to perform aiming movements, thereby planning their own individual actions in accordance with Fitts' law (Augustyn & Rosenbaum, 2005) or accordingly judging observed others' actions as possible or impossible (Grosjean et al., 2007). Here we show that such expectations also hold in interactive settings where deviations from Fitts' law are used by Leaders and detected by Followers, even in the absence of visual feedback. Taken together, Experiment 1 extends previous work on sensorimotor communication in interaction contexts that highlighted the role of spatial movement parameters (Pezzulo et al., 2013; Sacheli et al., 2013;

[2] As Figure 2C demonstrates, one Follower consistently performed at chance level. Removing this particular outlier pair from the analysis leads to a significant correlation, $r = .764$, $p < .01$.

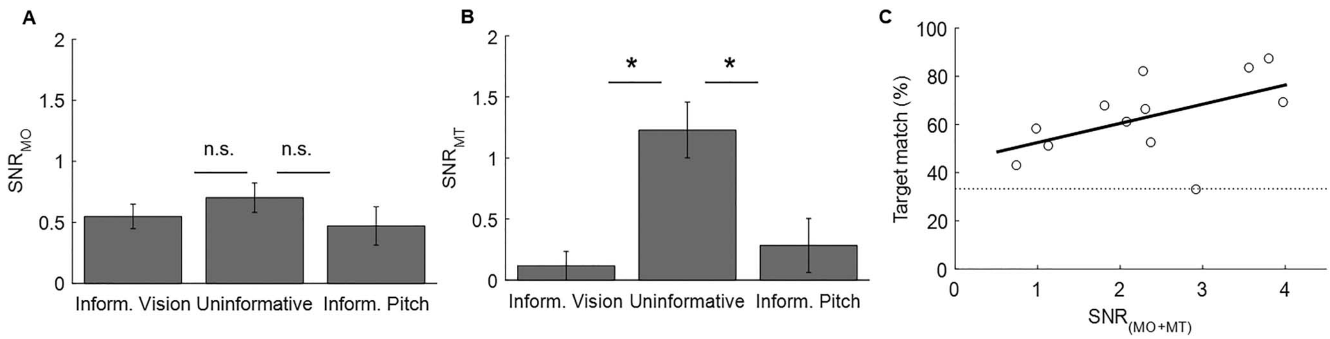

Figure 2. Results of the signal-to-noise ratio analysis in Experiment 1 for (A) movement onset time (SNR_{MO}) and (B) movement execution time (SNR_{MT}). Error bars show the *SE* and asterisks mark significant differences. (C) Leaders' communicative behavior in the "Uninformative" condition as indicated by the signal-to-noise ratio of the overall time to target ($SNR_{(MO\,+\,MT)}$) plotted against dyads' target match accuracy. The dotted line shows chance performance at 33.3%. SNR = signal-to-noise ratios; MO = movement onset time; MT = movement execution time.

Vesper & Richardson, 2014) by demonstrating that action duration provides a further potential communication channel.

Experiment 2

Based on the findings of Experiment 1, we investigated in a second experiment whether Leaders would modulate the duration of their movement execution, thereby simultaneously realizing instrumental and communicative goals, even if they were given the choice to communicate in a way that temporally separates the two goals. To examine this question, Leaders in Experiment 2 received an additional opportunity for communication. Specifically, the duration of the tone that was triggered when Leaders hit a target

