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Abstract

Comprehending action language recruits the action system. To what extent do action simulations reflect the fine-grained parameters of real world action? We investigate whether action simulations are sensitive to speed of an action. In two experiments participants completed a motor task where they moved slowly or quickly, followed by a sentence sensibility task. We found an overall action effect for sentences describing hand actions: moving slowly increased accuracy (Exp.1) and reduced response time (Exp. 2). For sentences describing full-body actions, responses were more accurate when movement speed matched the speed implied in the sentence, in Experiment 1 only. This study demonstrates online action simulation and provides evidence that speed of action can be simulated during sentence comprehension.

Keywords: embodiment; mental simulation; action; speed

Introduction

A plethora of studies in the embodied language framework shows that comprehending action language recruits motor simulations (see Fischer & Zwaan, 2008, for review). For example, responses to sentences describing actions towards or away from the body (e.g., *open/close the drawer*) were faster when the direction of motion in the sentence matched the direction of physical response (Glenberg & Kaschak, 2002). Evidence from brain imaging also shows that action language activates the motor cortex (Hauk, Johnsrude, & Pulvermuller, 2004; Tettamanti et al., 2005).

A critical remaining question however, is the level of abstraction from physical actions to action simulations; it is unclear to what extent action simulations mirror real-world actions. They may include coarse representations, coding for salient features such as effector (Hauk et al., 2004) and direction (Glenberg & Kaschak, 2002), but may not contain fine-grained temporal and spatial features that actions require for precision. The current study was designed to evaluate whether fine-grained features like the *speed of an action* shape mental simulations during comprehension of action language. We investigated this by assessing for the first time whether comprehension of sentences describing fast and slow actions is affected by prior engagement in fast or slow actions. If action simulations closely mirror real-world actions then we expect parameters vital for accurate motor performance to be coded in these action simulations.

Recent research has shown that online simulations are sensitive to speed. When listening to sentences describing actions with fast and slow connotations (e.g., *The lion dashed/ambled to the balloon*) looking times towards a concurrent visual scene were longer for slow actions compared to fast actions (Speed & Vigliocco, 2014). Imaging evidence also shows that sentences about fast motion are mentally simulated differently to sentences about slow motion (van Dam, Speed, Lai, Vigliocco, & Desai, 2017). Speed, van Dam, Hirath, Vigliocco, and Desai (2017) provide crucial evidence that speed of action is represented in the meaning of speed-related words. In an explicit semantic similarity judgment task, individuals with Parkinson's Disease (PD), who have difficulty moving quickly, had difficulty making judgments about fast words. Furthermore, this difficulty was specific to verbs describing fast actions performed with the hand.

To further this growing evidence, in the present studies we test the effect of movement speed on sentences about speed of motion using a sentence sensibility judgment task, a task more implicit than semantic similarity judgments. We also further explore the potential difference between language about speeded *hand* actions (e.g., *to grasp*) and speeded actions involving the whole body (e.g., *to run*).

How can we modify speed of action in an experiment? Manipulating physical speed during sentence processing may lead to unwanted attentional demands, and could interfere with response time measures of comprehension. So, we decided to manipulate action speed before the language task. Other studies have shown that sufficient motor activity prior to performing a language task can affect processing of action language. For example, Locatelli, Gatti, and Tettamanti (2012) found that a 3-week action training period affected performance on a sentence-picture matching task for sentences about similar hand actions. In fact, training the motor system for only 20 minutes can induce comprehension effects. Glenberg, Sato, and Cattaneo (2008) had participants move 600 beans from one container to another, towards or away from the body. After this short duration the motor system had adapted to a particular direction, which facilitated responses for sentences describing movement in a matching direction.

In Experiment 1 we used a motor task where participants wore weights in order to slow down movement, and in Experiment 2 participants had to balance balls on the back of a spoon, which made them move slowly. They then completed a sentence sensibility task on sentences with fast, slow, or no motion connotation. If the speed of an action is encoded in comprehenders' mental simulations then prior execution of "fast" or "slow" movements should affect comprehension of language denoting "fast" and "slow" actions. In sum, we predict an interaction between movement speed (fast or slow) and sentence type (fast or slow).

