The role of the motor system during language comprehension

De rol van het motorsysteem tijdens taalbegrip

Thesis

To obtain the degree of Doctor from the
Erasmus University Rotterdeam
by command of the
rector magnificus

Prof.dr. H.G. Schmidt

and in accordance with the decision of the doctorate board

The public defense shall be held on

September 2, 2010

By

Lawrence John Taylor

born in Belton, Texas, USA

ERASMUS UNIVERSITEIT ROTTERDAM

Doctoral committee

Promoter: *Prof. Dr. R. A. Zwaan*

Other members: *Dr. Diane Pecher*

Prof. Dr. Fred Paas

Prof. Dr. Gun Semin

Table of Contents

Chapter 1

ACTION IN COGNITION: THE CASE OF LANGUAGE

This chapter is published as: Taylor, L. J. & Zwaan, R. A. (2009). Action in cognition: The case of language. *Language and Cognition*, *1*, 45-58.

Abstract

Empirical research has shown that the processing of words and sentences is accompanied by activation of the brain's motor system in language users. The degree of precision observed in this activation seems to be contingent upon (1) the meaning of linguistic construction and (2) the depth with which readers process that construction. In addition, neurological evidence shows a correspondence between a disruption in the neural correlates of overt action and the disruption of semantic processing of language about action. These converging lines of evidence can be taken to support the hypotheses that motor processes (1) are recruited to understand language that focuses on actions and (2) contribute a unique element to conceptual representation. This article explores the role of this motor recruitment in language comprehension. It concludes that extant findings are consistent with the theorized existence of multimodal, embodied representations of the referents of words and the meaning carried by language. Further, an integrative conceptualization of "fault tolerant comprehension" is proposed.

A common function of language is to describe actions. But how are linguistically-mediated actions understood? A considerable amount of experimental evidence has supported the notion that the motor modality, in particular, is involved in the comprehension of language about action. That is, when a person hears or reads text involving action, there is activation of the motor system in his or her brain, which corresponds to the referential semantic content of the description (e.g. Glenberg & Kaschak, 2002; Zwaan & Taylor, 2006). This finding has been referred to as "indexing" (Glenberg & Robertson, 1999) or "referential motor resonance" (Fischer & Zwaan, 2008). An alternative view maintains that this approach and its effects "can be explained by a disembodied view of cognition if appropriate assumptions are made about the dynamics of activation flow between cognitive systems" and that "sensory and motor information plays, at best, a supportive but not necessary role in representing concepts" (Mahon & Caramazza, 2008). According to this view, there most likely exists a level of abstraction above (or consisting of) multimodal representations (see Ghazanfor & Schroeder, 2006 for partial support). At first glance, these two approaches appear to be completely at odds with one another. However, one goal of this paper is to demonstrate how closely coupled the two approaches are. To begin laying out our argument, we consider the neural overlap between action, imagination, and language comprehension.

Overlapping neural substrates underlie overt action, imagination, and language comprehension

If the action system plays a role during the comprehension of action descriptions, then action, the imagination of action, and the comprehension of language about action should involve overlapping neural substrates. Several functional-magnetic resonance imaging (fMRI) studies have indeed demonstrated that actively imagining an action is associated with activation in motor and premotor regions of the cortex (e.g., Filimon et al., 2007). Experiments using techniques with relatively high temporal resolution, such as transcranial magnetic stimulation (TMS; Buccino et al., 2005; Pulvermüller et al., 2005), magnetoencephalograms (MEG; Pulvermüller, 2004; see Hauk, Shtyrov, & Pulvermüller, 2008 for a review), fine-grained movement-kinematic measures (Boulenger et al., 2006; Glover & Dixon, 2002; Gentilucci & Gangitano, 1998), and behavioral studies (Zwaan & Taylor, 2006; Glenberg & Kaschak, 2002) converge to demonstrate rapid, brief, automatic, and somatotopic (Pulvermüller, 2005) motor activation during or immediately following the presentation of language describing action. Often, this is the case even when the word is not deeply processed (e.g., Pulvermüller, 2004; Boulenger et al., 2006 who only exposed participants to a word) and during online reading (e.g., Taylor & Zwaan, 2008). Given the spatial overlap (Raposo et al., 2008) between the regions that are involved in the execution of overt actions (Penfield & Rasmussen, 1950), active imagery (Postle et al., in press), viewing actions (Calvo-Merino et al., 2005), and hearing, reading, and/or processing action descriptions (Glenberg & Kaschak, 2002; Zwaan & Taylor, 2006; Kemmerer et al., 2008), a reasonable conclusion is that these processes all rely on similar or partially overlapping, but probably not completely co-extensive brain regions.

Neurological data provide evidence for an important point. Lesioned or dysfunctional motor neurons are associated with disrupted semantic processing of action-related language. Although patients with such afflictions are typically capable of some form of comprehension, this is probably suboptimal at best. For example, Parkinson's patients, who typically display motor deficits while performing overt actions, have abnormal lexico-semantic processing for action verbs, but not for concrete nouns. When they are treated with Levodopa, which restores normal motor functioning, they come to have relatively normal processing for both concrete nouns and action verbs (Boulenger, et al., in press). Likewise, patients with clinically and electrophysiologically-confirmed motor neuron disease have consistent and selective impairment for both the comprehension and production of verbs relative to nouns (Bak et al., 2001). Awaiting further neuropsychological data, the claim that motor neurons are not necessary to action-related language comprehension seems justified, as action word processing is impaired, but still possible, when motor neurons themselves are impaired. However, these data also support the claim that motor neurons provide a unique and substantive portion of conceptual representations of linguistic constructions about actions.

The degree of motor involvement appears to depend on the depth of semantic processing. An fMRI study revealed somatotopically organized activation in motor and premotor areas for action execution, but not for a "lexical task," such as passive word viewing (Postle et al., in press). This reflects a general pattern seen in fMRI studies; action execution and observation is often associated with detectible somatotopic organization using fMRI, but comparable effects are difficult to pin down for action words (see Postle et al., in press for a review; however, see Rüschemeyer, Brass, & Friederici, 2007, reviewed in the next section), specifically when relatively shallow processing tasks, such as lexical decision or passive word viewing, are used. Conversely, a deeper semantic task (Semantic Similarity Judgment) that requires participants to make very fine-grained semantic judgments (i.e. is *trudge* more similar to *limp* or *stroll*?)

reveals remarkably fine-grained organization in the cortex for action parameters such as whether an action involves motion, contact, change of state, or tool use (Kemmerer et al., 2008). Given the poor temporal resolution of fMRI, finding processes associated with accessing word meaning is a serious challenge to researchers using that methodology (Postle et al., in press). With a sufficiently deep semantic task, however, verb meaning and neural states show a remarkable overlap that can be revealed with the superior *spatial* resolution of fMRI (Kemmerer et al., 2008). Obviously, the issue of how processing depth interacts with motor effects during language comprehension warrants further exploration and research.

Brain imaging studies show that exposure to action words activates motor and premotor areas (see Hauk et al., 2008 for a review). Unfortunately, they do not offer sufficient detail to provide decisive evidence vis à vis the claim that there is a high correspondence between the semantic content of action-related language and activation in the motor system. Behavioral studies are uniquely suited towards this end. Either premeditated action-planning or semantic processing that is deeper than simple word detection is sufficient to cause priming between linguistic input and goal-directed action; word-exposure (or lexical decision) alone has not been found to prime a goal-directed action (Lindemann et al., 2006). Dominant-handed responses to hand action verbs, relative to foot action verbs, are disrupted during a semantic decision task, but not during a lexical decision task and not (1000 ms) after a semantic decision has already been made (Sato et al., 2008). During a reach-to-grasp movement visual exposure to action verbs, relative to nouns denoting non-graspable objects, rapidly (within 200 ms) affects the reaching action (Boulenger et al., 2006); nouns denoting graspable objects (Glover et al.,

2004) and adjectives describing size (Gentilucci & Gangiitano, 1998; Glover & Dixon, 2002) have similar effects on a reach-to-grasp movement. When judging the sensibility of sentences describing actions towards and away from the body, responses towards the body are faster when following a sentence about an action towards the body (e.g., opening a drawer; Glenberg & Kaschak, 2002). When reading sentences about direction-specific manual rotation (e.g., opening a jar) while engaging in manual rotation themselves, language users read action verbs faster when the sentence describes rotation that is congruent with the action that they are performing during reading (Zwaan & Taylor, 2006).

Two important conclusions can be drawn exclusively from the behavioral data. First, the neural activation associated with linguistic input, reviewed above, most likely codes for actions that bear a close resemblance to those described by text. Second, this *action-specific* activation seems to only become manifest during tasks that require a depth of comprehension beyond simple word-detection or lexical decision (note the broad, often less-than-effector-specific activation for shallow linguistic tasks; however, see Rüschemeyer et al., 2007).

The literature reviewed above offers support for a few key points. First, overt actions, viewing actions, actively imagining actions, and reading about actions most likely rely on overlapping neural substrates and processes in motor and premotor cortical regions. Second, the neural activation observed during action word processing most likely codes for action-specific activation that matches the semantic content of text with some degree of precision beyond mere effector-specificity. Third, while we cannot say that healthy motor neurons are necessary for the comprehension of language about action, we can fairly say that motor neuron deficits induce a quasi-normal and suboptimal sort of comprehension that is often selective for verbs and action related language (e.g., Bak et al., 2001). Taken together, the literature suggests that neural regions that code for action performance are recruited to play a substantial role in the conceptual representation and semantic processing of language about action. Two issues clearly warrant further research: (1) how the depth of semantic processing affects the degree to which the motor system is activated during linguistic processing and (2) how comprehension works in people with neuronal dysfunctions that clearly lead to sub-optimal processing.

Although the findings we have reviewed up to this point are intriguing and lend credence to the claim that the motor system assists in or is required for the comprehension of language about action, a growing need to uncover the linguistic constraints for language-based motor resonance remains. Where and when in a strentch of language can we expect motor resonance to occur? It is to this question that we turn next.

The Linguistic Focus Hypothesis

The goal of comprehending a stretch of language is normally the construction of a mental representation of the referential situation, a situation model (van Dijk & Kintsch, 1983; Zwaan & Radvansky, 1998). Language constitutes a set of cues for forming such mental representations. It does so by systematically and sequentially guiding attention to aspects of the referential world (Langacker, 2001; MacWhinney, 2005; Zwaan, 2004). Under this view, the recruitment of motor representations during comprehension occurs under the governance of linguistic constructions, which direct focus on the referential world. There is initial evidence for this Linguistic Focus Hypothesis (LFH) with regard to motor recruitment (Taylor & Zwaan, 2008; Zwaan, Taylor, & de Boer, in press).

In one experiment (Zwaan & Taylor, 2006, Experiment 4), participants read sentences about direction-specific manual rotation while manually rotating a knob in order to proceed through sentences in groups of one to three words. When participants' actual manual rotation matched the direction of rotation described by the sentence, they were faster to read the critical verb that disambiguated the direction of rotation than when there was a mismatch between implied and actual rotation direction. In a subsequent study (Taylor & Zwaan, 2008) the same paradigm was used, but the critical items were re-written such that the critical verb was followed by an adverb. The adverbs were intended to maintain focus on the action (e.g. *quickly*, *slowly*) in Experiment 1 and to direct focus towards the sentence subject (e.g. *happily*, *obediently*) in Experiment 2; this was done in accordance with the distinction made by linguists between action- and subject-modifying English adverbs (Nakamura, 1997; Jackendoff, 1972). According to the LFH, sustained focus on the action should be accompanied by sustained motor resonance while switching focus to the subject should not; the results supported this prediction (Taylor & Zwaan, 2008).

A further experiment (Taylor, Lev Ari, & Zwaan, 2008) explored an untested assumption from Zwaan & Taylor (2006). The critical items in Zwaan and Taylor's (2006) Experiment 4 were designed such that the critical verb consistently disambiguated the direction of manual rotation. The underlying assumption was that this would be critical or essential to facilitating motor resonance compatible with the action. In the Taylor, Lev Ari, and Zwaan (2008) experiment, the critical items (e.g. *He examined* *the/pie through/the microwave/window and/turned the/timer./The cooking/time needed/to be/shorter [longer]*.) were designed such that the instance of manual rotation was mentioned in the first part of the sentence, but without disambiguating information about the direction of rotation. The direction of manual rotation was clarified in a second sentence within each item, but this relied on an inference being drawn by participants (e.g. the cook turned the timer in order to reduce the remaining amount of cooking time. Therefore, he turned the timer counter clockwise.). Also, it is of interest to note that the critical disambiguating word in these items is an adjective, not a verb or adverb, as in all previously reported experiments using this methodology. The results supported the prediction that motor resonance for rotation direction was associated with text that disambiguated the direction of rotation (Taylor, Lev-Ari, & Zwaan, 2008; see also: Gentilucci & Gangitano, 1998; Glover & Dixon, 2002 for results supporting the claim that adjectives referring to size rapidly affect the motor system).

Zwaan, Taylor, and de Boer (in press) provided further support for the LFH. They incorporated manual rotation sentences in stories (in Dutch) about a bank robbery. The critical sentences were descriptions of (1) actions being performed, (2) actions having been performed in the past and (3) actions intended to be performed. Motor resonance occurred only on the first two types of sentences. Zwaan and colleagues hypothesized that the focus in the latter type of sentence was not on the action itself, but on the preparation for it, which could not be detected by the rotation paradigm. For example, preparing to start the car does not involve manual rotation, but might involve taking the key out of one's pocket and inserting it into its slot. Moreover, in the first two sentences, motor resonance occurred as soon as sufficient information about the action had accrued.

Because of the nature of Dutch syntax, this was often before the main verb in the sentence had been encountered. An example is *Hij greep de dop/en begon de fles/open te draaien (He grasped the cap/and started the bottle/to screw open*). In sentences such as this, the preceding context and the object noun provide sufficient specification of the action, while the auxiliary verb provides focus on the action. Thus, the LFH can explain the—at first sight counterintuitive—finding that motor resonance sometimes does not occur on the action verb itself.

If language indeed systematically guides attention to different aspects of a referential situation, then we would not expect effects as those reviewed above to be limited to a single word class or to only occur in conjunction with a single word class, such as verbs. Instead, when discourse leads a language user to focus on an overt action that is being performed in the referential world, then we should expect the motor system to be activated. However, if the discourse focus is on a different aspect of the situation (e.g., the location or shape of an object or the mental state of a protagonist), then we would expect no such activation. Consistent with this claim is the finding that action words such as *kick* produced activation in corresponding motor areas of the brain when presented in isolation and to a lesser extent when presented in literal sentences, but not when presented in idiomatic phrases (e.g., *kick the bucket*; Raposo et al., 2007). Action verbs also do not produce motor resonance when they are the base of an abstract word (Rüschemeyer et al., 2007). For example, *greifen* (which literally means to grasp) produces motor activation, but *begreifen* (which means to understand) does not. The literature reviewed in this section offers support to the LFH in that entire sentences, verbs, adverbs, and adjectives induce motor resonance as a function of whether the content of the sentence focuses on or disambiguates some element of an overt action that is being performed in the referential world described by discourse.

We are now in a position to advance a theoretical proposal with regard to the role of the motor system in language comprehension, which we outline in the following section.

<u>The Multimodality Hypothesis</u>

Given the available data and after taking theoretical considerations into account (e.g., Barsalou, 2008), we should be prepared to say that motor system activation is neither necessary nor sufficient for understanding action descriptions (see also Fischer & Zwaan, 2008); however, this does not warrant the conclusion that the motor system plays an insubstantial role in understanding action descriptions. The <u>multimodality hypothesis</u> proposes that the representation of word meanings consists of “multimodal representations captured during experiences with its instances [being] reactivated to simulate how the brain represented perception, action, and introspection associated with” a word or concept’s referent in the world (Barsalou, 2008). This hypothesis is consistent with the occurrence of suboptimal comprehension when one or more modalities are dysfunctional or are otherwise incapable of contributing to a word’s representation.

A series of examples may help to illustrate this point. In a recent conversation, one author of this paper spoke to the other author of a “double lutz” being performed. The listening author had no idea what a double lutz could be and could not remember ever hearing of it, but could figure out that it was some action that could be performed by experienced athletes. The listener could tell that the speaker’s sentence was grammatical, but could not comprehend it in the same capacity that the speaker could.

Finally, during the conversation, the speaker explained that it was a jump that an ice-skater could perform. After receiving a scant, purely verbal description of what the action entailed (based on the speaker's limited experience of having seen double-lutzes performed on TV) the listener could at least make sense of the preceding conversation and had some level of comprehension of what was being described. The listener had ice-skated before and had jumped before (though never on ice-skates). This was enough for him to have some idea of what "double lutz" meant. However, this very scant "comprehension" likely cannot hold a candle to the comprehension that a professional figure skater, with years of experience double lutzing would have. Thus the non-expert listener can comprehend "double lutz" in context, but his comprehension is peculiar and quasi-normal, or "impoverished and isolated" (Mahon & Caramazza, 2008).

This example illustrates that a direct mapping between motor experience and semantic content is not necessary for what a normal person would call comprehension. In fact, one would find it quite difficult to learn from reading a book if one required detailed experiential traces for its entire referential content! After all, reading books is one avenue by which we learn new things about the world. An empirical finding supports this view. Motor areas for simple motor programs were activated in nonexpert language users reading about expert actions, whereas motor areas for complex actions were activated in the experts (Beilock et al., 2008). Ostensibly, the understanding that some action was being performed, presumably based on the knowledge of the other words in the sentence and on the syntactic knowledge that the unknown word was a verb, produced some form of motor resonance in the non-expert.

This fits well with the treatment of the multimodality hypothesis discussed above, which allows for comprehension to go forward even if one modality is completely "ignorant" or inexperienced within a given domain. This can occur if a concept consists of "multimodal representations captured during experiences with its instances [being] reactivated to simulate how the brain represented perception, action, and introspection associated with" a concept's referent in the world (Barsalou, 2008). For example, visual experience can help us understand discourse about a high-jumper breaking a world record, even if the motor system of a listener has never been involved in performing a Fosbury flop before.

The focus of this article is the comprehension of language about action. At the risk of moving away from this focus, we will mention here that a more comprehensive multimodal account that includes experiential traces from several modalities (sensory, motor, emotional, and introspective) may help to account for the representation of abstract concepts such as "300,012, incredulous, astute, theory, embodied, false, and on and on" (Mahon & Caramazza, 2008). This "pure multimodality" approach (Barsalou, 2008) is, however, only one of what we see as five competing approaches to accounting for the same phenomenon: the representation of abstract concepts. A second, and closely related approach, is one proposing that multimodal representation inherently requires a level of abstraction that either consists of, or is a level above, multimodal representation (Mahon & Caramazza, 2008). A third approach, second-order multimodality, holds that in order to account for some of these concepts, it may be necessary to propose a model that allows for some concepts to only be defined in terms of other concepts, which are themselves more directly grounded in experiential traces; a well-known example is that “zebra” could be grounded in terms of “horse plus stripes” (Harnad, 1990). A fourth approach, metaphorical extension (Lakoff, 1987), holds that abstract concepts are grounded in experiential traces (or “image schemata” to be more precise), but those traces are largely limited to the sensorimotor domain; time, for example, is represented as a function of space (Boroditsky, 2000). Finally, a fifth approach, the modularity hypothesis, maintains that there exists an abstract “language of thought,” (Fodor, 1983) that processes symbols in a way similar to a Chinese Room (Searle, 1980) and that meaning is extracted as a result of an encapsulated process consisting of symbol manipulation.

Surely a harmony between the data, theoretical considerations, and our own intuitions exists. However, “the goal of developing a theory of concepts will not be served by collecting more of the same data” (Mahon & Caramazza, 2008). The key to moving forward, then, partially consists of taking all of the available data into account and moving forward with the most parsimonious account possible. We feel that the involvement of the motor system in comprehending text about intentional actions provides for a substantial portion of the “essence” of comprehension. Two key questions for moving forward are (1) whether this is the result of a straightforward learning mechanism (e.g., Hebb, 1949) that pairs words with referents and (2) whether and exactly how this representation scheme scales up to “abstract” language.

We would like to propose an account for conceptual representation that attempts to harmonize the data and some of the theoretical approaches outlined above, which we call the fault tolerant theory of conceptual representation. On hypothesis one, multimodality, the behavioral, neuroimaging, and neuropsychological data suggest that comprehension of action-related language without motor experience, or with dysfunctional motor neurons, is quasi-normal and suboptimal, or impoverished and isolated. On hypothesis two (Mahon & Caramazza, 2008), the neuropsychological data (e.g., Boulenger, et al., in press) tell us that comprehension and deep semantic processing of action-related language is still at least somewhat possible without relevant motor experience or fully functional motor neurons. On hypothesis three, second-order multimodality, philosophical considerations (e.g., Harnad, 1990) and examples (e.g. "double lutz") tell us that comprehension can go forward with as little as a scant definition of a novel verb, which we believe results in a second-order multimodal representation. On hypothesis four, metaphorical extension, the data tell us that users are less proficient at performing even a simple motor task when forced to activate an image schema that contradicts the internal one that they have for a given concept (Casasanto & Dijkstra, submitted).