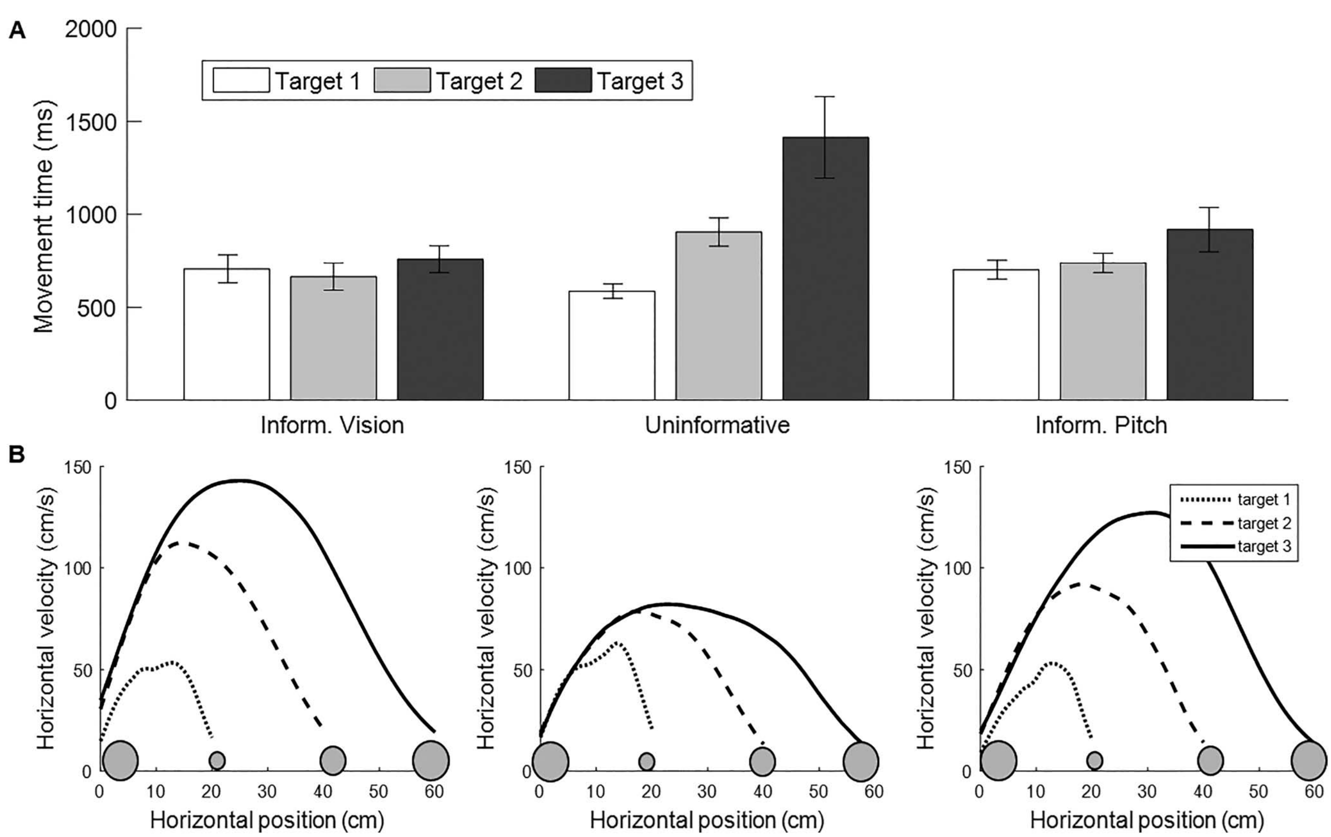

Figure 3. (A) Movement execution time (with *SE* as error bars) and (B) time-normalized grand-average velocity profiles, shown separately for each target.

was not fixed but could itself be actively controlled by Leaders. As long as they would keep their fingers in the target area, a continuous tone would be played that only stopped when they withdrew their finger from the target. Thus, Leaders now had a choice between using the movement interval between start and target hit to communicate (as Leaders in Experiment 1 had done) or to switch to communicating with the duration of their dwell time (DT) on the target. Arguably, this latter form creates a temporal and functional separation of instrumental and communicative goals and might, therefore, be more easily recognized as communicative because the target hit constitutes the goal, or end state, of Leaders' instrumental action of moving to the target. As there is no obvious instrumental function to keeping one's finger on the target after it was reached, if Leaders chose to extend the DT on the target this might more likely be recognized as a communicative act (or as "ostensive"; Csibra & Gergely, 2009; Sperber & Wilson, 1995).

Which form of communication would Leaders in Experiment 2 prefer to use? There are arguments in favor of predicting a preference for either strategy. On the one hand, modulating movement duration taps into motor simulation processes that are easy to implement for the Leader and easy to recognize for the Follower (Sartori et al., 2011; Wilson & Knoblich, 2005; Wolpert et al., 2003). Experiment 1 already showed that co-actors can successfully use this form of communication. There is, thus, no necessity to change a well-working communication strategy and switch to other forms of communication.

On the other hand, a separation of instrumental and communicative action goals might provide a more efficient basis for exchanging information. It has previously been suggested that the ability to recognize a communicative intention behind others' actions is a unique human trait that evolved precisely because it allows richer and more stable forms of communication (Scott-Phillips, 2015). Separating instrumental and communicative goals might, therefore, simplify the processes involved in distinguishing nonefficient from efficient action performance. In the present case, Followers might more easily recognize that Leaders intentionally keep their fingers on the target than understand that Leaders intentionally adjust their movement time toward the target. It could also generally require less cognitive and motor effort on the side of the Leader because it might be easier to create consistently distinct durations of a static posture (DT) compared with consistently modulating a dynamic movement (MT). Following these arguments, it is possible that Leaders in Experiment 2 would make use of this new opportunity and now modulate the target DT instead of (or in addition to) the MT. Modulations of DT would be expected to provide a clearer signal than modulations of MT.

Irrespective of whether Leaders would use the time *to* the target or the time *on* the target as a means to communicate, we expected that they would do so only in the Uninformative condition as the two other conditions already provide sufficient information via the visual or auditory modality. We also predicted that Followers' matching performance would depend on the clarity of the communicative signal provided by Leaders.

Method

The methods in Experiment 2 were identical to experiment 1 with the following exceptions.

Participants. A new set of 12 women and 12 men participated in randomly matched pairs (4 women only pairs, 4 men only pairs). Participants were between 19 and 39 years old ($M = 26.3$ years, $SD = 4.9$ years), right-handed and had normal or corrected-to-normal vision.

Procedure. The only procedural difference to Experiment 1 was that in Experiment 2, the Leader's arrival at a target triggered a continuous tone that only stopped when the Leader moved her finger away from the target. Consequently, Followers were now explicitly instructed to start moving only when the Leader's target tone had stopped. The pitch of the tones was the same as in Experiment 1 and, therefore, differed between targets only in the Informative Pitch condition.[3]

Data preparation and analysis. The durations of two time intervals were extracted from Leaders' raw movement data. MT was calculated in the same way as in Experiment 1, that is, as the duration of the interval between Leaders leaving the start location (onset criterion based on the measured calibration points: horizontally outside of a 2.4 cm radius or vertically above 2 cm) and the moment when Leaders reached a target position (offset criterion based on the measured calibration points: horizontally inside a radius of 0.8 cm/1.6 cm/2.4 cm and vertically below 2 cm). A new parameter, DT, was calculated as the duration of the interval between the moment Leaders reached the target and generated the target sound until they left the target and the sound stopped (same offset criteria). The signal-to-noise ratio for DT was calculated like in Experiment 1 according to Equation 2, that is, SNR_{DT} was calculated for each participant and each condition as the averaged difference between mean DTs for adjacent targets, divided by the mean of the *SD*s of DT to all targets. 0.9% of all trials ($SD =$ 1.3%) were excluded from further analysis because Leaders moved to the wrong target or because their overall time to target exceeded 2 *SD*s around the mean.