Experiment 1 Method

Participants

Seventy-two native English speakers (M_{age} = 21.24, *SD* = 2.54, 49 females) were recruited from the University of South Carolina subject pool and assigned to either the weights (*n* = 36) or no weights group (*n* = 36).

Material

The experiment was divided into two sentence sets, to be analyzed separately due to matching constraints.

Arm/hand sentences Eleven fast and slow verbs describing actions with the hand/arm (e.g., *to shove* vs. *to roll*) were placed into sentences (e.g., *Rick shoved the bag behind the cupboard*), as well as 11 abstract verbs (e.g., *to scare*) for "neutral" sentences. Speed (i.e., fast vs. slow) and concreteness (i.e., speed vs. abstract/neutral) were manipulated between items because the fast and slow hand actions were too different to each other to fit into the same sentence frame. Each participant saw all sentences.

Full-body sentences Thirteen fast and slow verbs describing actions with the whole body (e.g., *to storm* vs. *to sneak*) were placed into sentences (e.g., *The professor stormed down the corridor*), as well as 13 abstract verbs (e.g., *to mourn*) for "neutral" sentences. Speed (i.e., fast vs. slow) was manipulated within items and concreteness (i.e., speed vs. abstact/neutral) was manipulated between items. Each participant saw only one version of each full-body sentence.

Norming Each verb used in the experiment was rated for speed by a separate set of participants (*n* = 7) on a scale of 1 (very slow) to 7 (very fast) with an option of 'none' available. For each sentence set words were matched across conditions on critical psycholinguistic variables (all *p*s for main effect of verb type in a three-way ANOVA were > 0.05): number of letters, log decision frequency, number of orthographic neighbors, number of phonemes, number of syllables, lexical decision RT, lexical decision accuracy and naming RT (taken from the English Lexicon Project; Balota et al., 2007).

Design

Participants either wore wraps with weights (five pounds on each ankle and three pounds on each wrist) or without weights, manipulated between subjects. Sentence speed was manipulated within subjects (fast, slow, none/abstract).

Procedure

Cover story Participants were told that the study investigated how skin conductance changes as a function of movement size: moving cans around a table (large arm movements) and completing a reading task on the computer (small hand movements and eye movements). Four fake recording devices were fitted to each participant along with wraps that either contained weights or did not. Electrodes were attached to the forearms and calves of each participant and simulated a recording system. Wraps were placed around each subject's wrists and ankles. Two experimenters acted out a process of checking an electrode's signal and subsequently altering its position.

Movement task Participants stood at one end of a table in front of five full tin cans. They were instructed to move the cans, one at a time, using alternate hands, to the other end of the table and place them as indicated by stickers. Participants had to move their legs and arms to reach the location. They then had to move the cans back to the original position in the same manner. This was completed eight times.

Sentence sensibility task After completing the movement task the electrodes were checked again and participants were reminded that the purpose of the next task was to make small movements with the hands and eyes. It was explained that eye-movements were not being recorded but that we were measuring accuracy on the task to check that they were actually reading the sentences.

Whole sentences were presented on the screen and participants had to decide if they made sense or not by responding "j" for "yes" and "f" for "no" on the keyboard. There were six practice trials with feedback. All sentence types were presented in one block in a random order. The sentence sensibility task took around 15 minutes. Subjects were then debriefed. No subjects indicated awareness of the true aims of the study.

Results

Those wearing weights took significantly longer to complete the movement task (*M* = 501s, *SD* = 142s) than those not wearing weights (*M* = 437s, *SD* = 70s), $t(69)$ = 2.32, p = .02). Items were removed from analysis if overall accuracy was less than 75%: for full-body sentences 6 items were removed and for hand sentences one item was removed. Individual trials were removed if RT was outside 2.5*SD* of a subject's mean RT(<2% of the data). Three subjects were removed for having accuracy less than 80% and one subject was removed for having dyslexia.