We propose, then, that language comprehension is fault tolerant because it benefits from a multi-variegated representation system that includes literal experiental associations, such as clockwise manual rotation and screwing in light bulbs (Zwaan & Taylor, 2006), second-order multimodal representations, such as understanding "double lutz" as "an ice-skating jump," and metaphorical representations, such as "pride" activating an image schema for upward motion (Casasanto & Dijkstra, submitted). If it is indeed the case that comprehending a text is tantamount to the construction of a situation model, or a mental representation, of the state of affairs denoted by the text (van Dijk & Kintsch, 1983), then language users are going to engage any information within their memory that they have at their disposal to integrate the information that appears within the text. If it is indeed the case that conceptual representation is multi-variegated in this way, then we would expect comprehension to be possible even when one or two of the representation systems are "ignorant" of a given concept. Even without ever witnessing or performing a "double lutz," one can still understand text about double-lutzing, given that one knows that it is the sort of jump a person does while on ice skates. In other words, the comprehension system exhibits "graceful degradation." Having experience witnessing or performing an action leads to a rich mental representation, which eases the construction of a situation model of the described state of affairs, but comprehension is not rendered impossible by the absence of such detailed and fitting experiential traces.

A further example may help to illustrate the unique contribution that "embodied" (visual or motor) information can make to language comprehension. If a person had never witnessed an athlete performing a high-jump and had never high-jumped himself, but did understand that high-jumpers compete to jump over the highest bar, then they could understand the sentence, *The athlete attempted to win the gold medal by high-jumping over the bar*. However, if the remainder of the discourse required experiential knowledge to comprehend, then a person without visual or motor experience would fail to construct an adequate situation model. If a second sentence read, *His form was slightly off on his last attempt and he injured his neck on the landing*, a person who had never witnessed nor performed a high-jump would have difficulty understanding how this is a reasonable outcome, as the Fosbury flop is not an incredibly intuitive way to jump over horizontal bars.

That comprehension is not an all-or-none phenomenon is becoming increasingly apparent. If one is to comprehend a text, one must construct a situation model of the described state of affairs. The situation model may require background knowledge from any of the many mediums within the multi-variegated conceptual representation system of the language user. *The athlete attempted to win the gold medal by high-jumping over the bar* only requires a scant definition of what high-jumping consists; …*he injured his neck on the landing* requires a more-detailed background knowledge about the form that Olympic high-jumpers use when high-jumping. Obviously, a person's ability to comprehend text can be absent, in the case of a person who does not know the language in which the text appears, or it can be highly sophisticated, detailed, or masterful, in the case of the Nobel Laureate author, economist, or scientist. However, between these two extremes, normal seven-year-olds have what we would call a rudimentary ability to comprehend text. Normal high school graduates or university students have an ability to make more fine-grained semantic distinctions and can therefore produce and comprehend more sophisticated text. Normal university graduates and professionals have a still more high-resolution semantic knowledge. The differences between these groups, we believe, is primarily influenced by background knowledge, which comes from experience reading text and experience in the world.

Bringing the available data and theories together, comprehension, according to the approach advocated by this paper, relies on a multi-variegated system for conceptual representation that relies on experiential memory (including motor, sensory, and intuitive experiential traces, e.g. Barsalou, 2008), second-order grounding within the semantic network (e.g. Harnad, 1990), and metaphorical extension (Lakoff & Johnson, 1980). For a given discourse that requires the construction of a situation model to comprehend, one can not claim that any one of these parts of the conceptual system is necessary or sufficient for successful comprehension. This combination of representational options makes the comprehension system fault tolerant. Comprehension, then, can be likened to a table with six or more legs. Each of the legs of the table represents a part of the multi-variegated conceptual system and the degree to which the table is horizontal and stable represents the success of comprehension. If one or two legs of the table are removed, it may become less stable, but it will most likely remain reasonably horizontal. However, as one removes the legs, one-by-one, the table will eventually cease to be a table and comprehension will eventually become peculiar and quasi-normal. Thus, one unexpected outcome of the research on motor involvement in language comprehension is that it causes us to further scrutinize what it means to "comprehend language."

This thesis focuses on the role of motor activation during language processing. Chapter 2 addresses whether language that focuses on action results in motor resonance relative to language that shifts focus to other elements of the referential situation. Chapter 3 finds that motor resonance occurs as text disambiguates further information about the action being described. Chapter 4 incorporates the idea of action parameterization from the action-planning literature and finds that different action parameters are activated and combined to form fuller, composite simulations of more complex actions. Chapter 5 finds that objects that appear graspable activate motoric 'affordances' (Gibson, 1979), but that this effect is negated when a label identifies the object as being a non-graspable object (i.e. a planet). Chapter 6 summarizes the results of the thesis and offers a further review of the literature.

Author note

We would like to thank Katinka Dijkstra, Mike Kaschak, David Kemmerer, members of the Language and Cognition Group at Erasmus, and an anonymous reviewer for helpful comments on previous versions of this chapter.

Chapter 2:

MOTOR RESONANCE AND LINGUISTIC FOCUS

This chapter is published as: Taylor, L.J. & Zwaan, R.A. (2008). Motor resonance and linguistic focus. *Quarterly Journal of Experimental Psychology*, *61*, 896-904.

Abstract

Previous studies have demonstrated that verbal descriptions of actions activate compatible motor responses (Glenberg & Kaschak, 2002; Zwaan & Taylor, 2006). The present study replicates previous findings showing that, within a sentence, such activation is localized on the verb that denotes the action. Moreover, motor resonance is found to yield to linguistic focus. If a post-verbal adverb maintains focus on a matching action ("slowly" or "quickly"), motor resonance occurs, but if the adverb shifts the focus to the agent (e.g., "obediently" or "eagerly"), a cessation of motor resonance ensues. These findings are discussed within the context of theories of motor resonance, action understanding, mental simulation, and linguistic focus.

Evidence from neuroscience suggests that both the performance of actions and the recognition of the actions of conspecifics produce motor resonance in primates (Keysers & Perrett, 2004). For example, the motor cortex is active whether a monkey grasps an object, observes an experimenter grasping an object (Gallese et al., 1996), watches a hand go behind a screen that occludes an object (Umiltà et al., 2001), or hears a nut being cracked (Kohler et al., 2002). These findings generalize to humans with the important qualification that such instances of motor resonance seem to occur reliably only when the action falls within an individual's action repertoire (Calvo-Merino et al., 2004; Buccino et al., 2004).

When such evidence from neuroscience is considered with theories that propose a strong link between the performance and conceptual understanding of actions (Prinz, 1997; Rizzolatti & Craighero, 2004; Wilson & Knoblich, 2005), the involvement of the motor system is expected during the comprehension of language that describes actions (Rizzolatti & Arbib, 1998). Indeed, previous studies have shown that sentences describing simple motor actions both facilitate compatible motor responses (Glenberg & Kaschak, 2002) and activate the brain regions that are active when similar actions (i.e. those that involve the same effector) are performed (Tettamanti et al., 2005; de Vega et al., 2004).

Other results have shown that individual words that denote actions yield similar behavioral (Zwaan & Taylor, 2006) and neural effects (Pulvermüller et al., 2005; Hauk, Johnsrude, & Pulvermüller, 2004). Along similar lines, studies in the action literature have shown that the presentation of an irrelevant word (e.g., "large" or "small") subtly influences the dynamics of a goal-directed action (e.g., grip aperture of a participant's hand) while the participant reaches for an object in anticipation of grasping it (Glover & Dixon, 2002; Gentilucci & Gangitano, 1998). Similar effects have been found for incidentally presented nouns (e.g. "baseball" or "tweezers") that are either larger or smaller than the target object (Glover, Rosenbaum, Graham, & Dixon, 2004). Such effects offer support to the claim that the meanings of words and the affordances (Gibson, 1979) of manipulable objects that nouns can denote produce subtle, but immediate, effects in the motor system of a person who comprehends them.

Most importantly, in some experiments these effects have been demonstrated with a relatively high degree of temporal resolution during the processing of action sentences. Compatible responses are facilitated as soon as constraining information becomes available, before an entire sentence (Zwaan & Taylor, 2006; Chambers et al., 2002) has been presented. These findings offer support to the notion that understanding actions through language relies on mental simulation of the described action and that mental simulation of actions is driven by motor resonance.

Most of the work on language-induced motor resonance has examined the effects of single words or entire sentences. In a recent study (Zwaan & Taylor, 2006) we examined motor resonance as it unfolds during the comprehension of a sentence. Two key findings with respect to the online profile of motor resonance to emerge from this study were that motor resonance (1) occurs immediately (i.e., as soon as enough specificity is provided by the linguistic context up to that point) and (2) motor resonance is short-lived (i.e., it does not extend beyond the action-specifying verb). The first finding is consistent with theories that view language comprehension as an incremental process, in which information is activated immediately, rather than after a particular chunk of linguistic information (e.g., a phrase or a sentence) has been processed (Chambers et al., 2002). The second finding is the focus of the current article.

Why was motor resonance short-lived in Experiments 4 and 5 of the Zwaan and Taylor paper? It is instructive to re-examine a representative item from those experiments: *After/lighting/the candles/for the/romantic/evening/he/dimmed/the/lights.* The target word here is *dimmed*, which produced motor resonance. The next part of the sentence shifts attention away from the action itself to its result or to the patient of the action. We speculated that this shift of attention was responsible for the extinction of motor resonance. This shift hypothesis is consistent with MacWhinney's (2005) perspectival framework, according to which multiple "perspective shifts" occur as a person reads a sentence. These perspective shifts occur between linguistic constituents that code for different elements of the referential situation (e.g. location, objects, and events) that a body of text describes. When these different elements are combined to form a coherent representation, comprehension is successful (MacWhinney, 2005). Here, we postulate the Linguistic Focus Hypothesis (LFH). According to the LFH, motor resonance falls under the scope of linguistic focus. As long as the action is within linguistic focus, motor resonance occurs. However, as soon as the focus shifts, the mental simulation shifts along with it. The LFH makes sense in light of the common assumption of the cognitive system as a satisficer, not engaging in more activity than is minimally required to perform the task.

Combined with previous findings on motor resonance and mental simulation, the LFH makes specific predictions about the localization of facilitated motor processes during language comprehension. Consider the sentence *While at the gas station, he* *selected unleaded and opened the gas tank* (Zwaan & Taylor, 2006; Experiment 4). According to the LFH, motor resonance for counterclockwise manual rotation is limited to the verb “opened” (which describes an act of counterclockwise manual rotation) because the subsequent linguistic content shifts focus away from that particular action to other elements of the referential situation (namely the acted-upon object). If this is a correct explanation, then when the subsequent content continues to focus on the action, as the adverb “slowly” does in the sentence *He placed his hand on the gas cap, which he opened slowly*, then a continuation of the motor simulation should be observed. Experiment 1 was designed to test this prediction.

Experiment 1

Participants were presented with the critical sentences shown in Appendix 1. For each experiment, the paradigm used by Zwaan and Taylor (2006; Experiment 4) was used. Participants read sentences by turning a knob continuously during the frame-by-frame presentation of a sentence. Words were presented in groups of one to three. Every five degrees of rotation caused a group of centrally-presented words to be replaced by the next group of words in the sentence. On critical trials, a sentence describing an act of manual rotation (e.g., *The runner/was very/thirsty./A fan/handed him/a bottle/of cold/water/which he/opened/quickly*, with slashes indicating the boundaries between frames) was presented. For each item, the tenth frame presented the critical verb and the eleventh frame presented the adverb intended to keep the action within linguistic focus. Participants read sentences about manual rotation that were either diagnostically clockwise or counterclockwise while turning a knob either clockwise or counterclockwise. If our prediction generated from the LFH is supported, we should find a significant match advantage not only on the verb, but also on the subsequent adverb.

Method

Participants. 73 undergraduate psychology students participated in the experiment for course credit. The data for three participants were eliminated due to accuracy below 85% on the comprehension questions (M=95.6%, SD=5.1 for both experiments) and the data for two participants were eliminated because they were not native English speakers. The final analysis included data from 68 participants.

Apparatus and Design. The apparatus, design, and sentences from a previous study (Zwaan & Taylor, 2006) were adapted for this experiment. Each item described an act of direction-specific manual rotation (see Appendix 1). Items were presented in random order. All sentences were constructed so that they consisted of 11 frames. The 10th frame of each sentence contained the verb and the 11th frame contained the adverb. Each sentence was designed so that the direction of rotation was as unambiguous as possible by the time the verb appeared. Words were presented in black text on a white background, left justified in the center of the screen.

A knob that allowed rotation-contingent, subject-paced text presentation was used in both experiments (see also Zwaan & Taylor, 2006). The knob contained springs that returned it to the centered position when released. As the knob was turned from the center position, the computer logged a keypress response approximately every five degrees. Each key press logged a reading time for a given frame of text and resulted in the presentation of the next frame. Manual rotation direction was manipulated within participants. The linguistically implied rotation direction and manual rotation direction were counterbalanced across four lists. There were 17 participants on each list.

Procedure. Participants read sentences by turning the knob in either direction (clockwise or counterclockwise). For the first half of the experiment, they turned the knob in one direction to proceed through the sentences and then switched direction for the second half. After each sentence, participants released the knob so that it returned to the center position. Each participant read 48 sentences (16 experimental, 32 filler) during the experiment. A yes-no comprehension question pertaining to the content of the immediately preceding sentence followed half of the filler items. Participants responded to these comprehension questions using a standard keyboard.

The experiment began with a participant seated in front of a computer monitor, a keyboard, and a knob wired to the keyboard. After sitting, the participant laid the keyboard across his or her lap to answer comprehension questions. The knob remained on the desk and centered in front of the monitor for the duration of the experiment. Before the experiment began, each participant completed 20 practice trials under experimenter supervision. The experimenter made sure that participants were turning the knob smoothly throughout the duration of each sentence instead of doing the task with repetitive, jerking motions. After the practice trials, every participant was judged to be able to do the task well enough to proceed. Most participants reached this criterion after four or five practice sentences.

A trial began with the knob at the center position and the first frame of text of a sentence presented on the screen. When the participant turned the knob in the correct direction for approximately 5 degrees, the second frame of text was presented. When the participant turned the knob an additional 5 degrees, the third frame of text was presented. This continued until the 11th frame, at which point the participant was either instructed to release the knob and wait for the next sentence or was presented with a comprehension question. Questions required a response on the keyboard.

Results. Segment reading times <75 ms and >2000 ms were removed from the analysis as well as times more than 3 standard deviations from a subject's cell mean. In total less than 1% of the observations were removed. All analyses used mean reading times. Initial analyses of variance (ANOVAS) with list (a between-participants factor) showed that interactions between this factor and match (when the direction of a participant's manual rotation matched the direction of the manual rotation described by a sentence) all had p-values greater than .15, so this factor was dropped from further analysis and t-tests were used (Pollatsek & Well, 1995).

Directional tests showed that there was match advantage on the verb by participants [$t_1(67)=1.69$, $p<.05$] and by items [$t_2(15)=1.77$, $p<.05$] and, crucial to our hypothesis, also on the adverb [$t1(67)=2.08$, $p<.025$; $t_2(15)=1.57$, $p<.07$]. There were no significant effects on the preceding segments [$ps>.16$].

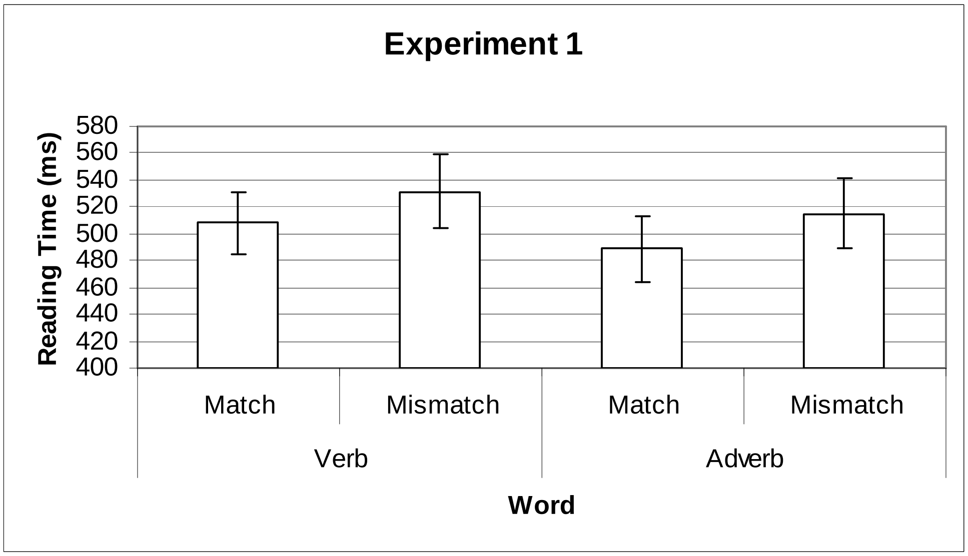

Figure 1.

Mean reading times and standard errors for the critical regions in Experiment 1.

Discussion

These results support the LFH. In addition to finding motor resonance on the verb describing the action, a finding that replicates Zwaan and Taylor's (2006) Experiment 4, we now also found motor resonance on adverbs that modified the described action and immediately followed the verb.

Experiment 2

The adverbs in Experiment 1 primarily modified the described manual rotation. In Experiment 2, those action-modifying adverbs were replaced with agent-modifying adverbs: words that did not primarily modify the action (e.g. *happily*, *eagerly*, or *nervously*). These adverbs denote information that is most relevant to the mental or motivational state of the protagonist performing the action, not the action itself. This manipulation is compatible with linguistic taxonomies of adverbs that draw a distinction between subject-oriented adverbs and process- or manner-oriented adverbs (Jackendoff, 1972; Nakamura, 1997). In Experiment 2, the methods from Experiment 1 were repeated with the exception that we replaced adverbs that primarily modify actions with adverbs that do not (see Appendix 2) as discussed above.

Method

Participants. 64 undergraduate psychology students participated in the experiment for course credit. The data for one participant were eliminated due to accuracy below 85% on the comprehension questions and the data for three participants were eliminated because they had cell means that were greater than three standard deviations from the mean reading times for all participants. The final analysis included data from 60 participants.

Apparatus and Design. The apparatus and design from Experiment 1 were used in Experiment 2, with the exception that the adverbs were replaced (see Appendix 2).

Procedure. The procedure from Experiment 1 was repeated.

Results. As in Experiment 1, segment reading times <75 ms and >2000 ms were removed from the analysis as well as times more than 3 standard deviations from a subject's cell mean. In total 1.25% of the observations were removed.

Initial analyses of variance (ANOVAS) with list showed that interactions between this factor and match all had p-values greater than .15, so this factor was dropped from further analysis and t-tests were used (Pollatsek & Well, 1995).

Directional tests showed that there was a match advantage on the verb by participants and a marginally-significant match advantage by items [$t_1(59)=2.59$, $p<.025$; $t_2(15)=1.87$, $p=.08$] but not on the adverb [$t_1(59)=.824$, $p=.41$; $t_2(15)=.786$, $p=.44$]. There were no significant effects on the preceding segments [ps>.24]. The lack of a match effect on the adverb was not due to a lack of statistical power. The power to detect a 25 ms match advantage, as observed in Experiment 1, was .91 for a one-tailed test (Lenth, 2006).

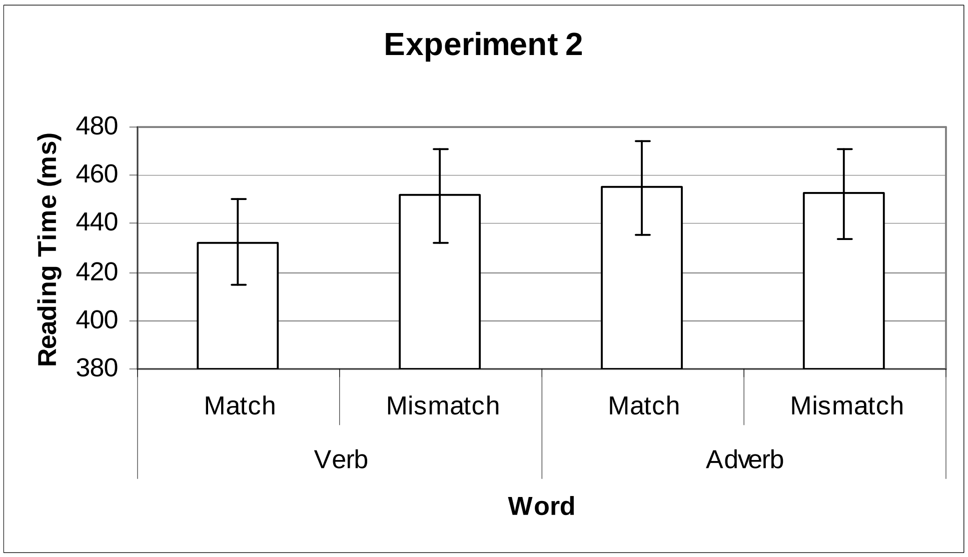

Figure 2.

Mean reading times and standard errors for the critical regions in Experiment 2.

Discussion

These results replicate the match advantage on the verb observed in Experiment 1, but show that the match advantage we found on action-modifying adverbs did not occur if the adverb does not primarily modify the action that is described before it.

General Discussion

The results from these two experiments support predictions made by the LFH. When a verb is modified by an adverb, compatible motor responses are facilitated on the adverb only if it primarily modifies the action (e.g., *quickly* and *slowly*) and not when some other element of the referential situation is modified (e.g., *happily*, *eagerly*, or *nervously*). Experiment 1 represents an initial attempt to extend the localized motor resonance effect (Zwaan & Taylor, 2006) from the verb to an adverb that immediately follows it. Compatible responses were faster on the verb as well as on the subsequent action-modifying adverb. This was not the case with Experiment 2, in which the action-modifying adverbs were replaced with agent-modifying adverbs.