Results

Modulation of action duration. We performed the same analyses as in Experiment 1 to investigate whether Leaders adapted their action performance to inform Followers about the target location, but additionally we included the signal-to-noise ratio of DT (SNR_{DT}) as a dependent variable. The results of these analyses show that Leaders now modulated this DT in the Uninformative condition instead of MT, thereby providing Followers with a clearly distinguishable signal to indicate to which target they should go. Specifically, there was no main effect of condition for SNR_{MT} (Figure 4A), $F(2, 22) = .12$, $p > .8$, $\eta_p^2 < .01$, but for SNR_{DT} (Figure 4B), $F(2, 22) = 56.83$, $p < .001$, $\eta_p^2 = .84$. The SNR_{DT} was significantly higher in Uninformative than in Informative Vision, $p < .001$, and also compared with Informative

[3] We also asked Leaders to fill in a self-report questionnaire (IRI; Davis, 1980) in the very end of the experiment. The data are not published here.

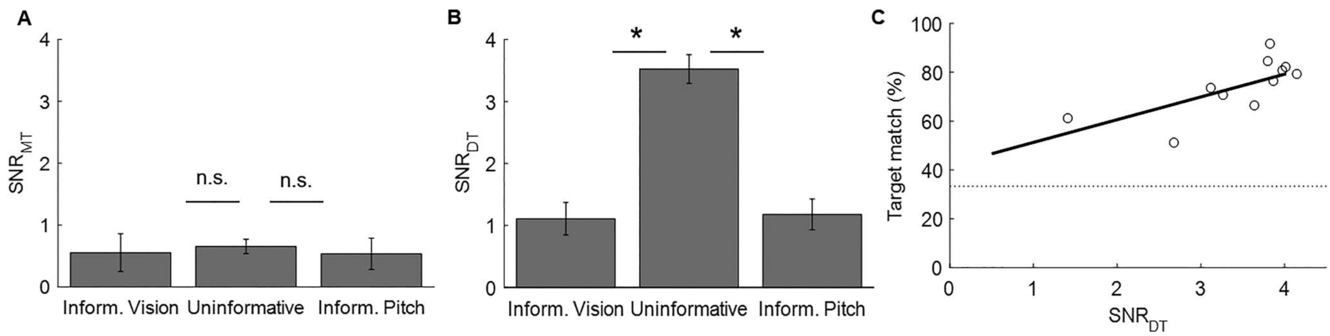

Figure 4. Results for Experiment 2 showing signal-to-noise ratios of (A) movement execution time (SNR_{MT}) and (B) dwell time (SNR_{DT}). Error bars show the *SE* and asterisks mark significant differences. (C) Correlation of Leaders' signal-to-noise ratio of dwell time (SNR_{DT}) in the "Uninformative" condition and the consequent joint target match accuracy. The dotted line shows chance performance. SNR = signal-to-noise ratios; MT = movement execution time; DT = dwell time.

Pitch, $p < .001$.[4] We did not analyze velocity as there were no differences in SNR_{MT}, suggesting that Leaders did not modulate their movement execution by adapting velocity. The absolute means and *SD*s for the two movement phases are reported separately per joint condition and target in Table 1.

Target match accuracy. As in Experiment 1, task performance of the two co-actors was measured as percent target match that indicates how well Followers understood the communicative signal that contained information about the correct target location. A main effect of condition, $F(2, 22) = 20.3$, $p < .001$, $\eta_p^2 = .65$, revealed that participants performed significantly worse in Uninformative (74.8%) compared with Informative Vision (93.9%), $p < .001$. Uninformative and Informative Pitch (78.2%) did not differ significantly, $p > .1$.

However, match performance in Uninformative was still significantly above chance performance (33.3%, $t(11) = 13.08$, $p < .001$). Therefore, we further tested whether the clarity of Leaders' SNR_{DT} signal would predict Followers' target match performance. As expected, the correlation of these two parameters (Figure 4C) was significant, $r = .706$, $p < .05$, such that the better Leaders' communicative signal was the better Followers could understand and use the given information.

Between-experiment comparison. Based on the finding that Leaders in Experiment 2 chose to communicate target information via the DT rather than the MT, we performed a follow-up analysis comparing signal quality and match performance in Uninformative between the two experiments. As expected, the SNR_{DT} of Experiment 2 was significantly higher than $SNR_{MO + MT}$ of Experiment 1, $t(22) = -3.04$, $p < .01$, suggesting that modulating DT provided a clearer communicative signal. Consistent with this, Followers in Experiment 2 reached higher, though only close-to-significantly different, match percentage in Uninformative than Followers in Experiment 1, $t(22) = -2.04$, $p = .055$. To further investigate how the quality of Leaders' communication might have exceeded the quality of Leaders' communication in the previous experiment, we separately compared the signal component (i.e., the mean difference in action duration between the three targets) and the noise component (i.e., the mean *SD* of action duration). This analysis revealed that the noise was smaller in Experiment 2 (155.7 ms) than in Experiment 1 (240.8 ms), $t(22) = 3.06$, $p < .01$, whereas the signal was roughly the same (529.3 ms in Experiment 2 and 568 ms in Experiment 1), $t(22) = .34$, $p > .7$. Thus, Leaders' choice in Experiment 2 to use DT instead of MT allowed them to improve the communicative signal by reducing the noise level.