Linear mixed effects models (LME) in R (lme4 package) were used to analyze the data, with subjects and items as crossed random effects and sentence type and group (weights vs. no weights) as fixed effects. Loglinear models were used for analyses of accuracy. Markov chain Monte Carlo approximation was used in RT analyses to estimate *p* values. For both accuracy and RT each sentence set was analyzed using a model including all three sentence types, with neutral sentences as the reference level (Model 1) and then with a model with neutral sentences removed, in order to compare fast and slow sentence types (Model 2). The analyses for each sentence set are reported separately.

Hand/arm sentences Sentences describing both fast and slow hand movements were responded to faster than neutral sentences ($t = 2.33$, $p = .02$; $t = 1.94$, $p = .05$), but there was no difference between fast and slow sentences ($t < 1$). Contrary to expectation, wearing weights led to faster responses than when without weights ($t = 2.06$, $p = .04$). None of the interactions were significant.

For accuracy there was no difference across sentence types ($z < 1$) and no effect of group ($z = 1.47$, $p = .14$). There was however a significant interaction between sentence type and group for neutral and fast sentences ($z = 2.5$, $p = .01$) but not neutral and slow sentences ($z = 1.62$, $p = .11$), although there was a trend for the same pattern. Responses to fast and slow sentences were more accurate when wearing weights than when not wearing weights, but this pattern was not present for neutral sentences. When collapsing fast and slow sentences into one "speed" condition, this pattern was reflected in a significant interaction between sentence type and group ($z = 2.55$, $p = .01$). Wearing weights affected sentence accuracy differently depending on whether the sentence described a hand action (regardless of speed) or an abstract (neutral) action (see Figure 1).

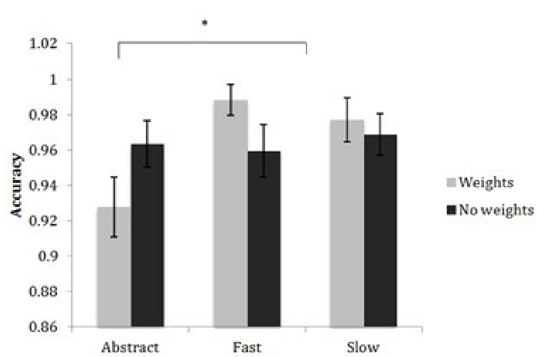

Figure 1. Accuracy for hand/arm sentences Experiment 1.

Full-body sentences Sentences describing both fast and slow full-body movements were responded to faster than neutral sentences ($t = 2.28$, $p = .02$; $t = 2.12$, $p = .03$), but there was no difference between fast and slow sentences ($t < 1$). Wearing weights did not affect RT ($t = 1.5$, $p = .13$), but there was a trend for responses to be faster with weights than without. There were no interactions between weights condition and sentence type ($t < 1$).

Slow full-body sentences were responded to less accurately than neutral sentences ($z = 2.74$, $p < .01$) but not fast full-body sentences ($z = 1.54$, $p = .12$), and there was no difference between neutral sentences and fast full-body sentences. Wearing weights did not affect accuracy and there was no interaction between group and sentence type in Model 1 (neutral vs. fast $z < 1$, neutral vs. slow $z = 1.13$, $p = .23$). In line with predictions however, there was a significant interaction between group and sentence type in Model 2 ($z = 2.12$, $p = .03$). Responses to fast full-body sentences were less accurate with weights compared to without weights, and conversely responses were less accurate to slow full-body sentences without wearing weights (see Figure 2). Moving at a certain speed led to difficulty comprehending sentences describing a different speed.