The primary contribution of this article is confirmation of a prediction made by a synthesis of the LFH and previous findings on the localization of motor resonance during language processing (Zwaan & Taylor, 2006). If the previous finding that motor resonance is localized on action verbs is due to the surrounding content shifting focus away from the action, then maintaining focus on the action by following the verb with an action-modifying adverb should cause motor resonance to extend beyond the verb to the adverb. Our experiments support this prediction.

Results discussed earlier (Glover, Rosenbaum, Graham, & Dixon, 2004; Gentilucci & Gangitano, 1998; Glenberg & Kaschak, 2002; Zwaan & Taylor, 2006; Experiment 2) suggest that language affects motor processes in a top-down fashion in that the higher-order process of understanding words or the actions described by sentences affects subsequent motor activity. However, a bottom-up effect is not only plausible, but consistent with previous findings (Zwaan & Taylor, 2006; Experiment 4; Lindemann, Stenneken, van Schie, & Bekkering, 2006) and the present experiments, in which participants perform an action in order to indicate that they have read a consistent or inconsistent word. For example, previous studies have shown that when participants form an intention to act (e.g. to pick up a magnifying glass and move it towards one's eye) before the presentation of a semantically-related word ("eye"), they are faster to respond to the word in a task that invites semantic processing of the word, such as categorization or lexical decision, but not when the task does not invite semantic processing, such as letter detection (Lindemann, et al., 2006). As with the current study, while bottom-up processing is consistent with the results, top-down processes could still explain the findings, as the word response is confounded with the compatible action. While this is an issue that warrants further investigation, either top-down processes, bottom-up processes, or both would be consistent with a claim that the semantic and motor systems rely on partially overlapping neurophysiological substrates. For example, results showing that visually-perceived rotation affects manual rotation (Zwaan & Taylor, 2006; Experiement 1) coupled with previous findings that manual rotation affects perception of an ambiguously rotating visual stimulus suggest that manual rotation and perception of visual rotation share common neural systems (Wohlschläger, 2000).

Several alternative explanations for our results could be proposed, but are demonstrably inviable. Possible alternative explanations for the results include: (1) they are due to demand effects (participants were somehow aware of the manipulation and this drove the differences of interest), (2) the effect on the adverb is merely a continuation of the original effect on the verb and does not reflect the influence of the adverb on maintaining focus on the action, (3) there was a confound between the items that actually caused the differences of interest, and (4) the effect on the adverb is really a sentence wrap-up effect. Each alternative explanation will be considered and addressed in turn.

First, a skeptic could argue that participants became aware of the intention behind the experiment since they were engaging in manual rotation while reading sentences about manual rotation. To prevent this from becoming an issue, the critical items were embedded inside a larger set of similarly worded items describing similarly mundane actions. When probed during post-experiment interviews, no participant reported having any knowledge of the manipulation. Further, even if correct, this would be an especially odd alternative explanation for the differences found on the adverb. A substantial proportion of the participants would have had to be sensitive to the distinction between action- and agent-modifying adverbs in order for this to explain the pattern found in the data.

Second, a skeptic could dismiss the findings on the adverb as merely a continuation of the original effect. According to this criticism, any word appearing directly around the verb is subject to ‘spillover’ motor resonance effects. This is an important criticism to counter, since the claim made here is that the result on the adverb supports the LFH. If it were the case that the verb simply influenced surrounding words regardless of their content, then there would be an effect on the agent-modifying adverbs in Experiment 2 or on the direct object which directly followed the verb in previously-reported experiments (Zwaan & Tayor, 2006, Experiments 4 and 5).

Third, it might be argued that the use of adverbs such as *quickly* and *slowly* should yield different response times given that they explicitly describe the speed with which the described action is performed. Although this is an interesting idea that is perhaps worth pursuing in a more sensitive paradigm, it is irrelevant to the current results, since any differences between items, other than the intended differences between conditions, were negated through counterbalancing. In other words, those differences are orthogonal to the manipulation and differences of interest.

Fourth, one could argue that, because the adverb was the last word in the sentence, the effect on that word is attributable to a motor resonance effect for the entire sentence (as in Experiments 2 and 3 in Zwaan & Taylor, 2006 or in Glenberg & Kaschak, 2002) and not continued focus on the action. However, if the last word of a sentence showed such an effect regardless of its content, then that pattern would have been found on the last word of other experiments in which the last word was not an action-modifying adverb (Experiment 2 in this paper and Experiments 4 and 5 from Zwaan & Taylor, 2006).

Although beyond the scope of the present article, these results invite future investigations into the specificity of language-induced motor resonance and the importance of motor resonance in providing the underpinnings of action understanding. For example, the distinction between *fast* and *slow* action-modifiers (e.g. q*uickly* vs. *slowly*) could be one that produces detectable differences in motor resonance. Additionally, adverbs that disambiguate the direction (e.g. *upwards* in the sentence *He moved his hand upwards*) of an action could show independent localization of motor resonance (that is, facilitation for compatible responses on the adverb only, not the verb). A related paradigm involves changing the position of the adverb. In the present experiments, the adverb directly follows the verb. An experimenter might predict no effect at all when the adverb precedes the direction-disambiguating verb (*…he quickly screwed in the light bulb*) but a re-emergence of motor resonance when a direct object interrupts the focus on the action (…*he screwed in the light bulb quickly*). Future research may address these issues.

The present results show that a verbal description of an action leads to a very subtle pattern of motor activation in the comprehender, which has not been shown previously. An important qualification of this research and other studies showing motor resonance during or after language comprehension is that this does not constitute direct evidence for the claim that action comprehension relies on a mental simulation (Rizzolatti & Craighero, 2004; see also the review article in this issue) of that action, though the present results are compatible with such a claim. Evidence for mental simulation requires showing that an action described by a sentence is facilitated by reading it. The present, and similar, results show a difference between matching and mismatching conditions, a result that is compatible with either facilitation of the matching condition or interference of the mismatching condition. We are currently running studies, which compare neutral, matching, and mismatching actions that will shed light on this issue.

Author note

We thank Christine de Jesus, Quanne Coombs, and Helena Yardley for assistance with data collection. This research was supported by grants MH-63972 from the National Institutes of Health and BCS-0446637 from the National Science Foundation.

Appendix 1

The critical sentences for Experiment 1 are listed below.

Clockwise

He had/been on/the highway/for a/long time./When he/saw a gas/station,/he/exited/slowly
During the/film,/the light/bulb/burned out./He found/a new /light bulb/which he/screwed in/rapidly
The gardener/noticed/that the/water/was still/running/He approached/the faucet/which he/turned off/quickly
The good/student/was about/to take/the SAT./He/picked up/his pencil/which he/sharpened/rapidly
The man/was/replacing/his tire./He placed/onto/the tire/a lugnut/which he/tightened/slowly
He hopped/into his car,/very late/for work./He placed/the key/into/the ignition/which he/started/quickly
He was/about to/attach the last/leg onto the/table./He picked up/the/screwdriver/and/screwed in/slowly
He wanted/to read/from his/favorite/book./He sat/next to/a lamp/which he/turned on/quickly

Counterclockwise

He was/craving a /juicy/pickle./On the/shelf, he/found a/closed jar/which he/opened/rapidly
He selected/unleaded/at the/gas station./He placed/his hand/on the /cap/which he/opened/slowly
His father/walked /into/the room./He/noticed/the loud/volume/which he/turned down/gradually
He wanted/to try/his new/satellite TV./Behind the/TV, he/grabbed the/cable/which he/unscrewed/quickly
The runner/was very/thirsty./A fan/handed him/a bottle/of cold/water/which he/opened/quickly
He waited/at the /intersection/before he/could turn./He saw/an/opening/and/turned left/slowly
The chicken/in the oven/looked cooked/perfectly./The cook/walked/over to/the oven/which he/turned down/slowly
He lit/the candles/for the/romantic/evening./He noticed/the bright/lights/which he/dimmed/slowly

Appendix 2

The critical sentences for Experiment 2 are listed below.

Clockwise

He had/been on/the highway/for a/long time./When he/saw a gas/station, /he/exited/eagerly
During the/film,/the light/bulb/burned out./He found/a new /light bulb/which he/screwed in/carefully
The gardener/noticed/that the/water/was still/running/He approached/the faucet/which he/turned off/thoughtfully
The good/student/was about/to take/the SAT./He/picked up/his pencil/which he/sharpened/nervously
The man/was/replacing/his tire./He placed/onto/the tire/a lugnut/which he/tightened/skillfully
He hopped/into his car,/very late/for work./He placed/the key/into/the ignition/which he/started/hastily
He was/about to/attach the/last leg/onto/the table./He picked up/a screw/which he/screwed in/patiently
He wanted/to read/from his/favorite/book./He sat/next to/a lamp/which he/turned on/eagerly

Counterclockwise

He was/craving a /juicy/pickle./On the/shelf, he/found a/closed jar/which he/opened/hungrily
He selected/unleaded/at the/gas station./He placed/his hand/on the /cap/which he/opened/carefully
His father/complained/about/the noise./John/walked up/to the/stereo/which he/turned down/obediently
He wanted/to try/his new/satellite TV./Behind the/TV, he/grabbed the/cable/which he/unscrewed/hastily
The runner/was very/thirsty./A fan/handed him/a bottle/of cold/water/which he/opened/eagerly
He waited/at the /intersection/before he/could turn./He saw/an/opening/and/turned left/skillfully
The chicken/in the oven/looked cooked/to perfection./The cook/walked/over to/the oven/which he/turned down/happily
He lit/the candles/for the/romantic/evening./He noticed/the bright/lights/which he/dimmed/carefully

Chapter 3

INFERENCES ABOUT ACTION ENGAGE ACTION SYSTEMS

This chapter is published as: Taylor, L.J., Lev Ari, S., & Zwaan, R.A. (2008). Inferences about action engage action systems. *Brain and Language*, *107*, 62-67.

Abstract

Verbal descriptions of actions activate compatible motor responses (Glenberg & Kaschak, 2002). Previous studies have found that the motor processes for manual rotation are engaged in a direction-specific manner when a verb disambiguates the direction of rotation (e.g. "unscrewed;" Zwaan & Taylor, 2006). The present experiment contributes to this body of work by showing that verbs that leave direction ambiguous (e.g. "turned") do not necessarily yield such effects. Rather, motor resonance is associated with a word that disambiguates some element of an action, as meaning is being integrated across sentences. The findings are discussed within the context of discourse processes, inference generation, motor activation, and mental simulation.

An emerging view in cognitive science holds that action understanding relies on the systems that are responsible for the performance of actions (Rizzolatti, Fogassi, & Gallese, 2001; Keysers & Perret, 2004). In primates, the mirror neuron system (MNS), which includes neurons in the primary motor cortex, pre-motor cortex, and inferior parietal lobule, (Rizzolatti & Craighero, 2004) is activated when an individual grasps an object, observes a conspecific grasping an object (di Pellegrino et al., 1992; Gallese et al., 1996), or sees a hand go behind a screen that occludes an object (Umiltà et al., 2001). In humans, such activation has been shown to occur when a given action falls within that individual's action repertoire (Calvo-Merino et al., 2004; Buccino et al., 2004). Similarly, the retrieval of episodic memories can be facilitated if an individual replicates the posture that she had during encoding (Dijkstra, Kaschak, & Zwaan, 2007). This research lends credence to the notion that the representations of actions rely on the MNS.

These results converge with theories proposing a strong link between the neural systems for action and the conceptual understanding of actions (Prinz, 1997; Rizzolatti & Craighero, 2004; Gallese, 2003; Wilson & Knoblich, 2005; Gallese & Lakoff, 2005; Fischer & Zwaan, in press). This leads to the prediction that the MNS is recruited to understand language that describes actions (Rizzolatti & Arbib, 1998). Indeed, previous studies have shown that sentences describing simple motor actions both facilitate compatible motor responses (Glenberg & Kaschak, 2002) and activate the brain regions that are active when similar actions (i.e. those that involve the same effector) are performed (Tettamanti et al., 2005; de Vega et al., 2004) or observed (Aziz-Zadeh et al., 2006). Other results have shown that individual words can be associated with subtle, but immediate behavioral (Zwaan & Taylor, 2006) and neural effects (Pulvermüller et al., 2005; Hauk, Johnsrude, & Pulvermüller, 2004). For example, the presentation of an irrelevant word (e.g. “large”or “small”) subtly influences the dynamics of a goal-directed action, such as the grip aperture of a participant’s hand, as she is reaching for an object with the intention of grasping it (Glover & Dixon, 2002; Gentilucci & Gangitano, 1998). Analogous effects have been demonstrated for incidentally presented nouns, such as “baseball”or “tweezers,” that are either larger or smaller than the target object (Glover, Rosenbaum, Graham, & Dixon, 2004). These effects offer support to the claim that words and the affordances (Gibson, 1979) of the objects to which they can refer produce subtle, but immediate effects in the motor system (or MNS) of a comprehender.

If motor activation plays a role in language comprehension, it should occur not only *after* the presentation of individual words or entire sentences, but also *during* the comprehension of sentences. Interestingly, some experiments have demonstrated a high degree of temporal resolution with regards to action sentences inducing motor resonance in participants. Motor responses that are compatible with a described action have been found to be facilitated as soon as constraining information becomes available, before an entire sentence has been read (Chambers et al., 2002). Similarly, verbs that disambiguate the direction of rotation in sentences about manual rotation are associated with a compatible motor response that is isolated on the verb (Zwaan & Taylor, 2006). Additionally, an adverb that maintains focus on the action (e.g. “quickly”) will show the same effect when it immediately follows the verb; however, an adverb that shifts focus to a non-action oriented element of the referential situation (e.g. “happily”) does not induce motor resonance (Taylor & Zwaan, in press). These findings offer support to the broader claim that language comprehension relies on a mental simulation of the described situation.

This is closely related to the claim that language users routinely construct representations of the situations described by language, not merely the text, and use them to derive meaning (Johnson-Laird, 1983; van Dijk & Kintsch, 1983; Zwaan & Radvansky, 1998; Glenberg & Robertson, 2000). Instead of memorizing the surface features of text, language users construct representations of the events described by a text, then attempt to integrate them with one another within a given discourse. These described events remain active as a reader proceeds through text. In addition to helping a reader construct situation models for an entire discourse, they also aid in making inferences and resolving ambiguities (Zwaan & Singer, 2003). Oftentimes, ambiguous words (such as pronouns) are retroactively disambiguated with a verb. Consider the following item ("Clinton confessed to Archie because he *wanted* / *offered* forgiveness."), in which the verb "wanted" implies that "he" refers to Clinton while the verb "offered" implies that "he" refers to Archie (Caramazza et al., 1997). Indeed, readers readily use information that is available after an ambiguous word in order to constrain their interpretation of the ambiguous word and to determine its meaning. Comprehension requires the integration of information within and across sentences, so if motor resonance is involved in comprehension, it should also be shown to occur as a result of meaning integration across sentences.

In the current experiment, participants read sentences containing a verb (and an immediately surrounding context) that left an element of the action ambiguous (the direction of rotation; e.g. *He examined the / pie through / the microwave / window and /*

turned the / timer. / The cooking / time needed / to be / longer [*shorter*].). The direction of manual rotation that the agent performs in the first sentence was not disambiguated until the final word of the second sentence. Participants were expected to use this information in order to resolve the ambiguity of the action described in the first sentence. Readers routinely construct such causal inferences during text comprehension (Graesser, Singer, & Trabasso, 1994). Given previous data (Zwaan & Taylor, 2006, Hauk, Johnsrude, & Pulvermüller, 2004), this information about the action should result in an immediate activation of the motor processes responsible for performing that action. "Longer" implies that the protagonist increased the cooking time by engaging in clockwise rotation, while "shorter" implies that the protagonist decreased the cooking time by engaging in counterclockwise rotation. The experiment is designed to test this prediction.

Methods

The method used by Zwaan and Taylor (2006; Experiment 4) was used. Participants read sentences by turning a knob continuously during the frame-by-frame presentation of a sentence. Words were presented in groups of one to three. Every five degrees of rotation caused a group of centrally-presented words to be replaced by the next group of words in the sentence. Participants turned the knob until the last word of the sentence disappeared from the screen. On critical trials, a sentence describing an act of manual rotation (e.g., *He examined the / pie through / the microwave / window and / turned the / timer. / The cooking / time needed / to be / longer* [or *shorter*]., with slashes indicating the boundaries between frames) was presented. On critical items, the first sentence included a verb that implied manual rotation, but kept the direction of rotation ambiguous. The tenth and final frame presented a word that disambiguated the direction of rotation that the protagonist performed. Participants read sentences that implied counterclockwise or clockwise manual rotation while engaging in counterclockwise or clockwise manual rotation. If our hypothesis is correct, then reading times should be faster on the critical word (the word that disambiguates the direction of the rotation mentioned in the first sentence) when the participant engages in an action that matches the direction that the critical word implies. Participants should be faster to read a word that implies clockwise rotation when they are turning the knob in the clockwise direction and vice versa.

Participants. 120 undergraduate psychology students from Florida State University participated in the experiment for course credit. The data for three participants were eliminated due to accuracy below 70% on the comprehension questions (M=90.6% SD=8.8) and the data for two participants were eliminated because they were not native English speakers. Due to the hand-sensitivity of some of our items (see Appendix 1), six left-handed participants were excluded. Five remaining participants were excluded in order to balance the number of participants in each of the eight lists. The final analysis included data from 104 participants.

Apparatus and Design. The apparatus, design, and sentences from a previous study (Zwaan & Taylor, 2006) were adapted for this experiment. Each item contained two sentences. The first sentence described an instance of manual rotation in which the direction was left ambiguous. The final word of the second sentence disambiguated the direction of rotation (see Appendix 1). Items were presented in random order. All sentences were constructed so that they consisted of 10 frames. Two versions of each item were designed such that one version implied counterclockwise rotation while the second version implied clockwise rotation. Words were presented in black text on a white background, left justified in the center of the screen. The two versions of critical items were counter-balanced between participants.

A knob that allowed rotation-contingent, participant-paced text presentation was used in both experiments (see also Zwaan & Taylor, 2006). The knob contained springs that returned it to the centered position when released. As the knob was turned from the center position, the computer logged a key press approximately every five degrees. Each key press logged a reading time for a given frame of text and resulted in the presentation of the next frame. Manual rotation direction was manipulated within participants. The linguistically implied rotation direction, manual rotation direction, and the two versions of each item were counterbalanced across eight lists. There were 13 participants in each list.

<u>Procedure</u>. Participants read sentences by turning the knob in either direction (clockwise or counterclockwise). For the first half of the experiment, they turned the knob in one direction to proceed through the sentences and then switched direction for the second half. After each sentence, participants released the knob so that it returned to the center position. Each participant read 48 sentences (16 experimental, 32 filler) during the experiment. A yes-or-no comprehension question pertaining to the content of the immediately preceding sentence followed half of the filler items. Participants responded to these comprehension questions using a standard keyboard.

The experiment began with a participant seated in front of a computer monitor, a keyboard, and a knob wired to the keyboard. After sitting, the participant laid the keyboard across his or her lap to answer comprehension questions. The knob remained on the desk and centered in front of the monitor for the duration of the experiment. Before the experiment began, each participant completed 20 practice trials under experimenter supervision. The experimenter made sure that participants were turning the knob smoothly throughout the duration of each sentence instead of doing the task with repetitive, jerking motions. After the practice trials, every participant was judged to be able to do the task well enough to proceed. Most participants reached this criterion after four or five practice sentences.

A trial began with the knob at the center position and the first frame of text of a sentence presented on the screen. When the participant turned the knob in the correct direction for approximately 5 degrees, the second frame of text was presented. When the participant turned the knob an additional 5 degrees, the third frame of text was presented. This continued until the 10^{th} frame, at which point the participant was either instructed to release the knob and wait for the next sentence or was presented with a comprehension question. Questions required a response on the keyboard.

Results and Discussion. Segment reading times less than 50 ms and greater than 2500 ms were removed from the analysis as well as reading times more than 3 standard deviations from a participant's cell mean. In total less than 1% of the observations were removed. All analyses used mean reading times. Initial analyses of variance (ANOVAs) with list (a between-participants factor) showed that interactions between this factor and match (when the direction of a participant's manual rotation matched the direction of the manual rotation described by a sentence) all had p-values greater than .28, so this factor was dropped from further analyses and t-tests were used (Pollatsek & Well, 1995).

The data were subjected to a 2 (sentence region) by 2 (match) ANOVA. The main finding is a significant interaction between region and match, F (1, 103) = 5.51, p=.021, [partial-eta squared] = .051. This is due primarily to the fact that participants were faster to read the critical word when it implied a rotation direction that was congruent with the action they were performing as they read it (see Figure 1), both by subjects [$t_1(103) = 2.67$, p=.0087] and by items [$t_2(31) = 2.31$, p=.028].

This match advantage on the critical word supports our hypothesis because it shows that motor resonance occurs on a word that, though a generated inference, disambiguates the direction of a previously mentioned action.