Discussion

After establishing with Experiment 1 that Leaders successfully used action duration as a means to communicate, Experiment 2 followed up on this finding and investigated whether Leaders would have a preference between modulating the duration of their action performance and modulating the duration of the action end state, that is, their DT on the target. Therefore, Leaders were given an additional opportunity for communication by controlling the duration of the tone that was triggered when they hit a target. This provided Leaders with a choice between using the movement interval between start and target hit to communicate (as Leaders in Experiment 1 had done) or to switch to communicating with the duration of their DT on the target. Functionally speaking, this allowed Leaders to choose between a sensorimotor communication strategy, in which their instrumental goal (moving to the target) was combined with the communicative goal of informing the partner about the correct target, and a communicative strategy, in which they could clearly separate their instrumental and communicative action goals.

The results indicate that Leaders in Experiment 2 switched to modulating the action end state. Their signal-to-noise ratio for target DT was significantly different in the Uninformative condition compared with the Informative Vision or Informative Pitch conditions. In contrast, no differences between conditions were found for the signal-to-noise ratio of MT. Thus, we replicated Experiment 1 by showing that Leaders used action duration as a means to communicate with a partner but we also provided an important extension to this novel finding by providing evidence that, if given the choice, they switched from sensorimotor communication to a communicative strategy based on temporal separation of instrumental and communicative goals. This is interesting

[4] A discriminant analysis showed that dwell time had the highest discriminatory power in the "Uninformative" condition.

because modulating MT had proven to be a successful basis for communication in Experiment 1 and, thus, Leaders in Experiment 2 could in principle have chosen the same strategy.

Why did Leaders in Experiment 2 prefer to modulate the action end state? Most likely, separating instrumental and communicative action goals proved to be more efficient for exchanging information than using the same information channel for both intended action goals. In particular, it might have simplified the cognitive processes involved in the Leaders' task of producing distinguishable action durations and in the Followers' task of distinguishing nonefficient from efficient action performance. It is possible that, if Leaders chose to extend the DT on the target, this might more easily be recognized as a communicative act (Scott-Phillips, 2015; Sperber & Wilson, 1995) because keeping one's finger on the target had no further function for the instrumental action goal of moving there. Generally speaking, it seems that the more clearly "dysfunctional" an action component is, especially in the absence of any conventional communication code, the more easily it is interpreted by a recipient as having a communicative intention (de Ruiter et al., 2010). How this is realized depends on the specific context as the invention, use, and interpretation of communicative signals is highly flexible and the same signal may be taken as having different meanings depending on how a potential reference stands out from others in the communicator's and recipient's shared environment (Misyak et al., 2016). Evidence that Leaders' choice to communicate with the action end state was beneficial comes from a comparison of Followers' matching accuracy in Experiment 1, where Leaders used movement duration to communicate, and Experiment 2, where Leaders chose to communicate with their target DT. Followers chose the matching target with a higher accuracy in Experiment 2 than in Experiment 1.

To understand better why end state-based communication might have been more efficient than movement-based communication, it is helpful to note that Leaders' signal-to-noise ratios were overall higher in Experiment 2 compared with Experiment 1. This opens up the possibility that Leaders had a higher degree of control over their actions that might, as a consequence, have made it easier to keep their action variability small. Sensorimotor communication creates a trade-off between signal and noise (Candidi et al., 2015; Vesper et al., 2016). Building on classical information transmission models (Shannon, 1948), efficient communication is characterized by large signals embedded in little noise. The signal-to-noise ratio that we used as our main dependent variable captures this relation and allows to quantify the clarity of a communicative signal. The clearer communicative signal in Experiment 2 can only be explained by either an increased signal or reduced noise (or both). A comparison of both parameters indeed suggests that the better signal in Experiment 2 is because of less noise compared with Experiment 1. Thus, it is likely that the preference for communicating with the end-state is because of increased motor control that allowed Leaders to keep their action variability small.[5]

Experiment 3

In the two previous experiments, we demonstrated that action duration can successfully be used as a communicative signal in online joint interaction. To further investigate whether Leaders in Experiments 1 and 2 created stable, generalizable communication systems or whether these were specifically tailored for their interaction partners, we designed a third experiment to test how well a new group of participants would be able to distinguish targets based on the data collected in Experiments 1 and 2.

Numerous previous studies have shown that people are sensitive to their conversation partners' individual linguistic differences. For example, such partner-specific representations are reported in the domains of speech perception (e.g., Eisner & McQueen, 2005; Kraljic & Samuel, 2007) or syntax (Kamide, 2012), showing that people adjust to the specifics of their interaction partners' speech. Similarly, interlocutors in conversation tend to entrain on referring expressions (Brennan & Clark, 1996; Brown-Schmidt, 2009). This lexical alignment process (Garrod & Pickering, 2004) depends on the common ground established between communication partners and positively affects their joint performance (Fusaroli et al., 2012). An important question following from this research is whether partner-specific expressions can also be understood by other people who are not part of the conversation itself. One study compared how well addressees and overhearers, who were present and could hear what was said but did not take part in the conversation, could follow instructions by a speaker (Schober & Clark, 1989). The results showed better task performance of addressees compared with overhearers, suggesting that the collaborative alignment processes between speaker and addressee is important for successful communication.

Experiment 3 of the present work extends research on partner-specificity to sensorimotor communication, in particular investigating it in the absence of pre-established linguistic symbols. To that end, Followers' understanding of communicative modulation of action duration was tested in an offline task setting. Specifically, the new group of participants performed a computer-based target prediction task. Participants were instructed to listen to tone intervals that were directly taken from Leaders in the previous experiments and to decide to which of three possible targets those Leaders had moved. In line with the previous experiments, participants who received data from Leaders of Experiment 1 heard tones that had a fixed sound duration, whereas participants who received data from Leaders of Experiment 2 heard tones that had a variable sound duration depending on the Leaders' target DT. Note that Experiment 3 focused on the understanding of the temporal information only, that is, on the action durations Leaders had previously produced, so that we made some obvious changes to the Informative Vision and Informative Pitch conditions. Specifically, there was never any visual or pitch information available such that the three conditions only differed with respect to the amount that previous Leaders had modulated their action duration.