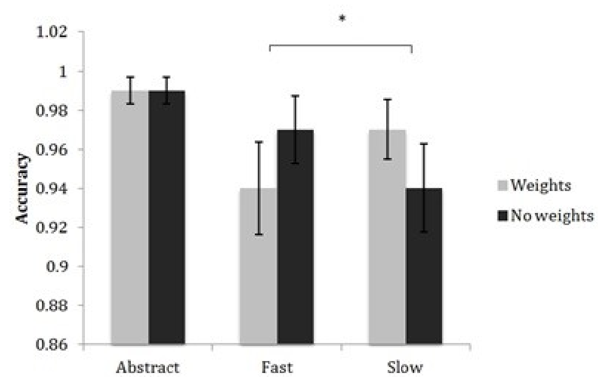

Figure 2. Accuracy for full-body sentences Experiment 1.

Discussion

Experiment 1 provides evidence that movement speed affects comprehension of speed-related sentences. For sentences describing hand actions the effect of weights was the same for fast and slow actions, but different compared to abstract/neutral sentences. Wearing weights (slowing movement) improved accuracy for fast and slow sentences but not neutral sentences, reflecting a general effect of action/motion. For sentences describing full-body actions however, we did find an interaction between described action speed and group. Wearing weights (slowing movement) reduced accuracy in comprehending sentences describing fast full-body actions, but increased accuracy in comprehending slow full-body actions. This suggests that comprehension is better when the action system matches the speed of the action being simulated.

One criticism of Experiment 1 could be that rather than movement speed we manipulated another parameter, such as force (more force was required to move whilst wearing weights). In order to test the generalizability of our findings, in Experiment 2 we introduced a new way of manipulating movement speed.

Experiment 2 Method

In Experiment 2 we manipulated speed without manipulating force by using a task in which participants had to move whilst balancing a ball on a spoon. In the fast group, participants balanced the ball on the regular side of the spoon, but in the slow group they balanced the ball on the back of the spoon, where a small hole had been drilled, making balancing more difficult.

Participants

72 native English speakers were recruited from the UCL subject pool (M_{age} = 26.7, *SD* = 8.4, 44 female) and were assigned to the fast movement group (*n* = 36) or the slow movement group (*n* = 36).

Material

The same sentences from Experiment 1 were used. For the movement task, a wooden spoon with a small hole drilled into the back, 8 small colored balls and 16 small glass dishes were used.

Design

Participants balanced balls on the normal side of the spoon (fast group) or the back of the spoon (slow group), manipulated between subjects. Sentence speed was manipulated within subjects(fast, slow, neutral/abstract).

Procedure

Cover story Participants were told that the experiment was part of a project investigating movement patterns under different conditions, and that this specific experiment looked at how concentration affects movements in two different tasks. The first task (movement task) would focus on balance and stability, and the second task (sentence task) would focus on concentration while reading. Participants were told that their movements were being recorded by a Vicon motion capture system that was present in the room. The experimenter attached three markers to each arm of the participant, and acted out a calibration sequence with them.

Movement task There were two tables in the testing room, and on each table there were 8 small glass bowls, with 4 containing balls. Participants were instructed to take each ball one at a time and transfer it to an empty bowl on the other table by carrying it with the spoon (on the regular side or back). Once all balls had moved to the opposite table, the task was completed again until the balls were in their original position. In total, 16 transfers were made. Participants were given some time to practice balancing with the ball before the task began.

Sentence sensibility task After completing the movement task participants sat down at the computer to begin the sentence task. The same task instructions as Experiment 1 were delivered. Before the task began, the experimenter acted out beginning the recording for the motion tracker. The sentence sensibility task took around 15 minutes. Subjects were then debriefed. No subjects indicated awareness of the true aims of the study.

Results

The slow group took significantly longer to complete the task than the fast group. Items were removed from analysis if overall accuracy was less than 80%: for full-body sentences 5 sentences were removed and for hand sentences 4 sentences were removed. Individual trials were removed if RT was outside 2.*5SD* of a subject's mean RT (3.2%). Four subjects were removed for having accuracy less than 80%. Analyses proceeded in the same manner as Experiment 1.