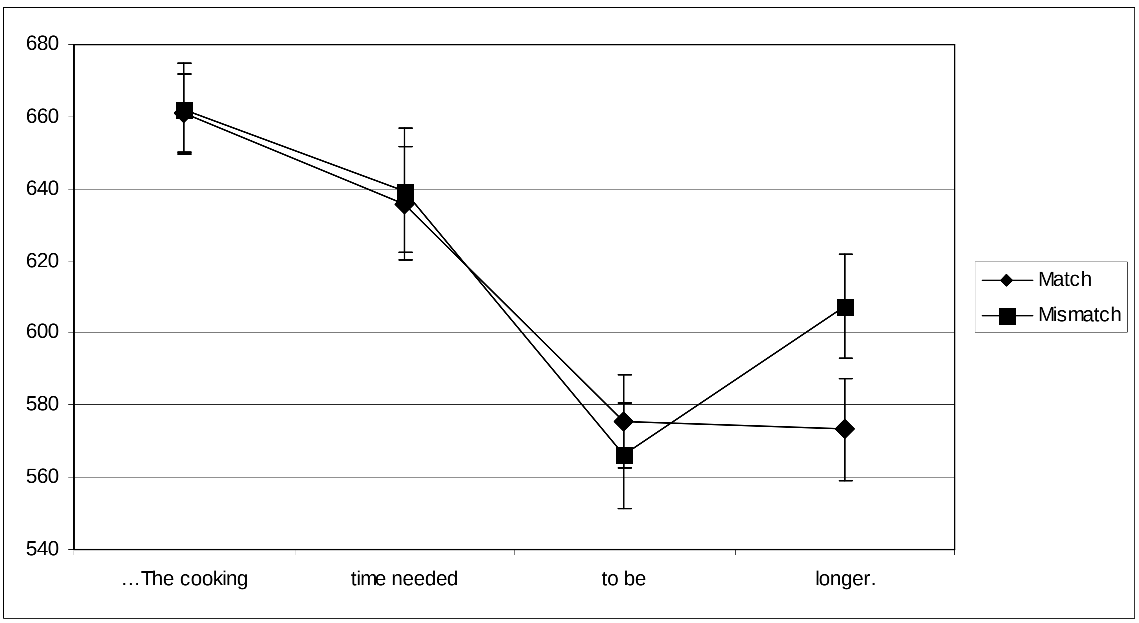

Figure 1.

Mean reading times and standard errors for the critical word and the preceding words.

General Discussion

The two primary issues addressed by this study concern inference-making and motor resonance during online motor processing. First, as comprehenders proceed through a text, they construct situation models of the described state of affairs. These remain active in order to be updated as the text elaborates on and resolves the ambiguities of previous events and sentences. Second, previous studies using this paradigm (e.g. Zwaan & Taylor, 2006; Experiment 4) have focused on the relationship between the verb and compatible motor resonance during online sentence comprehension. This study shows that a word that disambiguates an element of the action, regardless of whether it is a verb, can induce motor resonance. Previous studies have supported that non-verbs can engage the action system (Glover, Rosenbaum, Graham, & Dixon, 2004; Gentilucci & Gangitano, 1998).

The results from the experiment support the hypothesis that motor resonance is involved when a participant generates an inference about an action. When some element of an action (the direction of rotation) is left ambiguous, a word that disambiguates that element of the will involve motor resonance for an action that is compatible with it. In this experiment, a manual rotation verb that left direction ambiguous (e.g. “turned”) was presented in the first sentence. The second sentence disambiguated the direction on the critical word. Participants who read the critical word as they were engaging in a matching action responded faster than participants who read it as they were performing a mismatching action.

One alternative explanation for the results could be proposed but should be dismissed. The alternative explanation would propose that the results are due to demand effects (participants were aware of the manipulation and this drove the differences of interest). To prevent this from becoming an issue, the critical items were embedded inside a larger set of similarly worded items describing similarly mundane actions.

Further, when probed during post-experiment interviews, no participant reported having any knowledge of the manipulation.

The results are in line with the claim that semantic and motor systems rely on partially overlapping neural substrates (Prinz, 1997). This broader claim converges with a claim in cognitive science suggesting that verbs denoting motor actions are partially processed in the MNS. Indeed, motor verbs activate brain regions that are associated with action (Rüschemeyer, Brass, & Friederici, 2007) and these areas are unique from the areas activated by more "abstract," non-motor verbs (however, see Glenberg & Kaschak, 2002 for behavioral results suggesting that the understanding of abstract transfer relies on the motor system). In line with this view, a correspondence between degeneration of the motor system and the ability to conceptually process action verbs has been noted in clinical populations (Bak et al., 2006). Similarly, when intact participants identify objects, the location of brain activity is contingent upon the intrinsic properties of the stimulus (Martin, Wiggs, Underleider, & Haxby, 1996). More generally, conceptual knowledge is believed to be at least partially constrained by the modality-specific, perceptual and motor systems associated with concepts and the referents of words (Martin, 2007; Caramazza & Mahon, 2006; Gallese & Lakoff, 2005; Barsalou, 1999; Glenberg, 1997; for recent empirical support, see van Dantzig, Pecher, Zeelenberg, & Barsalou, in press).

The present experiment makes two contributions to the literature on language processing. First, as a person comprehends text, she constructs a situation model of the described state of affairs. In so doing, inferences are often routinely drawn within and between sentences in order to construct a coherent representation of the described state of affairs. Making such an inference about an action involves motor resonance that is compatible with the described action. Second, previous studies demonstrating the association between comprehending text about actions and action systems have primarily focused on verbs (Tettamanti, et al., 2005, Zwaan & Taylor, 2006; Taylor & Zwaan, in press); the present study demonstrates that motor resonance can be associated with any word that disambiguates some element of an action that a protagonist performs in text.

Appendix 1: The critical sentences for the experiment are listed below.

The carpenter /turned /the/screw./The boards /had/been/connected/too/tightly (loosely).

After testing the/temperature/of the /bath water,/he turned the/cold water/faucet./The water/had been too/hot (cold).

The technician/examined the height/of the fluid/in the test tube/he was pouring/into and adjusted/the angle./The fluid was/flowing too/slowly (quickly).

He put/the reading/glasses he/was holding/in his hand/back/in place./He put them/on/his face (the table).

He examined the/pie through/the microwave/window and/turned the/timer./The cooking/time needed/to be/shorter (longer).

The passenger/in the front/seat put his/hand out the/window and/adjusted /the side mirror./It was/a little too/high (low).

He was searching/for his favorite/radio station/by adjusting the/frequency by/turning the dial./The frequency/was a/little too /high (low).

The gardener/walked/up to/the house/and turned/the faucet./The/grass/was too/dry (wet).

When a/new song/began to play,/he approached/the stereo and/adjusted the/volume./The music/was too/loud (quiet).

The mechanic/entered/the car/and turned/the/key./Haltingly,/the/engine/stopped (started).

As the mechanic/was replacing/the car's/tire, he/used his /hand to turn/the lug nut./It was/too/tight (loose).

The corkscrew was/halfway inserted/into the cork,/so he continued/turning it./After some/struggle, the/corkscrew was/completely/removed (inserted).

The cook/decided to/adjust the/temperature/of the oven,/so he turned/the dial./The oven/had been too/hot (cold).

After checking/the time/on her computer/she adjusted/the time/on her/watch./It was/five minutes/fast (slow).

He was/bothered by/the amount of/light in /the room,/so he turned/the dimmer./The room/had been too/bright (dark).

While at/the gas/station,/the driver/turned/the gas cap./The/tank/was/empty (full).

Chapter 4

LANGUAGE MODULATES RESPONSE FORCE

This chapter is published as: Taylor, L.J. & Zwaan, R.A. (submitted). Language modulates response force. *Quarterly Journal of Experimental Psychology*.

Abstract

Sensorimotor simulation is believed to underlie our ability to understand events and actions described by language. The existing literature provides support for a tight coupling between linguistic input and motor activation in readers. Three experiments address a novel aspect of this phenomenon, response force, and test whether different action parameters (force and effector) combine to yield a more specific effect on the action system, in line with simulation theory. The experiments demonstrate that response force can be affected by understanding sentences that imply a high degree of force. Further, the activation of this force parameter is limited to the part of the body that would perform the action described by text. The results are discussed in terms of action parameterization, language comprehension, and the Linguistic Focus Hypothesis (Taylor & Zwaan, 2008).

Recent theoretical considerations argue that modality-specific systems provide the scaffolding for conceptual representation (Barsalou, 1999) and language comprehension (Zwaan, 2004). A considerable amount of experimental evidence has supported the notion that the motor modality is involved in the comprehension of language about action through "referential motor resonance" (Fischer & Zwaan, 2008). That is, when a person hears or reads text involving action, there is motor system activation in the comprehender corresponding to the action described in text, though the utility of such activation remains to be fully clarified.

Neuropsychological findings indicate that the motor system provides support for normal comprehension. Parkinson's patients, for example, typically display motor deficits while performing overt actions. This coincides with abnormal lexico-semantic processing for action verbs, but not for concrete nouns; this dissociation is eliminated upon treatment with medication that restores normal motor functioning (Boulenger, et al., in press). Other findings suggest that this pattern may hold for verbs in general, as patients with motor neuron disease show an impaired ability to produce all verbs relative to nouns (Bak et al., 2001).

Why is motor system activation at times relatively tightly coupled with the meaning of an utterance, as suggested by some data, yet relatively loosely, if at all, related to the meaning of an utterance, as suggested by other findings? One possibility is that the depth of processing required to complete a task, infer a causal relationship, or construct an adequate situation model (Zwaan & Radvansky, 1998) partially determines whether and how motor processes are activated during language processing (see Fischer & Zwaan, 2008 and Taylor & Zwaan, 2009 for a discussion). From this point of view, the motor system may enhance sentence and discourse comprehension, but is not always necessary or sufficient for comprehension to take place (Taylor & Zwaan, 2009). The Linguistic Focus Hypothesis (LFH; Taylor & Zwaan, 2008) predicts motor activity in readers to be coupled with information in a sentence that disambiguates an element of an action. That is, motor activity in readers becomes more specific as additional text disambiguates or specifies different aspects of the described action. For example, when an instance of manual rotation is described by one sentence, a reader's actual manual rotation is not affected until the direction of rotation is disambiguated by a second sentence (Taylor, Lev-Ari, & Zwaan, 2008).

Considering the organization of the action system itself may help to generate hypotheses and clarify the nature of motor activation associated with language comprehension. A potentially helpful framework for organizing the empirical evidence incorporates a claim from the action planning literature, which suggests that actions are neurally represented as a combination of stored action parameters (Schmidt, 1975). For example, the stored motor program for a given action, such as throwing a ball, can be modified through the specification of variable parameters, such as speed, effector, or direction. Different action parameters have been shown to be temporally distinguishable; for example, when participants are prompted to perform an action with a certain arm, direction, and distance, they process each parameter separately and serially (Rosenbaum, 1980). Action parameters may also serve as scaffolding for referential motor activity or conceptual processing; for example, a single group of neurons controls when a cat walks, trots, or gallops, based on firing rate (Gallese & Lakoff, 2005). Alternatively, conceptual action codes (e.g., Hazeltine, 2005) for force make a similar claim. Several past studies indicate that this may be a helpful construct in the study of language comprehension, as several parameters of the action system have been shown to affect, or be affected by, language processing, including effector, movement direction, and grip size or type.

Neural (Hauk, Johnsrude, & Pulvermüller, 2004; Glenberg et al, 2008) and behavioral (Sato et al., 2008) data demonstrate somatotopic activation of the motor system associated with processing words and sentences about effector-specific action, indicating that effector is one parameter of interest. For example, reading verbs referring to actions that are carried out with the arm, leg, or face (*pick*, *kick*, or *lick*), leads to activation in or adjacent to the areas of the motor strip that are associated with actual movement of the relevant effector (Hauk, Johnsrude, & Pulvermüller, 2004). Dominant-handed responses to hand action verbs, relative to foot action verbs, are disrupted during a semantic decision task, but not during a lexical decision task (Sato et al., 2008), indicating that such effector-specific effects vary as a function of the depth of semantic processing.

A second action parameter that has received empirical support is response direction. When participants judge sentences by making sensibility judgments towards the body, they are faster to do so when responding to sentences about transfers towards the body (Glenberg & Kaschak, 2002). This action-sentence compatibility effect has been extended to sentences about manual rotation (Zwaan & Taylor, 2006) and is tightly coupled with the presentation of verbs (Glenberg et al, 2008), other words that offer disambiguating information about the direction of movement (Taylor, Zwaan, & Lev-Ari, 2008), or words that maintain focus on the action (Taylor & Zwaan, 2008).

Hand shape is a third parameter that has received attention in the literature. Grip size during a reach-to-grasp movement is affected by the incidental presentation of nouns denoting large and small objects (Gentilucci & Gangitano, 1998) or parity judgments of large and small quantities (Lindemann et al., 2007). Qualitatively different hand shapes, such as power and precision grips (Tucker & Ellis, 2004) or functional and volumetric gestures have also been facilitated by nouns denoting objects that afford the associated hand shape. Further, sentences that merely refer to an object (e.g. *Jane forgot the calculator*) facilitate functional but not volumetric gestures, thus indicating that this sort of motor activation varies as a function of the semantic content of a sentence (Masson, Bub, & Warren, 2008).

Gallese & Lakoff (2005) suggest force as an additional parameter of interest, but this is yet to be studied in the context of language (however, see recent evidence from Scorolli, Borghi, & Glenberg, 2008). This is a potentially fruitful area of research, given that the degree of force is correlated with either increased or more widespread neural activation (Porter & Lemon, 1993). The goal of the first experiment reported in this article is to establish biomechanical force as a parameter of interest in the study of motor activation as a function of semantic content. Participants made sensibility judgments on sentences about actions that varied on a number of sensorimotor dimensions. However, between items, the biomechanical force required to perform the described action was varied by manipulating the verb ("He pushed the car" and "He started the car") in Experiment 1 and the patient ("He pushed the car" and "He pushed the button") in Experiment 2. Participants made judgments by squeezing a custom-built device that measures the pressure of the response with millisecond and kilo-Pascal precision.

Experiment 1

Participants

Fourteen right-handed undergraduate psychology students from Florida State University participated for course credit.

Apparatus

Participants responded by squeezing one of two rubber bulbs connected to a device via plastic tubes. The device recorded the air flow that resulted from the bulbs being squeezed and this measured the pressure inside the bulbs to the nearest kilopascal (kPa) and millisecond. The bulbs are comparable to those found on a sphygmomanometer (device for measuring blood pressure) and were mounted on the sides of the computer monitor and vertically centered with respect to the screen. A response was recorded when the pressure measured by the device exceeded a threshold of 10,000 kPa. No participant had any difficulty applying an adequate amount of force to reach the threshold pressure.

Procedure

Participants read sentences whose verbs were varied to imply either an action involving relatively high biomechanical force (e.g., "He pushed the car"), an action involving relatively low force (e.g. "He started the car"), observing an object (e.g., "He admired the car") or a nonsense sentence (e.g. "He swung the car"). They made sensibility judgments by squeezing the bulbs. Participants completed ten practice trials followed by 54 experimental trials. There were 18 critical items (9 high force and 9 low force), 9 filler items describing merely viewing an object, and 27 nonsense items. As a result of this design, participants saw each sentence patient (e.g. "car") six times over the course of the experiment (three times in sensible sentences; three times in nonsense sentences). This served to disguise the experimental manipulation as thoroughly as possible.

Sentences were presented in black text on a white background. Before each trial, participants were instructed to hold the L and A keys. After 500 milliseconds a sentence appeared. If the sentence made sense, participants released the L key and squeezed the right bulb. If the sentence did not make sense, they released the A key and squeezed the left bulb. This procedure was followed to ensure a reliable baseline measurement for every trial. Reaction time was recorded upon release of the appropriate key and response pressure was recorded as a person squeezed either bulb.

Results

Participants responded with more force when they made sensibility judgments on sentences describing actions that implied a high degree of force compared to sentences describing a low degree of force and this effect was significant by participants and items ($t_1(13) = 3.05$, $p < .05$; $t_2(8) = 4.50$, $p < .05$ see Figure 1). This difference is not due to processing difficulty as evidenced by the lack of a positive correlation between response pressure and reaction time ($r = -.018$; $p > .5$). This supports the hypothesis that sentences about biomechanical force engage the motor system processes that are responsible for applying force.

With filler items (observation sentences) included, there was an overall effect of condition ($F_1(2, 12) = 5.13$, $p<.05$; $F_2(2, 7) = 9.62$, $p<.05$) with non-action filler sentences yielding higher response pressures than low force items ($t_1(13) = 2.71$, $p<.05$; $t_2(8) = 2.86$, $p<.05$). The non-action filler sentences were not statistically different than high force items ($t_1(13) = 1.19$, $p = .25$; $t_2(8) = 1.91$, $p=.09$). This effect was not predicted, but may be due to an attenuation of a baseline level of response force in the case of low-force sentences; however, this should be interpreted cautiously (see General Discussion).

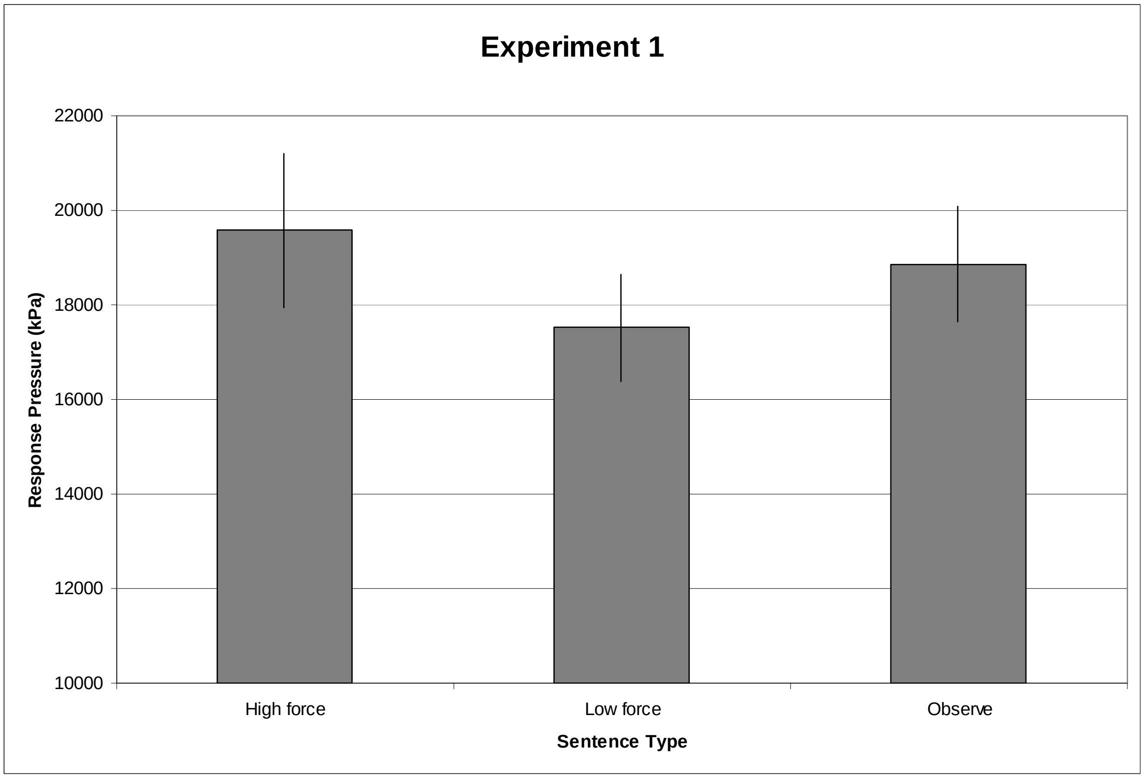

Figure 1.

Mean response pressures and standard errors as a function of sentence type in Experiment 1.

Discussion

There are two competing explanations for the difference between high and low force items in Experiment 1. One is that the verb alone, which was varied between items, conveys information about the force involved in each action and this drives the difference between items. The second explanation is that the degree of force is inferred from the meaning of each sentence, which relies on an integration of the verb with the object that is acted upon, and not necessarily the verb alone. This is in line with the Linguistic Focus Hypothesis (LFH; Taylor & Zwaan, 2008), which predicts that motor activation should occur once sufficient information is available to infer the nature of an action.

If this second explanation is correct, then the same effect should be found if the verb is held constant while the final word of each item (the patient) is varied in order to convey information about force. Previous behavioral research focuses on the role of verbs (e.g., Boulenger et al., 2006; Sato et al., 2008), but others indicate that the action system is affected by entire sentences (Glenberg & Kaschak, 2002) or other word classes within discourse that carry disambiguating information about a an action parameter (Taylor, Lev-Ari, & Zwaan, 2008). In line with this previous research, the aim of Experiment 2 is to demonstrate that manipulating the sentence patient can affect response force.

Experiment 2

Apparatus

The same device as in Experiment 1 was used.

Participants

Thirty right-handed undergraduate psychology students from Florida State University participated for course credit.

Procedure

The procedure was the same as Experiment 1, with the exception that the object nouns were varied in order to imply relatively high force (e.g., “He pushed the car”), relatively low force (“He pushed the button”), abstract actions involving no biomechanical force (“He pushed the agenda”), or nonsense actions (“He pushed the cloud”) while the remainder of the sentence was kept constant. As in Experiment 1, participants completed ten practice trials followed by 54 experimental trials. There were 18 critical items (9 high force and 9 low force), 9 filler items describing abstract actions, and 27 nonsense items. Note that the filler items in this experiment describe abstract actions (as opposed to the observation sentences in Experiment 1). This was a result of manipulating the patient of each sentence instead of the verb.

Results

Participants responded with more force when they made sensibility judgments on sentences describing actions that required more force both by participants and items ($t_1(29) = 2.21$; $p < .05$; $t_2(8) = 2.80$; $p < .05$; see Figure 2). As in Experiment 1, this difference can not be explained in terms of a processing difficulty confound between conditions, as reaction times were essentially uncorrelated with response pressure ($r = -.12$; $p > .20$). These results support the hypothesis that sentences about force engage the motor system processes that are responsible for applying force. Further, it extends the findings of Experiment 1 in that by varying grammatical category across experiments, namely the verbs in Experiment 1 and the object nouns in Experiment 2, we demonstrate that the action parameter is not activated by a single word within a sentence, but rather by the integration of information across words within a sentence and the extraction of meaning. This is in line with previous research and the LFH, as action-relevant language drives motor activation regardless of lexical category.