We hypothesized that participants in Experiment 3 would achieve higher prediction accuracy if they were provided with timing information from Leaders' Uninformative condition than from the Informative Vision or Informative Pitch conditions. Furthermore, we predicted that participants' prediction accuracy would be correlated with Leaders' signal clarity such that the clearer the signal was the better they would predict the action target.

[5] During the dwell time there is a continuous sound whereas the duration of movement execution is characterized by the silent interval between two sounds. Thus, saliency of the signal could potentially have influenced Leaders' choice. While it is unlikely that this fully explains our results, it leaves the possibility that attentional factors might have played a role.

Method

Participants. Fourteen women and 10 men, aged 19 to 40 years (M = 25.0 years, SD = 6.5 years), right-handed and with normal or corrected-to-normal vision, were randomly assigned to participate individually in either Experiment 3a or 3b. They gave prior written informed consent and were debriefed about the study purpose at the end of the experiment. Each participant was matched with data from one particular Leader from Experiment 1 (Experiment 3a) or Experiment 2 (Experiment 3b).

Apparatus. Four circles (diameters: 60, 30, 45, and 60 pixels, all aligned on the central vertical Screen axis) were presented on a white background on a 24" Asus computer screen (resolution 1,920 × 1,080 pixels, refresh rate 60 Hz). A start sound and an end sound (both 659 Hz) were used to mark the duration of Leaders' performance. The start sound had a fixed duration (80 ms). In Experiment 3a, also the end sound duration was fixed (80 ms), whereas in Experiment 3b, the duration of the end sound was determined by Leaders' DT measured in Experiment 2.

Procedure. Participants' task was to predict the correct target location by listening to sound intervals. They were told that they would receive data from previous participants who had performed reaching movements to different targets. Specifically, we used a cover story saying that each of the six experimental blocks they would perform came from a different previous participant. This had the purpose of providing a motivation why the blocks would differ in how difficult it would be to predict the correct targets. In reality, each participant only received data from one particular previous Leader, but from this Leader's performance in the three different joint conditions.

The procedure for each trial is shown in Figure 5. The screen with the start location was shown and simultaneously a start sound was played. After a variable interval that was determined by the previous Leaders' complete time to target (MO + MT, i.e., from the external start tone until target arrival), a second sound was played. The tone duration was either fixed (Experiment 3a) or depended on the previous Leaders' DT on the target (Experiment 3b). Participants then clicked with a computer mouse into one of the three target circles displayed on the screen to indicate which one they thought the previous participant had moved to. Feedback about the accuracy of their prediction was displayed for 600 ms: The chosen target turned green if it corresponded to where that Leader had moved to or red if not. After an intertrial interval of 400 ms, the following trial started.

Each condition was presented twice in blocks of 24 trials, corresponding to the last third of trials that previous Leaders had performed. The order of trials within a block was randomized. The order of blocks was pseudorandomized such that all three conditions occurred once in the first half and once in the second half of the experiment. Before a new block, an instruction screen prompted participants to believe that the upcoming data had been produced by a different previous participant. At the end of each block, feedback about the overall performance in this block was given as percentage of trials that were answered correctly.

Data analysis. We calculated prediction accuracy as the percentage of correct matches of participants' response and Leaders' original target locations. These percentages were submitted to within-subjects analyses of variance (ANOVAs) with the factor condition (Informative Vision, Uninformative, and Informative Pitch). Significant ANOVA results were followed up by Bonferroni-corrected *t test*.

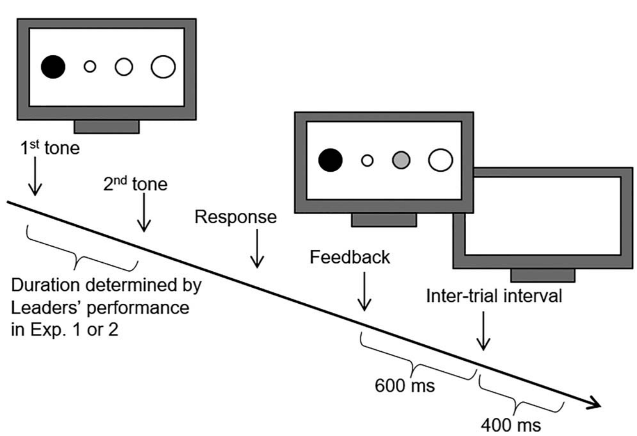

Figure 5. Procedure used in Experiment 3 to test the information content of Leaders' performances in Experiments 1 and 2. Note that, whereas in Experiment 3a the duration of the second tone was fixed as in Experiment 1, in Experiment 3b the duration of this tone was determined by Leaders' dwell time in Experiment 2.

Results

In Experiment 3a (Figure 6A), which was based on data from Leaders in Experiment 1, there was a main effect of condition, $F(2, 22) = 21.25$, $p < .001$, $\eta_p^2 = .66$. Specifically, we found that participants predicted the correct target with a significantly higher accuracy in Uninformative compared with Informative Vision, $p < .001$, and also compared with Informative Pitch, $p < .01$. Prediction accuracy in all but Informative Vision was above chance performance of 33.3% (Uninformative: $t(11) = 8.76$, $p < .001$, Informative Vision: $t(11) = 1.3$, $p > .2$, Informative Pitch: $t(11) = 3.86$, $p < .01$).