Hand/arm sentences In Model 1, there was no difference in response time between fast and neutral sentences (*t* = .1, *p* = .92), and slow and neutral sentences (*t* = .3, *p* = .77), nor an effect of group (*t* = .04, *p* = .97). There was, however, a significant interaction between sentence type and group for fast and neutral sentences (*t* = 2.93, *p* = .003) and slow and neutral sentences (*t* = 2.32, *p* = .02). Responses to fast and slow sentences were faster in the slow group than the fast group, but this was not the case for neutral sentences. When collapsing fast and slow sentences into one "speed" condition, there was a significant interaction between sentence type and group (*t* = 8.85, *p* = .003). Moving slowly affected response time depending on whether a sentence described a hand action (regardless of speed) or an abstract (neutral) action.

In Model 2, there was no difference between fast and slow sentences (*t* = .39, *p* = .70), no effect of group (*t* = 1.75, *p* = .08) and no interaction (*t* = .67, *p* = .50).

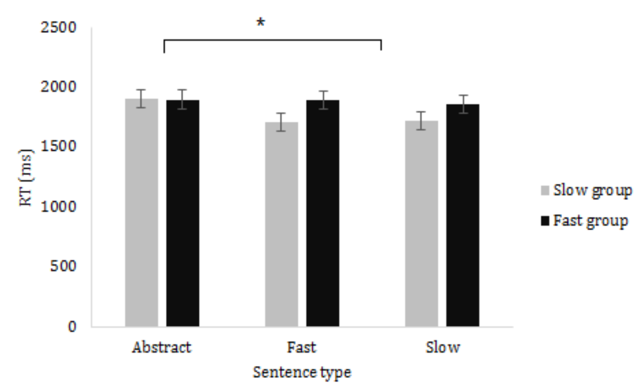

Figure 3. Response time for hand/arm sentences Experiment 2.

For accuracy there was no difference between fast and neutral sentences (*z* = .33, *p* = .74), or slow and neutral sentences ($z =$ 1.49 $p = .14$), no effect of group ($z = .66$, $p = .51$), and no interactions ($z =$ .05, $p = .96$; $z = 1.81$ $p = .07$) in Model 1. In Model 2, there was no difference between fast and slow sentences ($z = 1.1$, $p = .27$) and no effect of group ($z =$ .62, $p = .54$), but there was a marginal interaction between sentence type and group ($z = 1.9$, $p = .06$). There was a trend for accuracy to fast words to be higher in the slow group than the fast group, and conversely for accuracy to be higher to slow words in the fast group than the slow group.

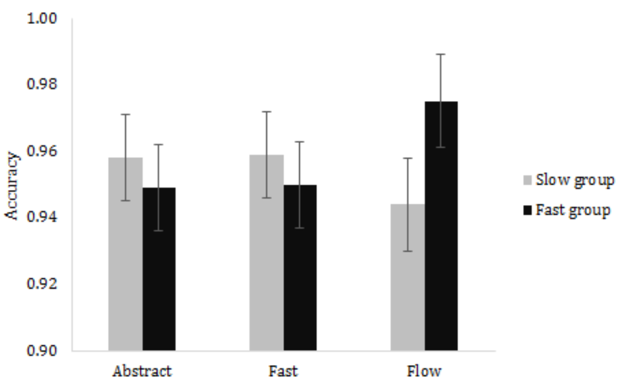

Figure 4. Accuracy for hand/arm sentences Experiment 2.

Full-body sentences There was no difference in response time between fast and neutral sentences ($t = .66$, $p = .51$), or slow and neutral sentences ($t = .91$, $p = .37$), no effect of group ($t = .91$, $p = .36$) and no interactions ($t =$ .36, $p = .72$; $t = .72$, $p = .48$). Similarly, there was no difference in accuracy between fast and neutral sentences ($z = 1.75$, $p = .08$), or slow and neutral sentences ($z =$ 1.32, $p = .19$). There was no effect of group ($z = .47$, $p = .64$) and no interactions ($z =$ .43, $p = .67$; $z =$ .09, $p = .93$).

Discussion

Experiment 2 provides converging evidence that moving slowly compared to quickly facilitates comprehension of language about hand actions. But, in contrast to Experiment 1, effects were found in response time, not accuracy.