With the filler items (abstract sentences) included, there was a marginally-significant effect of condition ($F_1(2, 28) = 2.36$; $p = .11$; $F_2(2, 7) = 3.44$; $p=.09$). This is primarily due to the difference between high and low force items; the abstract items were not different than either low force ($t_1(29) = 1.05$; $p = .30$; $t_2(8) = .68$; $p=.51$) or high force items ($t_1(29) = 1.32$; $p = .20$; $t_2(8) = .50$; $p=.71$).

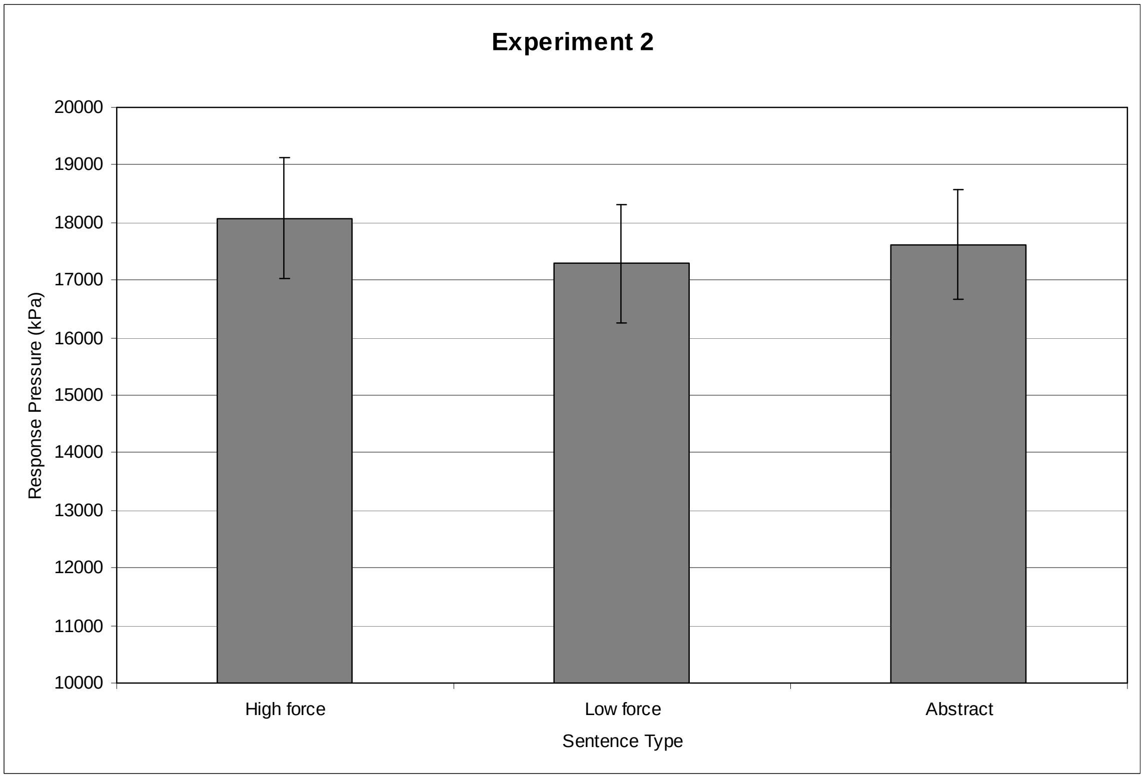

Figure 2.

Mean response pressures and standard errors across subjects as a function of sentence type in Experiment 2.

Discussion

Experiments 1 and 2 establish force as an action parameter that is activated by language describing high and low force actions. Additionally, this is not a function of individual words conveying information about force, but of entire sentences conveying meaningful information about certain kinds of actions and the force required to perform them with certain kinds of objects.

When a person reads about an action, are the individual parameters of that action processed separately or are they combined at some point in time to form a more coherent simulation of an action? Mounting evidence demonstrates the activation of individual action parameters (e.g., force, movement direction, or grip type), but theories of sensorimotor simulation claim that entire actions and events are simulated using the same systems that we would use for perceiving and performing those events and actions (Barsalou, 1999; Zwaan, 2004). Therefore, when different parameters of a given action are specified by text, they should constrain each other such that motor activation becomes increasingly narrow and action-specific in the reader.

A unique quality of force is that it can be involved in biomechanical actions of the body as well as in more abstract or mental actions (e.g., questioning a witness aggressively versus calmly). This leaves force in a unique position to adjudicate between approaches suggesting either strict, one-to-one simulation of actions or separable processing for individual parameters.

In Experiment 3, participants again made sensibility judgments on sentences by squeezing the pressure-sensitive device with their hands. The amount of force implied by each sentence was manipulated with adverbs implying high or low force (e.g., "He nudged the man *forcefully* (or *gently*)"). In order to ascertain whether activation of the force parameter is effector-specific, the critical items implied actions carried out with the hand and arms (e.g. "He nudged the man forcefully/gently"), legs ("He climbed the stairs quickly/slowly), or no effector at all ("He opposed the agenda directly/calmly").

Because participants respond by squeezing the bulbs with their hands, they should only show the force-congruence effect found in Experiments 1 and 2 for the hand/arm sentences if the simulation/parameter-combination account is correct. Conversely, if parameter activation is independent and coherent simulations are not formed, all three effector conditions should show the force-congruence effect found in Experiments 1 and 2.

Device

The same device that was used in Experiments 1 and 2 was used.

Participants

Thirty-four undergraduate psychology students from Erasmus University Rotterdam participated for course credit.

Procedure

Because the sentences in Experiment 3 were longer than those in Experiments 1 and 2, the procedure was modified in order to ensure that enough data were recorded to yield complete response profiles for each participant. Instead of presenting sentences in their entirety, sentences were presented in two segments. The first half of each sentence (the agent and verb) was presented for 1000 milliseconds and this was followed by the remainder of the sentence, including the adverb, which was presented alone until a participant responded.

Materials

Forty-eight critical sentences described actions involving the hands, the feet, or neither (this category involved more mental or non-physical actions, such as thinking about plans) and were modified with an adverb that implied either a relatively high or low degree of force. The sentences were presented in Dutch.

Results

Overall, there was a 2 (implied force) x 3 (effector) interaction by subjects ($F_1(2, 66) = 4.89$; $p < .01$; partial eta squared = .13; MSe = 2.51×10^6) and items ($F_2(2, 84)$ =

3.36; $p < .05$; partial eta squared = .074; MSe = 1.53 x 10^6). Crucially, this was primarily due to participants applying more pressure to high force hand items than to low force hand items both by participants ($t(33) = 2.45$; $p < .05$) and items ($t(15) = 2.15$; $p < .05$) and no such effect occurring for leg (ps > .30) or abstract sentences (ps > .20). In fact, the pattern for sentences with non-motor or abstract content was the reverse of what would be expected (see Figure 3) if the motor system was engaged for those sentences. As in Experiments 1a and 1b, there was no processing difficulty confound manifested as a significant correlation between response force and reaction time ($r = -.08$; $p > .25$).

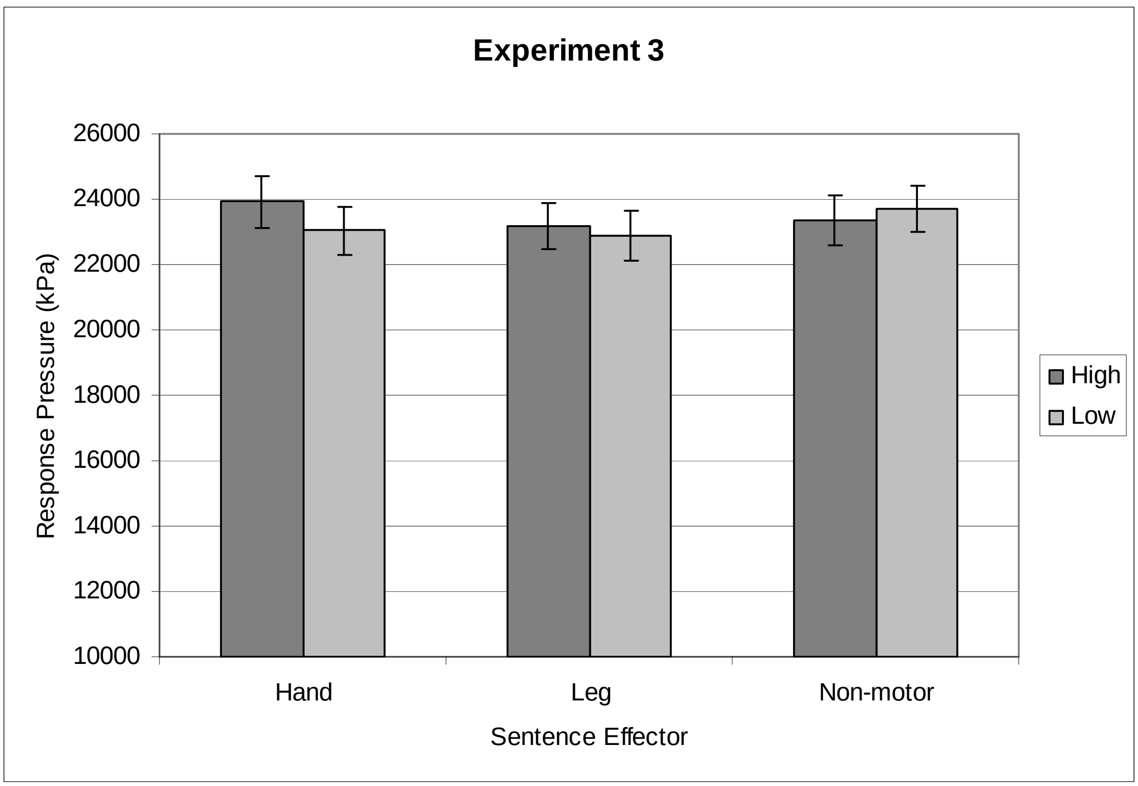

Figure 3.

Mean response pressure and standard errors as a function of sentence type in Experiment 3.

General Discussion

Experiment 1 demonstrates that response force is affected by sensibility judgments on sentences that vary in the amount of force that is implied by the verb. Experiment 2 shows that varying the patient of a sentence, while holding the verb constant, may affect the action system of a reader, thereby indicating that the force parameter is not only a function of the information carried by a verb, but by the meaning conveyed by an entire sentence. This lends support to the LFH, as it demonstrates motor resonance in readers is a function the action-relevance of linguistic input and not necessarily word class. Experiment 3 shows that only sentences about hand or arm movements affect the force applied by the hand; sentences describing leg or non-physical action have no effect. This finding suggests that different action parameters are activated by language so that they may be combined to support simulations of single, coherent actions.

One alternative explanation is that participants became aware of the manipulation, specifically attended to the force implied by the items, and strategically responded to that dimension of the sentences. In order to prevent this from becoming an issue, the critical items were embedded in a larger set of similarly-worded items. Further, explicitly judging the force implied by the items was irrelevant to the task (sensibility judgments) and no participant expressed awareness of the manipulation during the post-experiment interview.

The role of the motor system for abstract and observation sentences is unclear, so the unexpected difference between filler (observation) and low force items in Experiment 1 should be interpreted with caution. One possibility is that low force sentences reduced the force with which participants responded relative to the high force sentences and filler items. A second possibility is that sentences about observation facilitate manual gestures in their own right. The second possibility has received partial empirical support, as sentences referring to an individual attending to an object have been shown to prime functional manual gestures using a different paradigm (Masson, Bub, & Warren, 2008).

The first contribution of this study is confirmation of the prediction that biomechanical force can be affected by sentences describing actions involving various degrees of force. The second contribution is support for a prediction of the Linguistic Focus Hypothesis; referential motor resonance occurs as information about actions is gathered from text. In Experiment 2, participants' response force was shown to be affected by varying the sentence patient of the critical stimuli, thereby demonstrating that that the effect is a function of the integration of meaning for an entire sentence and not a single word class. A third contribution offers further support for existing accounts of action simulation during language processing. In Experiment 3, participants' hand responses were affected by the force implied by the critical sentences, but only when the sentences described actions carried out with the hand or arm. This adds to a growing body of research by strengthening the link between the organization of the action system (Schmidt, 1975; Rosenbaum, 1980) and language comprehension (Fischer & Zwaan, 2008).

Chapter 5

GRASPING SPHERES, NOT PLANETS

This chapter is published as: Taylor, L. J. & Zwaan, R. A. (2010). Grasping spheres, not planets, *Cognition*, *115*, 39-45.

Abstract

Memory for objects helps us to determine how we can most effectively and appropriately interact with them. This suggests a tightly-coupled interplay between action and background knowledge. Three experiments demonstrate that grasping circumference can be affected by the size of a visual stimulus (Experiment 1), whether that stimulus appears to be graspable (Experiment 2), and the presence of a label that renders that object ungraspable (Experiment 3). The results are taken to inform theories on conceptual representation and the functional distinction that has been drawn between the visual systems for perception and action.

Introduction

According to ecological approaches to cognition (Glenberg, 1997; Gibson, 1979), memory for objects helps us to determine how we can act given the constraints inherent to our bodies and what we are capable of doing in a given environment (i.e. "mesh"). Neuroimaging (Martin, Wiggs, Ungerleider & Haxby, 1996) and behavioral data (Myung, Blumstein & Sedivy, 2006) are consistent with the claim that functional actions are primed by functional objects (e.g. tools) and, at least partially, by nouns (object labels) that refer to them (e.g., Grafton, Fadiga, Arbib & Rizzolatti, 1997; Bub, Masson & Cree, 2008). This motor activation is often interpreted as contributing to object categorization (Martin et al., 1996), motor imagery (Postle et al., in press), or conceptual representation (Bub & Masson, 2006). Indeed, the action-relevant background knowledge that nouns provide about objects affects the hand during reach-to-grasp movements. For example, when grasping a block of fixed size, a participant's hand aperture is larger when "apple" is read as opposed to when "grape" is read (Glover, Rosenbaum, Graham & Dixon, 2004).

When people make reach-to-grasp responses to familiar objects, what information do they rely on? One possibility is that they rely exclusively on visual information to guide their grasp. A second possibility is that they rely on background knowledge about the object in question. A third possibility is that they rely on a combination of visual and background knowledge. More than a decade-and-a-half ago, Goodale and Milner (1992) distinguished between two systems of human vision that correspond to the anatomical separation between the dorsal and the ventral visual streams. The dorsal stream is necessary for normal visuomotor guidance ("vision for action"), whereas the ventral stream is necessary for object and scene recognition.

Much subsequent research has examined the role of the ventral stream, and thus memory representations, in visuomotor guidance. During the offline control of action (e.g. during planning), the ventral stream provides background information for the control of actions (Goodale, 2008; Glover, 2004). In line with this, behavioral studies demonstrate that action plans are influenced by relevant background and goal-related information. For example, grasping a familiar object requires knowing about its purpose. Crucially, coherent, goal-directed grasping partially relies on semantic processing; a concurrent semantic task (e.g., a free-association task) disrupts participants' ability to grasp an object in a manner that is appropriate for future action, relative to a non-semantic control task (e.g., articulatory suppression; Creem & Proffitt, 2001, Experiment 3). Moreover, co-actors seamlessly use information gleaned from each other, for example, about an object's weight (Meulenbroek et al., 2007), and information about shared goals (Sebanz et al., 2006) in order to act and co-act more effectively. One would grasp a pair of scissors by the handles when preparing to use them and by the blades when preparing to hand them to someone else; in general, goal-directed action consists of imposing an internally pre-specified, desired effect on one's environment (Waszak et al., 2005). Each result is consistent with the claim that background information is routinely recruited from a variety of sources (semantic memory, one's goals, the environment, or peers) in order to guide behavior.

Moreover, visuomotor guidance may be "contaminated" by exogenous semantic information. For example, when participants reach for objects, their hand movements are affected by seemingly irrelevant semantic information, such as words affixed to the objects (Gentilucci & Gangitano, 1998) or incidentally-presented adjectives (Glover & Dixon, 2002). Findings such as these can be accommodated by assuming that the dorsal stream is comprised of two functionally distinct streams: the dorso-dorsal stream, whose function it is to provide on-line control of actions (like the dorsal stream in Milner and Goodale's original framework), and the ventro-dorsal stream, which plays a role in action organization as well as action understanding and space perception (Rizzolatti & Matelli, 2003).

A neuroimaging study tested the effects of object "identity" and object-orientation on the dorsal and ventral streams (Valyear et al., 2006), participants passively viewed two images of objects presented in succession (with a 1.25 sec mask separating each image). The second image was either (1) exactly the same as the first, (2) the same object, but oriented differently, (3) a different object, but oriented identically, or (4) a different object that was differently oriented. The results demonstrated a double dissociation: the dorsal stream was sensitive to changes in object orientation (but not to object changes) while the ventral stream was sensitive to object changes (but not to orientation changes). The results were taken to demonstrate that the dorsal stream is sensitive to action-relevant information about a visually-presented stimulus (orientation), but not to information that is relevant to the "identity" of the object. Experiment 3 directly addresses this conclusion.

The primary motivation of the present series of experiments was to examine the boundaries of the semantic contamination effect on grasping. That is, does the availability of semantic information about an object exert a top-down influence on the relationship between its grasp-relevant physical properties and grasping behavior? The results can inform theories on the functional distinction that has been drawn between the ventral and dorsal streams and concept representations.

Participants made responses to objects shown on a computer screen, the imperative stimuli, by grasping and squeezing a different object, the pressure bulbs. There were two questions of interest. The first question was whether responses to the pressure bulbs would be influenced by the perceived affordances (Gibson, 1979), “graspability”, of the imperative stimulus (Experiments 1 and 2). The second question was whether the visual “graspability” of the imperative stimulus could be overridden by a verbal label (Experiment 3).

Participants held down two keys on a keyboard and then made a response to a visually presented stimulus, either to its shape (Experiments 1 and 3) or to its color (Experiment 2), by moving their hand to and squeezing one of two pressure-sensitive rubber bulbs mounted on either side of the computer screen. The bulbs were connected via tubes to a pressure gauge, which measured the air pressure inside the bulbs and tubes system, thereby providing an estimate of the amount of force used to squeeze the bulbs. When the air pressure passed a certain threshold, the visual stimulus disappeared from view. Participants received practice trials so that they could calibrate to the amount of force needed to advance to the next trial; participants were instructed to calibrate in this manner during the practice trials. For the current experiments, the threshold was set to 10 kPa. This threshold is rather low, given that the average response tends to be well over 20 kPa and the maximum possible response was approximately 80 kPa.

The bulb apparatus was a closed system (i.e. the amount of air in the apparatus remained constant during a response), so there was a functional relationship between the circumference of a participant's final grip and the amount of force that needed to be applied in order to reach that final state. We therefore assumed that maximum squeeze pressure could be taken as a measure of final hand aperture. That is, decreases in final grip size corresponded to increases in the pressure measured by the apparatus.

Experiment 1

Participants responded to spheres and cubes presented on a computer screen, which had diameters (or side lengths, in the case of cubes) of 100, 150, 300, and 400 pixels (which correspond to approximate actual display sizes of 4.0, 6.0, 12.0, and 16.0cm) respectively (See Figure 1). They responded with their right hand if the shape was a sphere and with their left if it was a cube. Only responses given with the dominant (right) hand were recorded. The key manipulation was that the 100 pixel stimuli appeared smaller, i.e., occupied less of a visual angle, than the bulbs, which measured 6.0 cm in diameter, whereas the other spheres appeared to be either the same size or larger. The bulbs were mounted on either side of the computer monitor that displayed the visual stimuli.

If subjects are sensitive to the affordances of the imperative stimulus in their grasping responses, they should apply more squeeze force in the 100 pixel condition than in the other three conditions, as if they were actually grasping the imperative stimulus, even though this two-dimensional stimulus is by definition not graspable. This reasoning leads to the following prediction regarding the maximum force amplitude associated with the four visual conditions: 100 > 150 = 300 = 400. This prediction is in line with previous research showing that manual responses are sensitive to the sizes of manipulable objects. Tucker and Ellis (2001) drew a distinction between two qualitatively different grasping actions: a precision grip (formed by grasping an object with the thumb and forefinger) and a power grip (formed by grasping an object with the thumb and all four fingers). Participants were presented with small objects that typically afford a precision grip (e.g. a match) and large objects that typically afford a power grip (e.g. a teapot). Participants indicated whether they were manufactured by pressing a switch with either the thumb and forefinger (a precision grip) or the other three fingers (a power grip). Participants were faster to respond to small objects with a precision grip and were faster to respond to large objects with a power grip.

On the face of it, our prediction runs counter to intuition. It predicts a difference between the two conditions with the smallest size difference and, moreover such that the smaller one will yield more force than the larger one. On the other hand, it does not predict any differences between the three largest sizes. An alternative prediction is that participants respond with more force to larger stimuli because they might appear heavier than the smaller ones if they were real objects. This prediction is consistent with earlier work showing a relation between stimulus intensity and response force (Angel, 1973; Jaskowsi, Rybarczik, Jarosyk, & Lemanski, 1995), a relation that seems to hold even when intensity is either a feature of non task-relevant stimuli (Mattes, Ulrich, & Miller, 2002; Miller, Franz, & Ulrich, 1999) or quantity (Lindemann et al, 2007). Like the previous prediction, this prediction is consistent with the notion that subjects respond to an irrelevant dimension of the imperative stimulus, but it does not invoke an account involving grasping. According to this prediction, force amplitude should increase with perceived size of the imperative stimulus, 100 < 150 < 300 <400. Finally, if the subjects are perfectly calibrated by using somaesthetic input from previous trials squeezing the bulbs, then the imperative stimulus should have no effect on force amplitude, 100 = 150 = 300 = 400.