Similarly, in Experiment 3b (Figure 6B), in which participants received data from Leaders in Experiment 2, there was a main effect of condition, $F(2, 22) = 20.41$, $p < .001$, $\eta_p^2 = .65$. Prediction accuracy was higher in Uninformative compared with Informative Vision, $p < .001$, and compared with Informative Pitch, $p < .01$. In all cases, accuracy exceeded chance performance (Uninformative: $t(11) = 17.26$, $p < .001$, Informative Vision: $t(11) = 3.88$, $p < .01$, Informative Pitch: $t(11) = 4.14$, $p < .01$).

To further investigate the impact Leaders' performance in the previous experiments had on the new participants' prediction accuracy, we correlated these two parameters. For Experiment 3a (Figure 6C), Leaders' $SNR_{(MO + MT)}$ acquired in Experiment 1 and participants' accuracy were significantly correlated, $r = .638$, $p < .05$. However, unexpectedly, this was not the case in Experiment 3b, where Leaders' SNR_{DT} from Experiment 2 was not significantly correlated with participants' accuracy, $r = .228$, $p > .4$. As Figure 6D suggests this is likely because of a ceiling effect as participants in Experiment 3b had overall very high accuracy rates.

Discussion

The results of Experiment 3, that explored the recipient side of communication, showed that even people who were not involved

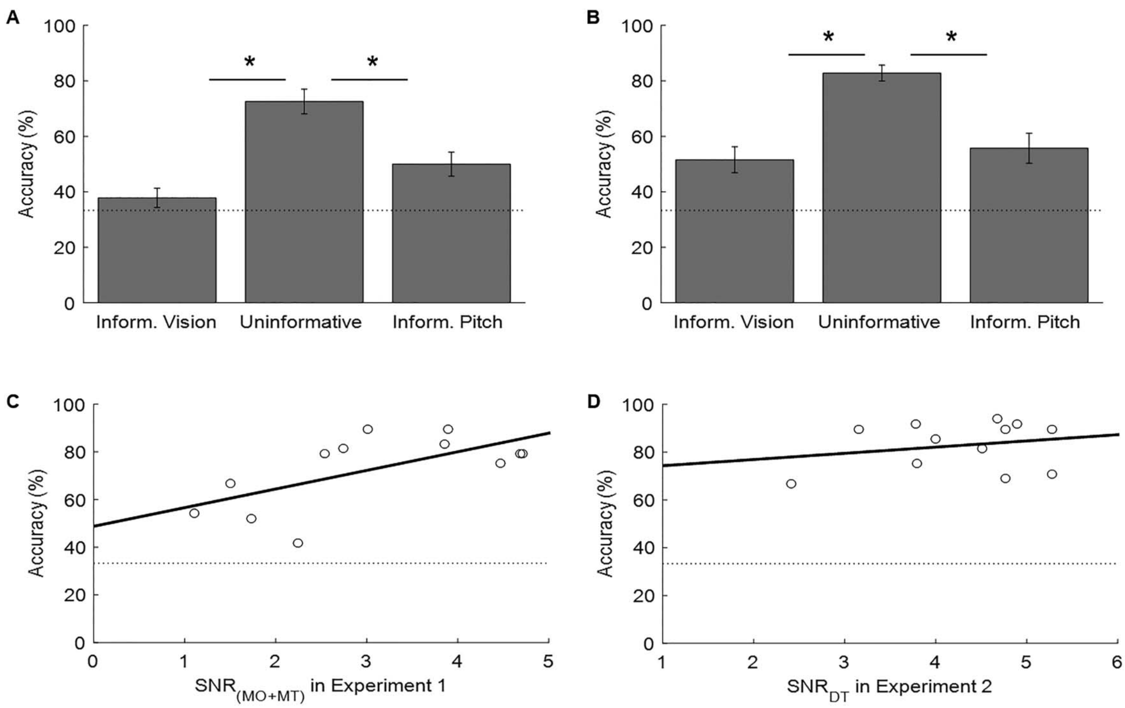

Figure 6. Results of accuracy rates in (A) Experiment 3a and (B) Experiment 3b which tested the information content of Leaders' action duration modulations observed in Experiments 1 and 2, respectively. Error bars show the SE and asterisks mark significant differences. In (C) (Experiment 3a/Experiment 1) and (D) (Experiment 3b/Experiment 2) accuracy rates in the "Uninformative" condition in Experiment 3 are plotted against Leaders' signal-to-noise ratios from Experiments 1 or 2. The dotted lines indicate chance performance at 33.3%.

in the online interaction that led to the creation of a communication system could successfully interpret communicative modulations of action duration. Participants were overall more accurate in the Uninformative compared with the Informative Vision and Informative Pitch conditions and significantly exceeded chance performance that would be predicted if they had merely been guessing the correct target. Thus, given that we found similar results in Experiment 3 as in the first two experiments, we conclude that the established communication systems are generalizable such that they can be transmitted to and understood by people who were not involved in the creation of these systems. To further test the generality of these communication systems, an interesting pathway for future research would be to study sensorimotor communication in longer transmission chains (Kirby, Cornish, & Smith, 2008), for example, by asking the group of participants who performed the offline task as in Experiment 3 to now be Leaders in a new interactive setting as in Experiments 1 and 2.