Furthermore, movement speed did not affect comprehension of sentences about fast and slow sentences. The discrepancies between Experiment 1 and 2 are discussed below in the General Discussion.

General Discussion

In two experiments we show that the speed of prior movement affects comprehension of sentences describing fast and slow motion. This provides supporting evidence for mental simulation of action, as well as evidence that fine-grained motion features (speed) can be incorporated into mental simulations during language comprehension.

For sentences describing hand actions (e.g., *to grasp*), we find that comprehension of both fast and slow sentences is better after moving slowly compared to moving quickly. This is reflected in higher accuracy (Experiment 1) and shorter response time (Experiment 2). The longer movement time in the slow group may prime the motor system to a greater extent than in the fast group, thereby facilitating comprehension of action language. However, we did not observe any interaction between sentence speed and group, suggesting the action but not its speed was simulated. One potential explanation may be that the duration of the described hand actions are too short for speed to be a salient feature of the simulation. For example, actions such as "*shove*" or "*roll*" have a shorter duration than walking or running down a corridor, and the brevity of the simulation may constrain the speed simulation. Yet Speed et al. (2017) found that Parkinson's patients have more difficulty with verbs about fast hand actions than verbs about slow hand actions, suggesting speed simulation does occur for hand verbs. The crucial difference however could relate to the task. Speed et al. (2017) used semantic similarity judgements on single verbs, where the judgments explicitly focused on "movement", therefore requiring more explicit processing. Speed simulation of hand actions therefore may occur during deep processing, but not during shallow comprehension.

Experiment 1 also showed that prior movement speed can affect comprehension of sentences describing fast and slow actions with the whole body (e.g., *to dash*). Comprehension accuracy for sentences describing fast full-body actions was higher after prior slow movement (weights) compared to prior fast movement (no weights), but this was the opposite for sentences describing slow action. This suggests that comprehension is better when the action system matches the speed to the action being simulated. The results mesh with the findings of a study of stroke patients (Desai, Herter, Riccardi, Rorden, & Fredriksson, 2015) where fine-grained parameters of reaching actions were measured. Total time to perform the action, and time to initiate the action, were correlated with speed of processing action verbs and nouns, relative to that of abstract words, in lexical decision and similarity judgment tasks. In Experiment 2 here however, we did not replicate this effect. One explanation for this could be that although participants did move more slowly in the "slow" condition, it was the hands that were particularly restricted in movement (keeping the ball balanced on the spoon), not the feet. In Experiment 1 however, both the hands and feet had weights attached, and moving the feet may be more relevant for the types of actions described.

We also note that effects were observed in measures of accuracy in Experiment 1, but response time in Experiment 2. Effects are typically observed in error measurements in tasks that are particularly difficult or when participants are under time pressure (e.g., Rueschemeyer, Lindemann, van Rooij, van Dam, & Bekkering, 2010). Rueschemeyer at al.

(2010) found effects in accuracy but not RT when the concurrent motor task was quite demanding (Experiment 1) but effects in RT when the motor task was easy (Experiment 2). In Experiment 1 of the present study, participants continued to wear weights during the sentence task, which meant that the hands were slightly restricted in movement (i.e., responding was more difficult). Additionally, participants tended to enjoy the balancing task in Experiment 2 more, seeing it as a challenge, whereas the task in Experiment 1 was mundane and repetitive. Further studies could investigate this explanation by manipulating task difficulty and time pressure and assessing comprehension accuracy.

Overall, this study has demonstrated that movement speed can affect comprehension of action language, with greater movement time facilitating comprehension. We further demonstrate that speed of action can be simulated during action sentence comprehension, but that coding of speed may be effector-specific (i.e., feet vs. hands). Using a method in which a specific dimension of action can be manipulated has enabled us to investigate further details and specifications of action simulation observed during comprehension. Action simulations may not contain simply coarse, highly abstracted action information, but reflect at least some fine-grained motion dynamics that are observed in real-world actions.

Acknowledgments

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