Method

Subjects. 33 right-handed undergraduates at Florida State University participated for course credit. All participants were native speakers of American English.

Stimuli. We constructed four critical stimuli (spheres; see Figure 1) which had diameters of 100, 150, 300, and 400 pixels (or actual display sizes of 4.0, 6.0, 12.0, and 16.0cm), respectively. The 150-pixel sphere matched the diameter of the response bulbs, which were mounted on either side of the display monitor, on the same plane on which the visual stimuli were presented. Four fillers items (cubes) were designed to match the color of the spheres and had side lengths equal to the diameters of the critical items.

Apparatus. The response bulbs were mounted on the sides of the computer monitor and centered with respect to the screen. When a response of 10 kPa was detected, a response was recorded and the next trial began.

Design and procedure. At the beginning of each trial, participants were instructed to hold the L and A keys on the keyboard with their index fingers in order to cause the next sphere or cube to appear on the screen. 500 milliseconds after each key was depressed, one of the stimuli appeared in the center of the screen. If the object was a sphere, participants released the L key and squeezed the right bulb; if it was a cube, they released the A key and squeezed the left bulb. This procedure was followed in order to ensure a reliable baseline measure for each participant (i.e. 500 millisecond during which the bulbs remained untouched) was collected.

Each participant performed 8 practice trials (one presentation of each stimulus); they were instructed to calibrate themselves during this phase in order to avoid applying unnecessarily high pressure during the experiment. Participants made a total of 80 shape judgments (10 responses for each stimulus). All items were presented in random order.

Results. Figure 3 shows the maximum air pressure as a function of stimulus size. There was a main effect of stimulus size, (F (3,96)=2.83, p<.05). In accordance with the grasp affordance hypothesis, the 100-pixel condition yielded more force than the 150-pixel (F(1,32)=5.45, p<.05), the 300-pixel (F(1,32)=4.63, p<.05) and the 400-pixel conditions (F(1,32)=4.80, p<.05), while the latter three were statistically equivalent (Fs<1). These results rule out the alternative hypothesis that squeeze force is correlated with apparent weight of the imperative stimulus. The results are consistent with the prediction that the affordances of the imperative stimulus affect responses to a different object.

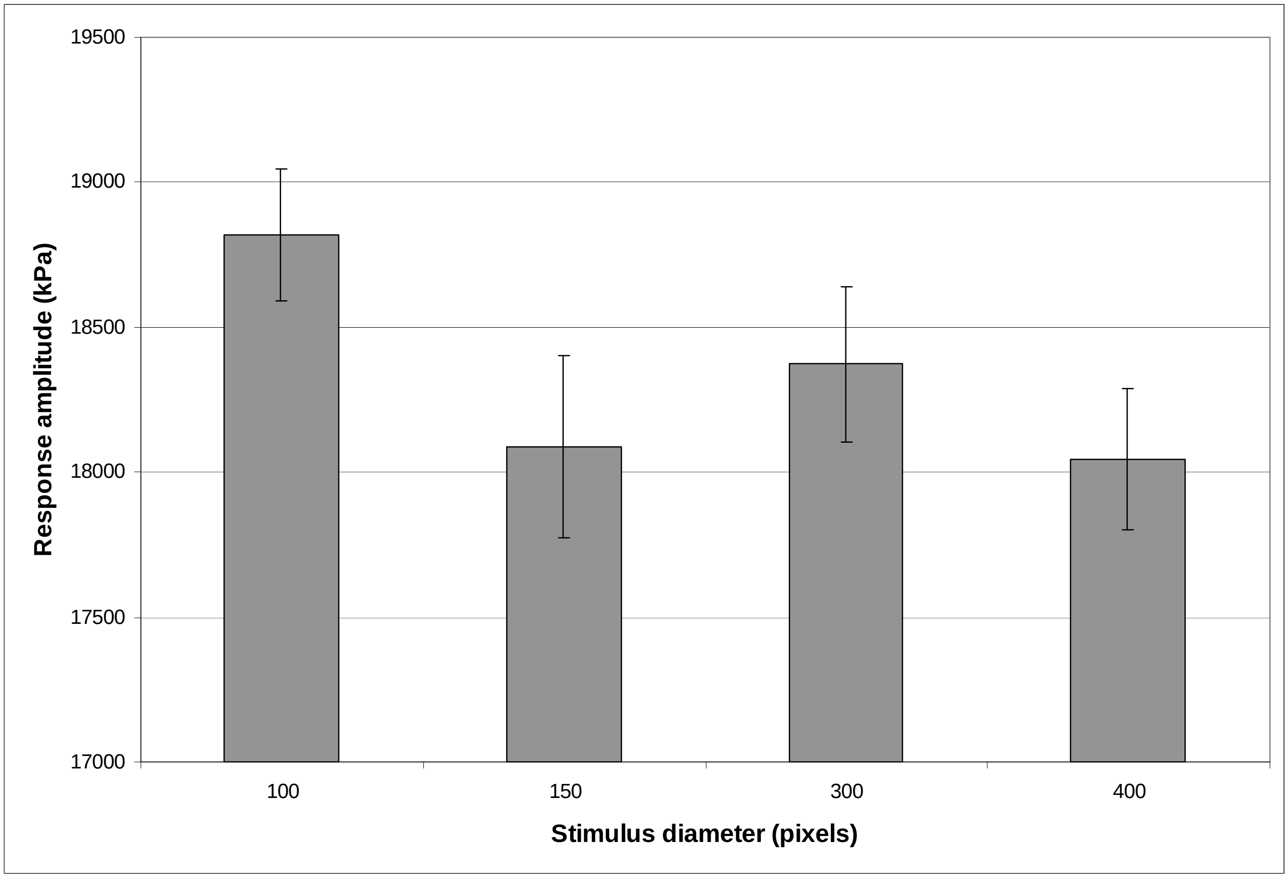

Figure 3.

Response amplitude as a function of stimulus diameter in Experiment 1.

Experiment 2

The results of Experiment 1 do not allow us to determine whether the affordance effect is due to grasping affordance of the object in question or to some other aspect of its size. To adjudicate between these possibilities, we created a second set of stimuli, spiked spheres (see Figure 2). By attaching spikes to the spheres, we intended to render them "ungraspable" and thus remove the grasp affordance. We also retained the "spikeless" spheres from Experiment 1. Thus, if the grasp affordance hypothesis is correct, there should be an interaction between sphere type and sphere size, such that there is a size effect in the spikeless spheres, but not in the spiked ones.

Method

Subjects. 37 right-handed undergraduate students from Florida State University participated for course credit. All participants were native speakers of American English.

Stimuli. The stimuli from Experiment 1 were supplemented with a set of spiked spheres. Only the 100-pixel and the 400-pixel conditions and only the spheres from Experiment 1 were used. The spiked spheres measured 100 and 400 pixels from spike tip to spike tip (see Figure 2). All spheres items were colored either red or blue. This resulted in four critical stimuli (two red spheres and two red spiked objects) and four filler stimuli (two blue spheres and two blue spiked objects).

Design and procedure. The procedure was identical to Experiment 1, with the exception that participants made color judgments on the imperative stimuli. Red objects required a response with the right hand and blue objects required a response with the left hand. As with Experiment 1, only right-hand responses (i.e. those to red stimuli) were recorded.

Results. The type by size interaction predicted by the grasp affordance hypothesis was significant ($F(1,31)=14.01$, $p<.005$). As Figure 4 shows, this interaction is due in part to the spiked object, where a larger amplitude was found for the 400-pixel object than for the 100-pixel one, (F $(1,31)=8.79$, $p<.05$). This effect was not predicted. However, a plausible post-hoc explanation is that the larger object (if real) could be grasped by one of the spikes, which might have elicited a grasp affordance. The predicted amplitude difference for the spheres was significant ($F(1,31)=5.49$, $p<.05$), which is consistent with the findings of Experiment 1.

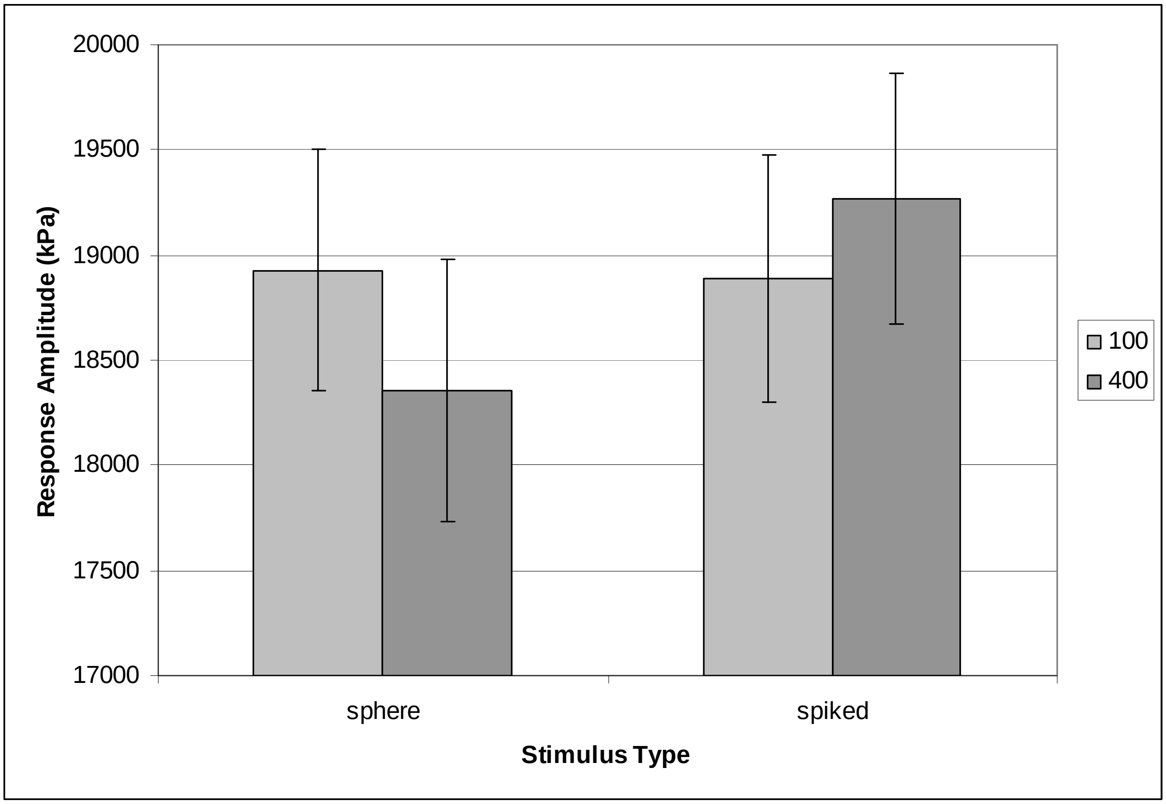

Figure 4.

Response amplitude as a function of stimulus diameter and stimulus type in Experiment 2.

Discussion

The results of Experiment 1 and 2 are in agreement with other work indicating that unfamiliar-but-graspable objects prime a grasping response; in fact, some data indicate that unfamiliar objects prime grasping more than known tools (Vingerhoets, Vandamme & Vercamen, in press). It may be argued that shape judgments prime more "grasp-relevant" information than do color judgments. This is one potential confound between Experiments 1 and 2 that we view as inevitable. Had the task in Experiment 2 been shape judgments, the experimental manipulation (of using spikes to render the distal stimuli ungraspable) would have become transparent, thereby potentially alerting participants to the purpose of the experiment. In light of these considerations, Experiment 3 was designed to be as similar to Experiment 1 as possible.

Experiment 3

Experiment 2 suggests that the effect is due to perceived affordances of the stimuli. However, these affordance effects were based on visual information. Is it possible to elicit affordance effects by using verbal labels to access memory representations? If so, this would strongly implicate the role of memory representations in grasping. We tested this hypothesis by using the stimuli from Experiment 1, but referring to them as "planets." This label should activate background knowledge that imposes a different interpretation upon the imperative stimulus, which should render them "ungraspable" and thus eliminate the affordance effect observed in Experiment 1. Because this hypothesis predicts a null effect, it would make the same prediction as the hypothesis that features of the imperative stimulus do not affect squeeze force. Therefore, we performed a cross-experiment analysis with the data from Experiment 1. The only difference between the two experiments was that in Experiment 1 the stimuli were called "spheres" and in Experiment 3 "planets," so that label functioned, in effect, as a between-subjects factor.

This experiment may best be juxtaposed with an imaging study discussed above (Valyear et al., 2006), in which object "identity" did not affect the dorsal stream. However, in that study, the visual characteristics of the critical object covaried with manipulations in "identity" (for example, a wrench was replaced with a screwdriver) and changes in identity did not affect the critical object's graspability. In this experiment, the identity of the imperative stimulus is manipulated by a verbal label that renders a previously graspable “sphere” into an ungraspable “planet.” This manipulation allows object identity and “graspability” to be varied independently of visual characteristics. Experimental evidence supports the notion that labels are used to infer the identity of ambiguous or unfamiliar objects (Preissler & Bloom, 2007).

Method

Subjects. 34 right-handed undergraduate students from Florida State University participated for course credit. All participants were native speakers of American English.

Stimuli. The stimuli from Experiment 1 were used.

Design and procedure. The experimental design was identical to Experiment 1. We replaced the word “sphere” with the word “planet” during all instruction (at the beginning of the experiment and between every trial).

Results. We predicted that labeling the objects as “planets” would eliminate the affordance effect. Indeed, there was no effect of object size on amplitude ($F<1$; see Figure 5). Next, we performed a cross-experiment analysis using the data from Experiment 1, with experiment as the between-subjects factor and size as the within-subjects factor. As predicted, there was a significant cross-experiment interaction ($F(3,195)=2.68$, $p<.05$). When the objects were labeled spheres, the 100-pixel condition yielded greater amplitude than the other three conditions, but this was not the case when the spheres were called “planets.”

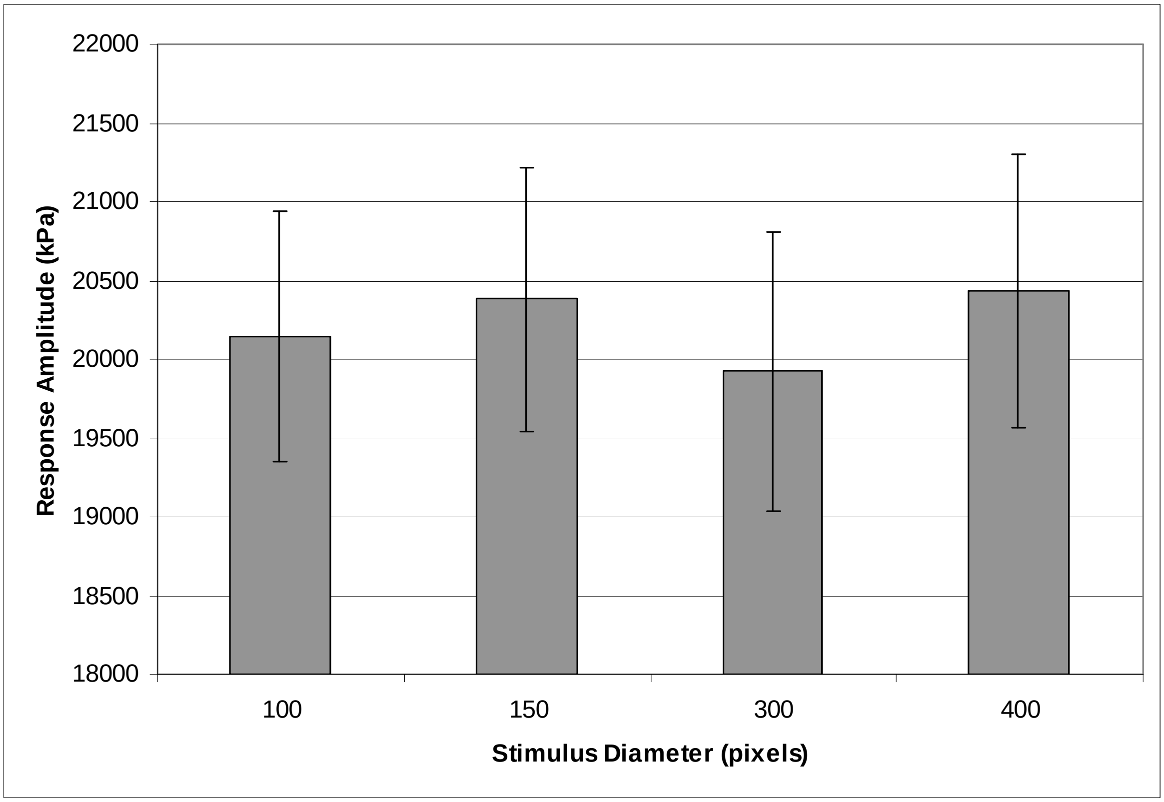

Figure 5.

Response amplitude as a function of stimulus diameter in Experiment 3.

General Discussion

These experiments investigated how the perceived affordances of a visual stimulus affect the grasping of a different object. Experiment 1 showed that the smallest of four spheres shown on a computer monitor yields smaller grasps (operationalized as greater squeeze force) than the other spheres. The defining characteristic of the smallest sphere was that its diameter appeared smaller than that of the rubber bulbs the participants were using to make responses, whereas the other spheres appeared larger (or the same, in the case of the second smallest sphere stimulus). In other words, only for the smaller sphere did the squeeze response appear to be "contaminated" by its perceived affordances. Experiment 2 showed that when the objects were visually rendered ungraspable, the affordance effect reversed (inexplicably). Experiment 3 showed that the presence of a semantic label could also render the objects ungraspable, thereby making the affordance effect disappear.

When considered in light of extant findings, the results can inform theories on the conceptual representation of objects and the functional distinction that has been drawn between the ventral and dorsal streams. The results of all three experiments support the idea that irrelevant information about a distal stimulus (i.e. its size when a participant is responding to its shape [Experiments 1 and 2] and its label when a participant is responding to its shape [Experiment 3]) affects motor behavior on a different response device. This supports a recent conceptualization of how the brain organizes visual experience, as the ventral stream (which processes visual information for perception) provides background information for the control of actions by the dorsal stream, which processes visual information in service of action (Goodale, 2008).

What do these results suggest with respect to grasping? First of all, motor processes involved in reaching-to-grasp are not impermeable to outside influence, a finding which is congruent with the extant literature. Grasping responses were clearly influenced by the features of an object that itself was not grasped and was inherently ungraspable (a two-dimensional visual stimulus). In Experiments 1 and 2, the effects were caused by the perception of the distal stimulus as an actual three-dimensional object that afforded grasping. In Experiment 3, the effect was negated by a memory representation for objects (planets) that are far too large to grasp.

In Experiment 2, when the imperative stimulus was rendered “ungraspable” by surrounding it with spikes, the affordance effect was eliminated (and actually slightly reversed inexplicably). This buttresses the interpretation of Experiment 1 as an effect due to the perceived affordances of the presented object. The affordance effect also disappeared in Experiment 3 when the imperative stimulus was simply labeled as a non-graspable object (a “planet”). In this case, information from long term memory, e.g., about the size of planets relative to that of the human hand, ostensibly overrode visual information, which in Experiment 1 was found to contaminate manual responses to a different object.

The results and implications of Experiment 3 can be immediately embedded in research showing semantic contamination of hand movement by words presented in a reach-to-act task (Gentilucci & Gangitano, 1998; Glover & Dixon, 2002; Glover et al., 2004; Lindemann et al., 2006). The present results suggest that grasp aperture is modulated by a mechanism that involves more than visual characteristics and memory for the to-be-grasped object. Not only do visual features of a different object, which in itself cannot be grasped, constrain the process, but so does the interpretation of this object based on activated background knowledge. These findings are consistent with constraint-satisfaction accounts of motor performance (e.g., Wolpert, Doya, & Kawato, 2003) and point to the relevance of motor tasks in studying cognitive representations and processes (see also Abrams & Balota, 1995; Rosenbaum, 2005).

This study departs from previous work in several regards. First, this is the only work, to our knowledge, showing that a manual response is affected by the identity of otherwise visually-identical objects. That is, the visually-discernible affordances of graspable “spheres” affected the diameter of participants’ grasp responses in Experiments

1 and 2, but visually-identical “planets” did not affect participants’ grasp responses in Experiment 3.

Second, previous research showing semantic contamination of a reach-to-grasp movement typically presents the linguistic and visual stimuli so that they are processed by participants as being unrelated to each other. Glover et al. (2004), for example, presented individual words before participants made a grasping response on an unrelated object. Other research (e.g. Glover & Dixon, 2002 and Gentilucci & Gangitano, 1998) involves adjectives printed on blocks that participants grasp while other movement kinematics are measured. In this study, a label for the visual stimulus was incidentally presented during the instruction phase of the experiment and served to identify the visual stimulus.

Third, previous research showing effects of visually-presented objects on grasping typically compare effects on qualitatively different grasping behaviors. Tucker and Ellis (2001), for example, found that large and small objects affected power (formed using the entire hand) and precision (formed using only the thumb and forefinger) grasp responses differently. In this study, objects of different sizes (Experiment 1), of different graspability (Experiment 2), and with different labels (Experiment 3) affect the grasping circumference of qualitatively similar squeeze responses.