It might be puzzling that participants still performed better than chance in some of the Informative Vision or Informative Pitch conditions. We had hypothesized that Leaders in Experiments 1 and 2 would exclusively adjust their action duration in Uninformative and would not deviate from their natural timing in all other cases. How could participants in Experiment 3 reach above-chance prediction accuracy? The most likely explanation for this finding is that Leaders' action durations also contained information about target locations in situations where external additional information was already available (i.e., visual or pitch information). Together with anecdotal evidence from debriefing participants, this suggests that Leaders might have reverted to modulations of action duration in cases where Followers had difficulties utilizing the externally given information. Indeed, a few Followers in Experiments 1 and 2 reported that they had problems distinguishing the three different pitches in the Informative Pitch condition. Leaders who noticed this would then also modulate their action duration to augment the information content for Followers. It is known from studies on natural verbal conversations that speakers tend to be highly sensitive to the needs of their listeners such that they monitor their state of knowledge and adjust at various linguistic levels ("audience design"; Brennan & Hanna, 2009; Clark & Krych, 2004; Lockridge & Brennan, 2002). For example, depending on listeners' visual perspective, speakers adjust the labels when referring to objects such that they provide more detailed descriptions when listeners are faced with ambiguity (Dumontheil, Küster, Apperly, & Blakemore, 2010). This is specific to the particular individual listener and conversational context. Moreover, in cases where an original communication attempt was unsuccessful, specific adjustments serve as a form of "repair" behavior to maintain common ground (Clark, 1996). In the present study, the redundant action duration information that some Leaders in Experiments 1 and 2 provided to their Followers especially in the Informative Pitch condition could be used by participants in Experiment 3 to detect the correct target locations with higher than chance accuracy.

An additional prediction for Experiment 3 was that participants' prediction accuracy would be better the higher the signal-to-noise ratio of the Leaders in Experiments 1 and 2 was. This prediction was confirmed in Experiment 3a but surprisingly not in Experiment 3b. Most likely, this was because of a ceiling effect as participants in Experiment 3b had overall high accuracy rates (on average 82.8%, $SD = 9.9\%$).

General Discussion

To increase our understanding of how communication based on instrumental actions is created and used, the present study investigated whether action duration provides a basis for establishing novel communication between a Leader and a Follower in a joint action. The aim of the present study was twofold: The first aim was to investigate whether action duration, a temporal parameter of action performance, would be used to establish a communication system for joint action. The second aim was to further investigate such communication based on action duration by testing whether Leaders, who provide the communicative signal, would have a preference for sensorimotor communication, where the communicative goal is embedded in the instrumental goal, or for a form of communication that temporally separates instrumental and communicative action goals. To that end, Leaders performed movements to target locations unknown to Followers who then attempted to quickly move to the same target location. Crucially, by equating expected movement times by adjusting target size to compensate for longer distances (Fitts, 1954), we created a situation where information about the correct target location could not be derived directly from unmodulated action duration and where pre-established communication systems could not be used. We hypothesized that Leaders would create novel communication systems by modulating the duration of their actions to inform Followers and that Followers would be able to use this information to choose which location to move to.

The results of three experiments clearly demonstrate that temporal action parameters can be modulated to serve a communicative purpose. Leaders in Experiments 1 and 2 consistently modulated action duration to inform naïve Followers about the location of a joint action target. In Experiment 1, Leaders modulated their action duration by adjusting velocity such that the movement to far targets took longer than to near targets. In Experiment 2, Leaders could have chosen the same successful strategy but instead they modulated the DT on a target. Specifically, by adjusting how long they dwelled on the respective target Leaders modulated the duration of a tone, thereby creating clearly distinguishable durations for Followers. Finally, Experiment 3 demonstrated that the communication systems that were established in Experiments 1 and 2 were stable and general enough that a new group of people, who had not been part of the original interaction, could also successfully determine the information content of the communicative signal.

The current findings are important in two respects. First, we provided first evidence that modulations of temporal action parameters can be used for communication in a joint context. Previous work only demonstrated that people tend to generally slow down their movements to facilitate recognition for a receiver (Sacheli et al., 2013; Vesper & Richardson, 2014). Given that people are highly sensitive to timing aspects of others' movements (Aglioti, Cesari, Romani, & Urgesi, 2008; Sartori et al., 2011; Umiltà et al., 2001; Vesper et al., 2013), allowing them for instance to make accurate predictions about when an actor will reappear behind an occlusion (Graf et al., 2007; Sparenberg et al., 2012; Stapel et al., 2016), we expected that interaction partners would also actively adjust their action timing to provide information to each other and thereby facilitate coordination. This was demonstrated in the present study.

Second, our study addresses the emergence of communication systems at the transition between, on the one hand, purely movement-based communicative action modulations and, on the other hand, a form of communication that functionally separates instrumental (i.e., movement-based) and communicative action goals. In the present study, Leaders in Experiment 2 had a choice between modulating the action execution itself and the action end-state. Our findings show that Leaders preferred to adjust the duration of the action end state, thereby realizing the communicative goal temporally detached from the instrumental goal instead of both simultaneously. Possibly this preference occurs because separating instrumental and communicative action goals is more recognizable as a distinctive communicative signal (Scott-Phillips, 2015; Sperber & Wilson, 1995). Additionally, modulating the action end state might be easier to control biomechanically. Thus, the present work provides insights about how, evolutionarily speaking, conventional communication systems like formal language might have developed from the requirements of real-time action coordination (see Barr, 2004, for a similar argument). Therefore, it significantly extends previous work on "experimental semiotics" (Galantucci et al., 2012) that has frequently demonstrated the remarkable creativity and flexibility with which people establish novel communication systems (Galantucci, 2005; Misyak et al., 2016; Newman-Norlund et al., 2009; Scott-Phillips, Kirby, & Ritchie, 2009; Volman et al., 2012).

Findings from the nonverbal communication domain are also consistent with patterns of duration in spoken language. For example, previous work on "motherese" (Fernald, 1985) has shown that adults speaking to infants and young children exaggerate not only phonetic aspects of their speech but also actively modulate vowel length to facilitate word learning (Swanson, Leonard, & Gandour, 1992). Moreover, in some languages vowel or consonant duration is distinctive such that the word meanings are changed depending on whether vowels are pronounced short or long. For instance, Japanese language distinguishes word meanings by the relative duration of vowels within a word (Hirata, 2004). Vowel length contrast is mostly invariant to speech rate and similar across different languages (Tsukada, 2009). Such modulations of temporal aspects of language can also frequently be observed in everyday speech, for example, when speakers attempt to communicate more clearly in noisy environments or when they specifically modulate cospeech gestures when there is a mismatch between speaker and listener (Hilliard et al., 2015). Our study extends previous work by showing that also nonconventional, nonverbal communication can rely on modulations of action duration.

The results of Experiment 2 suggest that communicators prefer to temporally and functionally separate instrumental and communicative action goals: The instrumental goal of reaching the target was performed first in a natural, efficient way; then the communicative goal of informing the partner was instantiated by modulating the duration of the DT on the target. According to some linguistic theories, one may interpret this separation of instrumental and communicative goals as a form of symbolic communication. For example, Allwood (2002) distinguishes between "iconic information" and "symbolic information" by suggesting that the information that is shared between a communicator and a receiver is homomorph, that is, clearly related by similarities, in the former but not the latter case (see also Galantucci, 2009; Garrod, Fay, Lee, Oberlander, & MacLeod, 2007). In this sense, the relation between movement time and movement distance qualifies as homomorph because it naturally takes longer to reach farther targets. Essentially, this relationship is part of what is captured by Fitts' law (Fitts, 1954). Thus, a communication system based on MT, as the one observed in Experiment 1, could be viewed as iconic rather than symbolic (although one might contest that even in this case for the interaction partners movement duration "means" or "symbolizes" target distance). In contrast, there is no such strong homomorphy between the DT on a target and the movement distance to the same target because the two are not intrinsically related. Longer distances do not automatically lead to longer DTs. In this respect, the relation between DT and distance in Experiment 2 is more arbitrary than the relation between MT duration and distance in Experiment 1. Therefore, a communication system based on DT, as the one observed in Experiment 2, could be considered to be more symbolic.

The above discussion points to the interesting possibility of a gradual transition from sensorimotor to symbolic communication (Arbib, 2005; Rizzolatti & Arbib, 1998). Indeed, evolutionarily speaking, it seems plausible to assume that modern language evolved gradually from subtle, nonverbal, behavioral adjustments that became conventionalized and more symbolic over the course of many generations. In particular, whereas modulating action kinematics is beneficial for many circumstances, it cannot easily be used to communicate about absent entities or remote objects. Thus, there might have been an evolutionary pressure promoting a separation of instrumental action and communicative action. Understanding this link is an important question that needs to be addressed empirically.

In everyday interaction, a communicator's and a receiver's actions are often not performed in sequence but overlap fully or partially. Future research may, therefore, investigate how the processes and mechanisms we observed in the present study are linked to synchronously performed joint action. In the present work, we have purposefully chosen sequential action performance as it allowed us to precisely measure Leaders' communicative modulation of action duration independently of the Follower's simultaneous performance. However, we predict that the communication system used in the present study may also be employed in a synchronous joint action setting. Indeed, previous research on synchronous joint action showed that joint action partners communicatively modulated the spatial kinematics of their actions while both persons' actions unfolded (e.g., Sacheli et al., 2013; Vesper & Richardson, 2014). Moreover, adjustments to the timing of kinematic signatures might additionally support synchronous joint action by displaying distinctive kinematic features early: One study showed that a communicator adjusted the velocity profile of target-directed aiming movements such that the maximum height, which was indicative of the location of a joint movement target, was reached particularly early (Vesper & Richardson, 2014). This allowed the task partner to distinguish the target from nontargets early and to move to the target in synchrony with the communicator. This observation is in line with the predictions made by a theoretical account of sensorimotor communication that postulates that disambiguating actions is supported by modifying timing so that critical information is received early (Pezzulo et al., 2013).

Taken together, the present study extends previous work on sensorimotor communication in interaction contexts that highlighted the role of spatial movement parameters by demonstrating that action duration offers a further potential communication channel. Our findings show that joint action coordination can benefit from communicative modulations that violate predictions about instrumental actions. Generating and perceiving systematic deviations from the predicted duration of a goal-directed action was sufficient to enable an effective nonconventionalized form of communication during joint action. Moreover, we found that knowledgeable co-actors had a preference to use a communicative strategy that temporally separated instrumental and communicative action goals. We hypothesize that the same principles of establishing novel communication systems that we identified in the present study also hold in natural communication settings of everyday human interaction. For example bowing in Japanese formal greeting relies on modulations of action duration to convey an actor's communicative intention (indicating politeness and respect) beyond the instrument goal (acknowledging another's presence). Similarly, by pressing a door bell for a substantial amount of time and thereby extending the duration of the tone, one can express the urgency of one's visit in addition to simply informing about one's presence.

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Correction to Bull et al. (2013)

In the article "Sex Differences in the Spatial Representation of Number" by Rebecca Bull, Alexandra A. Cleland, and Thomas Mitchell (*Journal of Experimental Psychology*: *General*, 2013, Vol. 142, No. 1, pp. 181–192. http://dx.doi.org/10.1037/a0028387), there was an error in the **Results** section of **Experiment 2**. The t value incorrectly repeated the beta weight ($-.25$). The correct value is $t(39) = -3.38$, $p = .002$. There was also an error in the **Discussion** section of **Experiment 2**. The reported result of $F(1, 94) = 4.27$, should read $F(1, 94) = 4.72$, $p = .032$. Finally, there was an error in the **Results** section of **Experiment 4**. The t value for was incorrectly reported as $t(50) = 1.56$, $p = .05$. It should be $t(50) = 1.98$. These typographical errors do not change the overall pattern of results or interpretation of the findings.

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