The results of this study imply that motoric information about the affordances of the referents of nouns are routinely activated, even when it is clearly neither necessary nor relevant for completion of the task. This is in line with developing theories suggesting that object concepts are grounded in perception and action. According to this theoretical framework, information about object concepts is organized according to properties of the objects that can be observed or experienced. Properties such as an object's appearance, how it moves, and how one can interact with it are represented in the modality-specific systems associated with first-hand, embodied experiences with each property (Martin, 2007). An active thread of research in this field focuses on the relationship between the brain regions that are active when objects are manipulated and the representation of manipulable objects (Culham & Valyear, 2006). The results of Experiment 3 indicate that semantic information, when it conveys grasp-relevant information, exerts a top-down influence on these representations.

The present study is compatible with existing evidence suggesting that the ventral and dorsal streams serve different functions, but are not entirely functionally separate. Future research may address exactly how and when background knowledge about the affordances of objects affects naturalistic behavior.

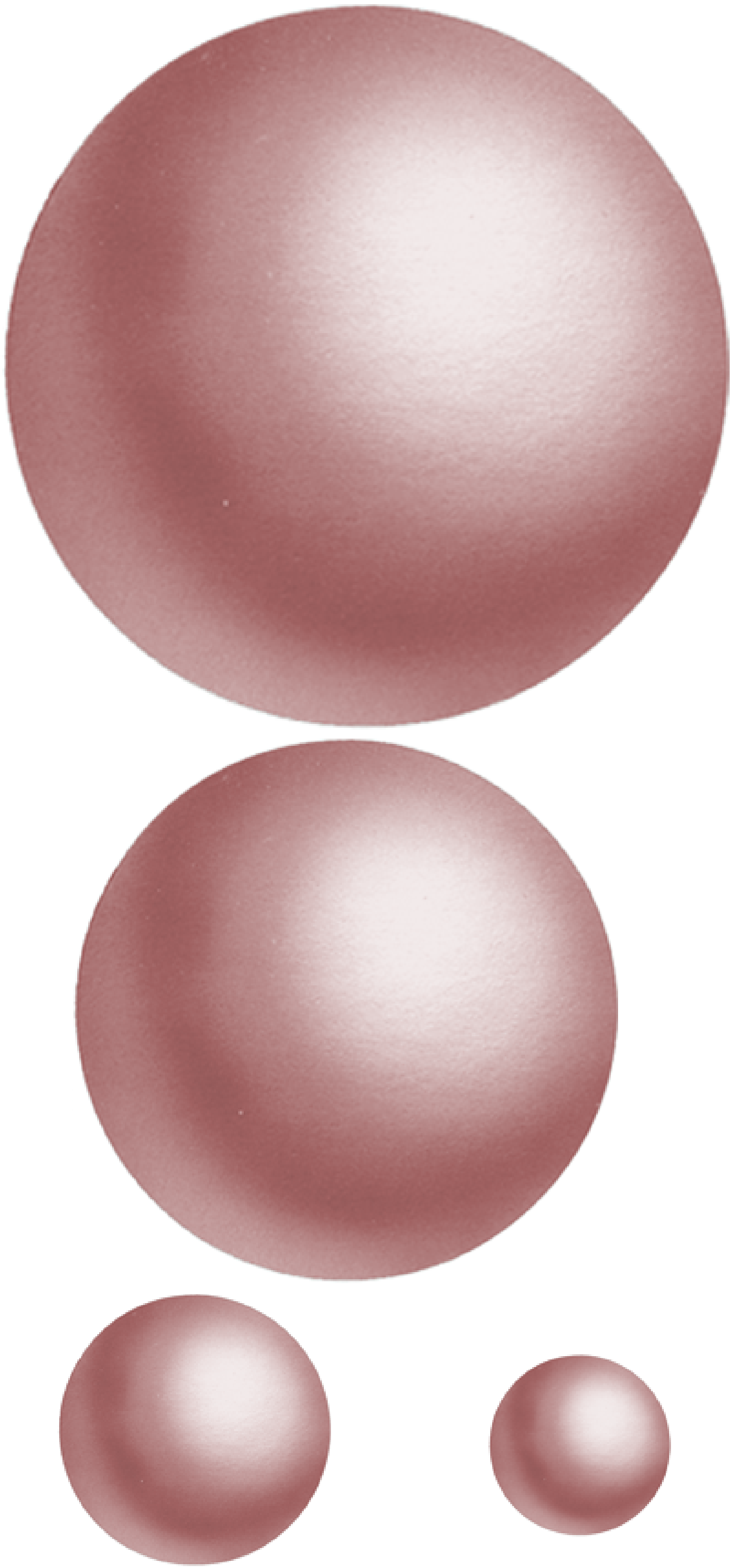

Figure 1: The critical stimuli used in all three experiments

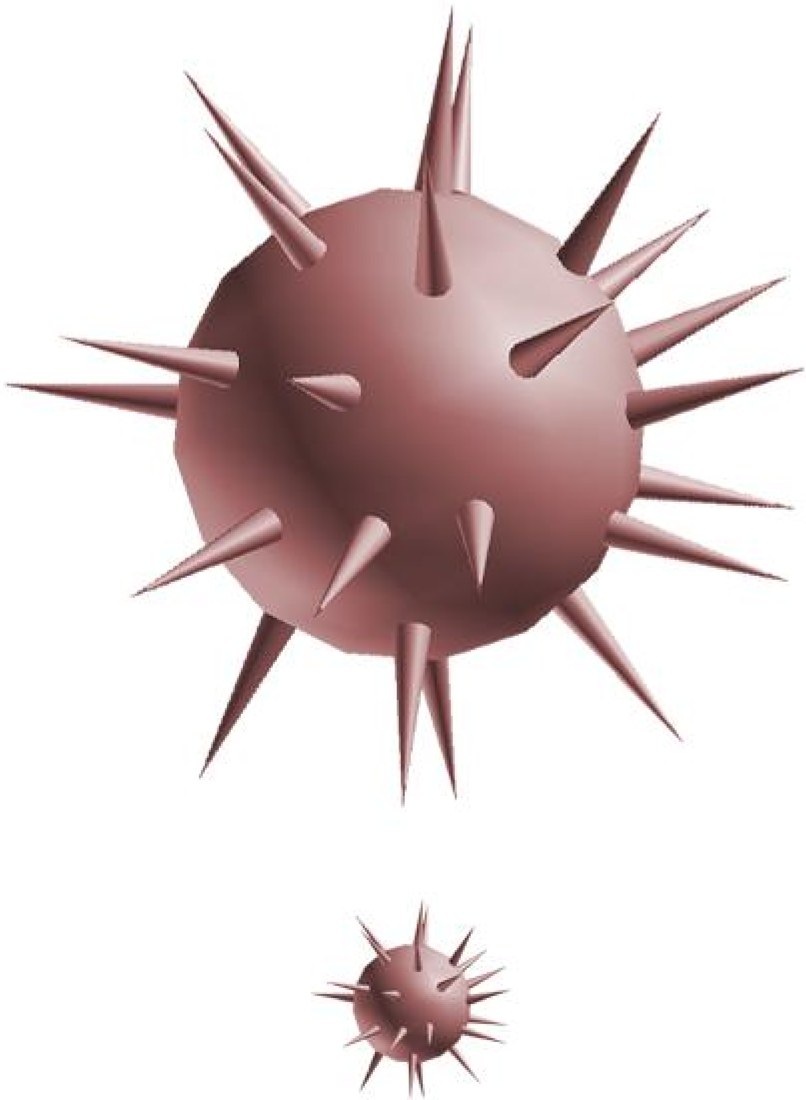

Figure 2. The “ungraspable” spiked stimuli used in Experiment 2.

Chapter 6

FAULT TOLERANT COMPREHENSION

When you read about a person double-lutzing off a cliff, your ability to understand what is described depends on your experience and world knowledge. Most people will at least surmise that the person is a death-defying thrill-seeker and imagine a precipice. Winter sports aficionados might peg the double-lutzer as a suicidal ice-skater, picture an icy cliff, and note that sticking the landing will be tricky. In addition to this, a professional figure-skater might mentally simulate the process of building up speed, jumping, and completing two revolutions while airborne or recall the last time he completed a double-lutz. This example illustrates two aspects of language comprehension that we will highlight in this chapter. First the depth of a person's understanding of a described event depends upon her experience and world knowledge. Second, as a reader's relevant knowledge decreases, his understanding of an event does not suddenly disappear, but degrades gracefully. That is, comprehension is a fault-tolerant process in which different people with various degrees of experience understand event descriptions at different levels of depth and granularity.

Language comprehension has long been viewed as the conversion of linguistic symbols to a 'language of thought' (Fodor, 1975; Kintsch & van Dijk, 1978). Recent evidence, however, suggests that language comprehension involves the activation of the brain's sensorimotor system (Barsalou, 2008; Martin, 2007). Some researchers have taken this evidence to mean that language comprehension consists entirely of the sensorimotor simulation of the situations described in language. Other researchers, on the other hand, argue that the observed sensorimotor simulation is epiphenomenal and that the backbone of comprehension still consists of the manipulation of abstract, arbitrary, and amodal symbols. Thus, the debate revolves around the question to which degree sensorimotor activation is relevant to language comprehension. We begin with the strongest claim: sensorimotor activation is *necessary* for comprehension.

An answer to this necessity question (Fischer & Zwaan, 2008) is not readily apparent. However, the current literature allows us to venture an educated guess. Lesioned motor neurons are associated with significantly disrupted, but intact, processing of action-related language. Patients with motor neuron disease have a consistent and selective impairment for the comprehension and production of verbs, relative to nouns (Bak et al., 2001; Bak et al., 2006). Patients with Parkinson's disease, which primarily impairs the performance of overt actions, perform abnormally on a lexical decision task with action verbs, but not for concrete nouns; treatment of the physical motor deficit brings performance on action verbs up to the level of concrete nouns (Boulenger et al., 2007). Converging evidence from healthy controls points to the importance of the motor cortex. Transcranial magnetic stimulation (TMS) allows researchers to selectively and temporarily change activity in certain regions of the cortex in healthy participants and observe the consequences on language tasks. Applying TMS to the hand and leg areas of the left hemisphere speeds lexical decisions on hand and leg verbs, respectively (Pulvermüller, et al., 2005). Meanwhile, disrupting the left motor cortex with repetitive stimulation causes participants to make morphological changes to action words (verbs and nouns) more slowly (Gerfo et al., 2008). Neurological studies consistently show an association between disrupted processing of action-related language and dysfunctions of motor neurons. In diseased populations, lexical or semantic processing tends to remain intact, but in a significantly slower or less fluent form.

This evidence suggests that motor activation is not necessary for minimal comprehension. To some extent this leads us to reconsider what we mean by comprehension. If the goal is a sparse representation with minimal mappings to the comprehender's experiential repertoire, then motor activation does not appear necessary. But what if we demand more from comprehension? Further research shows an association between motor activation and deeper understanding of actions. Functional magnetic resonance imaging (fMRI) occasionally lacks the sensitivity to detect activation in the motor cortex for shallow lexical processing of action words (e.g., Postle et al., 2008), but actively imagining actions leads to the expected activity in motor regions (Tomasino et al, 2007; Filimon et al., 2007).

The motor and premotor cortex appear to play a role in the more elaborate action representations of experts and their enhanced ability to understand language about actions that fall within their domain of expertise. The premotor cortex of experienced dancers is more active when they are viewing routines that they know how to perform (Calvo-Merino et al., 2005), relative to less familiar routines or styles. The effect of expertise extends to language comprehension; experienced hockey players understand sentences about hockey better than novices and show increased activity in the left premotor cortex while reading such sentences (Beilock et al., 2008). Deeper semantic processing on the individual level is associated with effects on the action system. Either premeditated action-planning or semantic processing that is deeper than simple word detection is sufficient to cause priming between linguistic input and goal-directed action; word-exposure (or lexical decision) alone has not been found to prime a goal-directed action (Lindemann et al., 2006). Dominant-handed responses to hand action verbs, relative to foot action verbs, are disrupted during a semantic decision task, but not during a lexical decision task and not (1000 ms) after a semantic decision has already been made (Sato et al., 2008).

Taken together, the research reviewed above suggests that referential sensorimotor activation (Fischer & Zwaan, 2008) during reading contributes to deeper levels of language comprehension. In line with this view, we would expect motor activation to become more situation-specific as linguistic context becomes more constraining. Words presented in isolation do not offer much information to language users. Likewise, when they are presented to participants and naturally processed, they typically result in the activation of relatively broad, underspecified (Sanford & Graesser, 2009) representations. Such underspecification is functional in naturalistic language processing because it allows that word to be more readily integrated with upcoming information from the physical, social, or linguistic environment. Relevant behavioral and neuroimaging research demonstrates that words presented in isolation activate experiential information consisting of individual modalities or effectors in language users. However, as more constraining information from text is processed, the associated activation in the reader becomes increasingly situation-specific; that is, readers construct a situation model that is increasingly precise in resolution or elaborate with details. That increased resolution is a function of text-based constraints is reflected in the granularity of the bodily activation in language users.

A very coarse level of granularity for experiential information is the experiential modality (e.g., visual or motor). Individual words presented in a relatively open-ended context reveal this broadest, or most underspecified, activation in language users. When participants perform a lexical decision task before reaching to grasp an object, their wrists reach their peak acceleration faster when they judge action verbs as opposed to concrete nouns denoting non-manipulable objects (Boulenger et al., 2006). Crucially, this occurs rapidly (within 200 ms) and regardless of whether the verb denotes actions carried out with the arm, leg, or mouth. A deeper semantic decision task on similar verbs results in a more complete activation of verb-related motor programs (Volta et al., in press), supporting a link between processing depth and the recruitment of the motor system (Taylor & Zwaan, 2009).

Further experiments have shown that the modality level of specificity is also activated by a deeper, more semantic task such as property verification. For instance, participants are slower to judge whether an object has a property when it is in the same modality as information that they are currently holding in short-term memory. That is, participants are slower to confirm that a lemon can be yellow when they have just been asked to remember three meaningless visual stimuli that they must recognize after the property judgment (Vermeulen, Corneille, & Niedenthal, 2008). Similarly, when participants are merely asked to confirm that they have detected a stimulus, subsequent concept-property judgments are slower when the judged property is in a different modality than the presented stimulus (van Dantzig et al., 2008).

A finer level of granularity beyond experiential modality is well-established within the motor modality; individual effectors of the motor system can be activated by language describing effector-specific actions. Passively reading verbs referring to actions that are carried out with the arm, leg, or face (*pick*, *kick*, or *lick*), leads to activation in the areas of the motor strip that are associated with actual movement of the relevant effector

(Hauk, Johnsrude, & Pulvermüller, 2004). Further behavioral research confirms that effector-specific activation remains intact up to the sentence and discourse level. When participants judge the sensibility of actions denoted by noun-verb pairs (e.g., "suck the sweet" and "unwrap the sweet" or "throw the ball" and "kick the ball") by speaking into a microphone or pressing a foot pedal, they make the judgment faster when they respond with the same effector that the phrase they have just read describes (Scorolli & Borghi, 2007; see also: Buccino et al., 2005).

Even finer than effector-specific activation, action parameters (Schmidt, 1975), such as the speed or direction of throwing a ball, have been shown to be tightly coupled to the content of a sentence. Crucially, parameter-specific activation appears to be effector-specific, indicating that the lower level activations merge to form a more holistic simulation (Taylor & Zwaan, submitted) of the described state of affairs. When participants judge sentences by making sensibility judgments towards the body, they are faster to do so when responding to sentences about transfers towards the body (Glenberg & Kaschak, 2002). A follow-up experiment showed differential activity of the hand muscles immediately after participants read the verbs of such transfer sentences (Glenberg et al., 2008).

Biomechanical intensity is also affected when people read or hear about actions. In one study, participants listened to a sentence about manually-interacting with a light or heavy object before lifting one of two visually-identical boxes that differed in actual weight. Participants were slower to lift the heavier box after hearing sentences about heavier objects (Scorolli, Borghi, & Glenberg, 2009). In a different study, participants made sensibility judgments on sentences describing high or low degrees of force (e.g., “He pushed the car” and “He started the car”) by using their dominant hand to squeeze a device that measured the force of the response. Participants systematically applied more force in response to sentences implying more force (Taylor & Zwaan, submitted). In a further study using the same methodology, participants responded to sentences describing high or low force actions with the arms (e.g., “He nudged the man forcefully/gently”), legs (“He climbed the stairs quickly/slowly”), or no effector at all (“He opposed the agenda directly/calmly”). Participants systematically applied more force in response to high force sentences, but only in response to sentences about arm actions. This provides evidence consistent with the claim that activation of the lower levels of the motor system, such as individual action parameters or specific effectors, combine to form narrower and more situation-specific simulations in comprehenders.

Additional research provides further support for this rapid pruning process (or constraint-satisfaction; Kintsch, 1988) during sentence comprehension. According to this account, the activation of language-induced experiential information is initially quite broad and diffuse but becomes increasingly narrow upon the presentation of linguistic context that reduces the potential interpretations of a word or sentence. For example, the verb *kick* presented in isolation results in more activation in the motor cortex than do literal phrases such as *kick the ball*; idiomatic phrases such as *kick the bucket* result in still less motor activation (Raposo et al., 2009). This result is compatible with the activation of more experiences of kicking in response to the lone verb, fewer experiences of kicking in response to the more constraining phrase *kick the ball*, and no experiences of literally kicking in response to *kick the bucket* (however, see Boulenger, Hauk & Pulvermüller, 2008). While this research shows information subsequent to a verb narrowing its interpretation, information presented immediately before an action verb narrows its interpretation as well. Abstract verbs with a motor stem (*begreifen*, which means “to understand”) do not result in motor activation while the stems themselves (*greifen*, which means “to grasp”) do (Rüschemeyer et al., 2007).

Functional relevance

An important criticism of research from this perspective is that sensorimotor activation is epiphenomenal to the processes underlying the understanding of the meaning behind text. Illustrating that such activation is functionally-relevant for language users helps to counter such a criticism. Indeed, the activation of sensorimotor information during text processing aids in understanding language, mapping language onto one’s environment, and acquiring information from text.

As incoming words of a text are processed and integrated into a situation model, attention is systematically guided towards different aspects of the referential situation. The more the comprehender is able to activate relevant information, the better he or she will be able to anticipate upcoming information and the more fluent the comprehension process will be (Zwaan, 2008; Zwaan & Kaschak, 2009). This points to a role of the sensorimotor system in comprehension: it enhances the fluency and completeness of the comprehension process.

In a set of studies, participants read about direction-specific manual rotation while manually rotating a knob in order to proceed through sentences in groups of one to three words. When participants’ actual manual rotation matched the direction described by the sentence, they were faster to read the verb that disambiguated the direction of rotation than when there was a mismatch between implied and actual rotation direction (Zwaan &

Taylor, 2006). In a subsequent study the same paradigm was used, but the critical items were re-written such that the critical verb was followed by an adverb. The adverbs were intended to maintain focus on the action (e.g., *quickly*, *slowly*) in Experiment 1 and to direct focus towards the sentence subject (e.g., *happily*, *obediently*) in Experiment 2. According to the Liguistic Focus Hypothesis (LFH), sustained focus on the action should be accompanied by sustained motor resonance while switching focus to the subject should not; the results supported this prediction (Taylor & Zwaan, 2008).

In a further study using the reading-by-rotation paradigm, participants read two sentences; the first sentence described an instance of manual rotation and the second sentence disambiguated the direction of rotation on a critical adjective (e.g., He examined the/pie through/the microwave/window and/turned the/timer./The cooking/time needed/to be/*shorter* [*longer*].). Again, participants were faster to read the critical disambiguating word when there was a match between the rotation direction implied by the sentence and the participants' actual manual rotation (Taylor, Lev Ari, & Zwaan, 2008).

In addition to guiding a reader's attention towards different aspects of the referential situation, bodily information may also help readers determine when events described in text are likely to co-occur. Likewise, participants are slower to read a sentence if it describes two actions involving the same effector being performed simultaneously (e.g., unlocking a studio door *while* painting a woman's face), which is either impossible or highly improbable. Crucially, participants are not slowed if the actions are described as being performed successively (e.g., painting a woman's face *after* unlocking a studio door) or if one of the actions is merely considered (e.g., thinking of driving a nail into the wall while writing a letter; de Vega et al., 2004; see also Zwaan, Taylor, & de Boer, in press). Earlier research had already demonstrated that reading about actions that cannot be performed simultaneously leads to impoverished long-term memory representations compared to reading about actions that *can* be performed simultaneously (Radvansky, Zwaan, Franklin, & Federico, 1998). These findings imply that one potential function of bodily activation in readers is to keep readers abreast of which actions are the most likely to occur, or which actions are even possible, given the constraints of the human body.

The rapid activation of situation-specific experiential knowledge during text comprehension is also functional when meaning must be mapped onto one's immediate environment. In one experimental paradigm (Altmann & Kamide, 1999), participants listen to a sentence ("the boy will move/eat the cake") and must judge whether it could reasonably apply to a simultaneously-presented depiction of what the text describes (a boy, a cake, and additional non-edible items). Relative to the verb "move," the verb "eat" facilitated eye-movements towards the cake before the onset of "cake." Participants rapidly used the information inherent in the verb "eat" to constrain the possibilities for upcoming information in the text. This led them to avert their gazes toward the only edible item in the scene (the cake) before the text explicitly mentions it by name. In a follow-up study differences in verb tense (e.g.,"…has drunk…" versus "…will drink…") differentially affected eye-movements towards an empty wine glass and a full beer glass (Altmann & Kamide, 2007). Similarly, when instructed to move a whistle, participants holding a hook in their hand are more likely to look at a whistle that can be picked up with a hook than a whistle that can't (Chambers, Tanenhaus, & Magnuson, 2004). In one study, participants made judgments on the size of spheres and cubes presented on a computer screen by squeezing a response device that gave an indication of grasping circumference (Taylor & Zwaan, submitted). The smallest spheres were found to yield the smallest grip responses when the experimental instructions referred to them as "spheres" (Experiment 1), but not when they were referred to as "planets" (Experiment 3), providing further evidence that linguistic input modulates the way a person attends to the environment.

Further evidence supports the notion that the activation of referential sensorimotor knowledge during reading affects the acquisition of information that can be learned from text or instruction. When children learn to map situation-specific knowledge gleaned from text onto an actual situation, their comprehension of passages of text is enhanced relative to children who read the same text twice (Glenberg et al., 2004). In a similar vein, Paulus, Lindemann, & Bekkering (in press) trained participants to recognize different functional uses for objects (that could be placed next to the ear to be heard or under the nose to be smelled). They found that participants' ability to recognize the functional actions was affected when they were made to perform a secondary task with the hands during the training phase.

Fault-tolerant Processing

Our considerations have led us to adopt the view that comprehension is a fault-tolerant process, in which understanding can be achieved at multiple levels (Taylor & Zwaan, 2009). The goal of this final section is to further lay out our view. We will do this by first considering different levels at which comprehension can be achieved. Consistent with earlier approaches (e.g., Graesser, Millis, & Zwaan, 1997; Kintsch & van Dijk, 1977; van Dijk & Kintsch, 1983; Zwaan & Radvansky, 1998), we define comprehension as the construction of a coherent mental representation of a stretch of language. Coherent means that all the elements of the representation are integrated and can be mapped onto world knowledge.

A minimally coherent representation (McKoon & Ratcliff, 1992) consists only of easily available information and those inferences that are required to make a text locally coherent. For minimally coherent comprehension, achieving global coherence within a larger body of text, making extraneous inferences, and constructing experience-based situation models might be superfluous. It is conceivable that such a skeletal representation is stored in memory and is later fleshed out when relevant experiential information can be brought to bear. For example, when a person's odd behavior is described in a way that only begins to make sense when that person is actually encountered.

A semi-embodied representation may be one that is only loosely based on one's own experience, such as a non-hockey fan reading about hockey (Beilock et al., 2008). While the main points of a text may be understood, many of the details are beyond the ability of the individual to grasp. For example, in reading about a gymnast doing ring exercises, comprehenders may only activate programs for contracting the biceps, rather than activating the motor programs appropriate for executing the complex routine.

Fully embodied representations are largely based on one's experiences and consist of a mental re-enactment of the events described in text using one's own sensorimotor systems for experiencing and acting on the world. The degree to which individuals activate such experiential information during language processing depends upon their personal experience with what the text describes and the depth with which they process the text.

While minimalist comprehension may be possible with little to no activation of experiential knowledge, embodied representations enhance the degree to which a text can be mapped onto world knowledge and the richness of that mapping. As reviewed above, they are functionally relevant to learning a new skill from a text, following verbal instructions, applying one's linguistic environment to one's immediate surroundings, or otherwise directly mapping word knowledge onto world knowledge.

According to embodied accounts of cognition, understanding verbal descriptions draws upon our experiences with the world. If this is the case, then how do we understand an utterance if and when we have very limited, or no, direct experience with what is being described? One advantage of multimodal representations that are based on several experiential modalities (visual, motor, auditory, and so on) is that they are fault-tolerant. That is, if one experiential modality is dysfunctional or is completely lacking experience with a concept, the other modalities can compensate for the missing information and prevent the comprehension process from failing entirely. This helps to account for the peculiar performance seen in individuals with damaged motor neurons on tasks involving action-related language; they are usually slower, but better-than-chance on tasks that require semantic processing of action-related language. According to our account, their experiences encountering those actions through other experiential modalities are able to help them understand language about actions even if their motor system is not capable of contributing to the process as it normally would.

The functional disruption in such patients, however, betrays an underlying role for motoric representations in language processing that is substantive and unique. Behavioral research on healthy participants indicates that the motor system is uniquely situated to provide several streams of information that the other modalities are not well-suited to provide. First, it keeps readers abreast of which actions are likely or possible given the constraints of the human body. For example, it is unlikely that a person would paint a picture while opening a door, as both typically involve actions carried out with the hands (de Vega et al., 2004). Second, details of action parameters such as the force (Scorolli, Borghi, & Glenberg, 2009) or direction (Glenberg & Kaschak, 2002) of a movement are readily provided by the motoric representations. Third, details of action from procedural memory for interacting with objects and the world (e.g.,the shape of a hand when operating a calculator) are based in the motor system (Masson, Bub, & Warren, 2008).

What happens in the event that the motor system fails to provide the requisite information for a life-like simulation of the events described in a stream of text? A life-like simulation of actions described in language can be carried out from the first person perspective (relying largely on the motor system of the reader) most effectively if the reader has extensive first-hand experience with the described set of actions (Beilock et al., 2008). If a reader is lacking sufficient first-hand experience, a first-person simulation can be constructed or partially activated based on one's limited experience and knowledge. For example, if a reader has never kicked a basketball, he can safely surmise that it is something like kicking a soccerball. In addition to falling back on first-person experiences, third-person simulations relying on the other modalities may provide still less-detailed fallback simulation. In this way, multimodal, experience-based representations are fault-tolerant; a small lack of relevant experience or a failure by one experiential modality to support a situation model can be supplemented by other experiences or the other modalities.

Conclusion

A review of neurological and behavioral research indicates that experiential information, particularly from the motor modality, optimizes language processing by adding depth to our understanding of event descriptions and helping us map the information conveyed through language onto the environment. Given that language comprehension relies on multimodal representations, motor activation can not be said to be necessary for forming a coherent representation of what is described by text. This is because language processing relying on multimodal representations is inherently fault-tolerant. Lacking relevant first-hand experience may result in sub-optimal processing, but other experiences may be recruiting to compensate for such shortcomings.

References

Abrams, R.A. and Balota, D.A. (1991). Mental chronometry: beyond reaction time. *Psychological Science, 2*, 153–157.

Altmann, G. T. M. & Kamide, Y (1999). Incremental interpretation at verbs: restricting the domain of subsequent reference. *Cognition, 73*, 247-264.

Altmann, G. T. M. & Kamide, Y. (2007). The real-time mediation of visual attention by language and World knowledge: linking anticipatory (and other) eye movements to linguistic processing. *Journal of Memory and Language, 57*, 502-518.

Angel A. (1973) Input-output relations in simple reaction time experiments. *Quarterly Journal of Experimental Psychology, 25*, 193-200.

Aziz-Zadeh, L., Wison, S. M., Rozzolatti, G. & Iacoboni, M. (2006). Congruent embodied representations for visually presented actions and linguistic phrases describing actions. *Current Biology, 16*, 1818-1823.

Bak, T. H., O'Donovan, D. G., Xuereb, J. H., Boniface, S. & Hodges, J. R. (2001). Selective impairment of verb processing associated with pathological changes in Brodmann areas 44 and 45 in the motor neurone disease-dementia-aphasia syndrome. *Brain, 124*, 103–120.

Bak, T.H., Yancopoulou, D., Nestor, P.J., Xuereb, J.H., Spillantini, M.G., Pulvermüller, F., & Hodges, J.R. (2006). Clinical, imaging and pathological correlates of a hereditary deficit in verb and action processing. *Brain, 129*, 321-332.

Balota, D. A., & Abrams, R. A. (1995). Mental chronometry: Beyond onset latencies in the lexical decision task. Journal of Experimental Psychology: Learning, Memory, á Cognition, 21, 1289-1302

Barsalou, L.W. (1999). Perceptual symbol systems. *Behavioral and Brain Sciences, 22*, 577-609.

Barsalou, L. W. (2008). Grounded Cognition. *Annual Review of Psychology, 59*, 617-645.

Beilock, S. L., Lyons, I. M., Mattarella-Micke, A., Nusbaum, H. C. & Small, S. L. (2008). Sports experience changes the neural processing of action language. *Proceedings of the National Academy of Sciences, 105 (36)*, 13269-13273.

Boroditsky, L. (2000). Metaphoric structuring: Understanding time through spatial metaphors. *Cognition, 75(1)*, 1-28.

Boulenger, V., Roy, A. C., Paulignan, Y., Deprez, V., Jeannerod, M. & Nazier, T. A. (2006). Cross-talk between language processes and overt motor behavior in the first 200 msec of processing. *Journal of Cognitive Neuroscience, 18(10)*, 1607–1615.

Boulenger, V., Mechtouff, L., Thobois, S., Broussolle, E., Jeannerod, M. & Nazir, T. A. (in press). Word processing in Parkinson's Disease is impaired for action verbs but not for concrete nouns. *Neuropsychologia*.

Bub, D. N. & Masson, M. E. J. (2006). Gestural knowledge evoked by objects as part of conceptual representations. *Aphasiology, 20(9)*, 1112-1124.

Bub, D. N., Masson, M. E. J. & Cree, G. S. (2008). Evocation of functional and volumetric knowledge by objects and words, *Cognition, 106(1)*, 27-58.

Buccino, G., Lui, F., Canessa, N., Patteri, I., Lagravinese, G., Benuzzi, F., et al. (2004). Neural circuits involved in the recognition of actions performed by nonconspecifics: An fMRI study. *Journal of Cognitive Neuroscience, 16*, 114–126.

Buccino, G., Riggio, L., Melli, G., Binkofski, F., Gallese, V. & Rizzolatti, G. (2005). Listening to action-related sentences modulates the activity of the motor system: a combined TMS and behavioral study. Cognitive Brain Research, 24, 355-363.

Calvo-Merino, B., Glaser, D. E., Grezes, J., Passingham, P. E. & Haggard, P. (2005). Action observation and acquired motor skills: An fMRI study with expert dancers. *Cerebral Cortex*, *15*, 1243–1249.

Caramazza, A., Grober, E., Garvey, C., & Yates, J. (1977). Comprehension of anaphoric pronouns. *Journal of Verbal Learning and Verbal Behavior, 16*, 601-609.

Caramazza, A., & Mahon, B.Z. (2006). The organisation of conceptual knowledge in the brain: The future's past and some future directions. *Cognitive Neuropsychology, 23(1),* 13-38.

Casasanto, D. & Dijkstra, K. *Motor action and emotional memory*. Submitted.

Chambers, C.G., Tanenhaus, M.K, Eberhard, K.M., Filip, H. & Carlson, G.N. (2002). Circumscribing referential domains in real-time sentence comprehension. *Journal of Memory and Language, 47*, 30-49.

Chambers, C. G., Tanenhaus, M. K., & Magnuson, J. S. (2004). Actions and affordances in syntactic ambiguity resolution. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 30*, 687–696.

Creem, S. H. & Proffitt, D. R. (2001). Grasping objects by their handles: A necessary interaction between cognition and action. *Journal of Experimental Psychology: Human Perception and Performance, 27(1)*, 218-228.

Culham, J. C. & Valyear, K. F. (2006). Human parietal cortex in action. *Current Opinion in Neurobiology, 16*, 205-212.

van Dantzig, S., Pecher, D., Zeelenberg, R., & Barsalou, L.W. (in press). Perceptual processing affects conceptual processing. *Cognitive Science*.

van Dijk, T. A., & Kintsch, W. (1983). Strategies in discourse comprehension. New York: Academic Press.

Dijkstra, K., Kaschak, M.P., & Zwaan, R.A. (2007). Body posture facilitates retrieval of autobiographical memories. *Cognition, 102*, 139-149.

Filimon, F., Nelson, J.D., Hagler, D.J., & Sereno, M.I. (2007). Human cortical representations for reaching: Mirror neurons for execution, observation, and imagery. NeuroImage, 37, 1315-1328.

Fischer, M. H. & Zwaan, R. A. (2008). Embodied language: A review of the role of the motor system in language comprehension. *Quarterly Journal of Experimental Psychology*.

Fodor, J. A. (1976). *The Language of Thought*. Hassocks, Sussex: Harvester Press.

Fodor, J. A. (1983). *The Modularity of Mind*. Cambridge, MA: MIT Press.

Gallese, V. (2003). A neuroscientific grasps of concepts: From control to representation. *Philisophical Transactions of the Royal Society, B., 358*, 1231-1240.

Gallese, V., Fadiga, L., Fogassi, L., & Rizzolatti, G. (1996). Action recognition in the premotor cortex. *Brain*, *119*, 593–6.

Gallese, V. & Lakoff, G. (2005). The brain's concepts: The role of the sensory-motor system in reason and language. *Cognitive Neuropsychology, 22*, 455-479.

Gentilucci, M. & Gangitano, M. (1998). Influence of automatic word reading on motor control. *European Journal of Neuroscience*, *10*, 752–756.

Gerfo, E.L., Oliveri, M., Torriero, S., Salerno, S., Koch, G., & Caltagirone, C. (2008). The influence of rTMS over prefrontal and motor areas in a morphological task: Grammatical vs. semantic effects. *Neuropsychologia*, *46*, 764-770.

Ghazanfar, A.A., & Schroeder, C.E. (2006). Is neocortex essentially multisensory? *Trends in Cognitive Sciences, 10,* 278-285.

Gibson, J. J. (1979). The ecological approach to visual perception. Houghton-Mifflin, Boston, MA.

Gigerenzer, G. & Goldstein, D. G. (1996). Reasoning the fast and frugal way: Models of bounded rationality. *Psychological Review, 103(4)*, 650-669.

Glenberg, A. M. (1997). What memory is for. *Behavioral and brain sciences, 20*, 1-55.

Glenberg, A. M. (1999). Why mental models must be embodied. In G. Rickhar & C. Habel (Eds.), *Mental Models in Discourse Prcessing and Reasoning,* 77-90. Amsterdam: Elsevier Science.

Glenberg, A. M., Gutierrez, T., Levin, J. R., Japuntich, S. & Kaschak, M. P. (2004). Activity and imagined activity can enhance young children's reading comprehension. *Journal of Educational Psychology, 96(3)*, 424-436.

Glenberg, A. M., Gutierrez, T., Levin, J. R., Japuntich, S. & Kaschak, M. P. (2004). Activity and imagined activity can enhance young children's reading comprehension. *Journal of Educational Psychology, 96(3)*, 424-436.

Glenberg, A. M. & Kaschak, M. P. (2002). Grounding language in action. *Psychonomic Bulletin & Review, 9*, 558–565.

Glenberg, A. M. & Robertson, D. A. (2000). Symbol grounding and meaning: A comparison of high-dimensional and embodied theories of meaning. Journal of Memory and Language, 43, 379–401.

Glenberg, A. M., Sato, M., Cattaneo, L., Riggio, L., Palumbo, D. & Buccino, G. (2008). Processing abstract language modulates motor system activity. *Quarterly Journal of Experimental Psychology, 61*, 905-919.

Glover, S. & Dixon, P. (2002). Semantics affect the planning but not control of grasping. *Experimental Brain Research, 146*, 383-387.

Glover, S. (2004). Separate visual representations in the planning and control of action. *Behavioral and Brain Sciences, 27,* 2-78.

Glover, S., Rosenbaum, D. A., Graham, J. & Dixon, P. (2004). Grasping the meaning of words. *Experimental Brain Research, 154*, 103-108.

Goodale, M. A. (2008). Action without perception in human vision. *Cognitive Neuropsychology, 25 (7-8)*, 891-919.

Goodale, M. A. & Milner, A. D. (1992). Separate visual pathways for perception and action. *Trends in Neurosciences, 15*, 20–25.

Graesser, A. C., Singer, M., & Trabasso, T. (1994). Constructing inferences during narrative text comprehension. *Psychological Review, 101(3)*, 371-395.

Grafton, S. T., Fadiga, L., Arbib, M. A. & Rizzolatti, G. (1997). Premotor cortex activation during observation and naming of familiar tools. *Neuroimage, 6(4)*, 231-236.

Harnad, S. (1990). The symbol grounding problem. *Physica D, 42*, 335-346.

Hauk, O., Johnsrude, I., & Pulvermüller, F. (2004). Somatotopic representation of action words in human motor and premotor cortex. *Neuron, 41,* 301–307.

Hauk, O., Shtyrov, Y., & Pulvermüller, F. (2008). The time course of action and action-word comprehension in the human brain as revealed by neurophysiology. Journal of Physiology, Paris, 102, 50-58.

Hazeltine, E. (2005). Response-response compatibility during bimanual movements: Evidence for the conceptual coding of action. *Psychonomic Bulletin & Review, 12(4)*, 682-688.

Hebb, D.O. (1949). *The Organization of Behavior: A Neuropsychological Theory*. John Wiley & Sons

Hintzman, D. L. (1986). "Schema abstraction" in a multiple-trace memory model. *Psychological Review, 93(4)*, 411-428.

Jackendoff, R. (1972). *Semantic interpretation in generative grammar*. Cambridge, MA: MIT Press.

Jaskowski, P., Rybarczyk, K., Jaroszyk, F. & Lemanski, D. (1995). The effect of stimulus intensity on force output in simple reaction time task in humans. *Acta Neurobiologiae Experimentalis, 55(1)*, 57-64.

Johnson-Laird, P. N. (1983). *Mental models: Towards a cognitive science of language, inference, and consciousness.* Cambridge, MA: Harvard University Press.

Kemmerer, D., Castillo, J. G., Talavage, T., Patterson, S. & Wiley, C. (2008). Neuroanatomical distribution of five semantic components of verbs: Evidence from fMRI. *Brain and Language*, *107(1)*, 16-43.

Keysers C. & Perrett D.I. (2004). Demystifying social cognition: A Hebbian perspective, *Trends in Cognitive Sciences, 8,* 501-507.

Kintsch, W. & van Dijk, T. A. (1978). Toward a model of text comprehension and production. *Psychological Review, 85(5)*, 363-394.

Kohler, E., Keysers, C., Umiltà, M. A., Fogassi, L., Gallese, V., & Rizzolatti G. (2002). Hearing sounds, understanding actions: Action representation in mirror neurons. *Science, 297,* 846–848.

Lakoff, G. (1987).*Women, fire, and dangerous things: What categories reveal about the mind.* Chicago: University of Chicago.

Langacker, R. W. (2001). Discourse in cognitive grammar. *Cognitive Linguistics, 21(2)*, 143-188.

Lenth, R. V. (2006). Java Applets for Power and Sample Size [Computer software]. Retrieved December 13, 2006, from http://www.stat.uiowa.edu/~rlenth/Power.

Lindemann, O., Abolafia, J. M., Girardi, G., & Bekkering, H. (2007). Getting a grip on numbers: Numerical magnitude priming in object grasping. *Journal of Experimental Psychology: Human Perception and Performance, 33(6)*, 1400-1409.

Lindemann, O., Stenneken, P., van Schie, H. T. & Bekkering, H. (2006). Semantic activation in action planning. *Journal of Experimental Psychology: Human Perception and Performance, 32*, 633–643.

MacWhinney, B. (2005). The emergence of grammar from perspective taking. In D. Pecher & R. A. Zwaan (Eds.), *Grounding cognition: The role of perception and action in memory, language, and thinking* (pp. 198–223). Cambridge, UK: Cambridge University Press.

Mahon, B. Z. & Caramazza, A. (2008). A critical look at the embodied cognition hypothesis and a new proposal for grounding conceptual content. *Journal of Phsysiology – Paris, 102*, 59-70.

Martin, A. (2007). The representation of object concepts in the brain. *Annual Review of Psychology, 58*, 25-45.

Martin, A., Wiggs, C. L., Ungerleider, L. G., & Haxby, J. V. (1996). Neural correlates of category-specific knowledge. *Nature, 379*, 649–652.

Masson, M. E. J., Bub, D. N., & Warren, C. M. (2008). Kicking calculators: Contribution of embodied representations to sentence comprehension. *Journal of Memory and Language*, *59(3)*, 256-265.

Mattes, S., Ulrich, R., & Miller, J. (2002). Response force on RT tasks: Isolating effects of stimulus propability and response probability. *Visual Cognition, 9,* 477-501.
McKoon, G & Ratcliff, R. (1992). Inference during reading. *Psychological Review, 99(3)*, 440-466.
Meulenbroek, R. G. J., Bosga, J., Hulstijn, M. & Miedl, S. (2007). Joint-action coordination in transferring objects. *Experimental Brain Research, 180*, 333-343.
Miller, J., Franz, V. & Ulrich, R. (1999). Effects of auditory stimulus intensity on response force in simple, go/no-go, and choice RT tasks. *Perception and Psychophysics, 61*, 107–119.
Myung, J., Blumstein, S. E. & Sedivy, J. C. (2006). Playing on the typewriter, typing on the piano: Manipulation knowledge of objects. *Cognition, 98*, 223-243.
Nakamura, W. (1997). A cognitive approach to English adverbs. *Linguistics, 35*, 247–287.
Paulus, M., Lindemann, O., & Bekkering, H. (in press). Motor simulation in verbal knowledge acquisition. *Quarterly Journal of Experimental Psychology*.
di Pellegrino, G., Fadiga, L., Fogassi, L., Gallese, V. & Rizzolatti, G. (1992). Understanding motor events: A neurophysiology study. *Experimental Brain Research, 91*, 176-180.
Penfield, W. & Rasmussen, T. (1950). *The cerebral cortex of man*. Macmillan.
Pollatsek, A., & Well, A. D. (1995). On the use of counterbalanced designs in cognitive research: A suggestion for a better and more powerful analysis. *Journal of Experimental Psychology: Learning, Memory, & Cognition, 21*, 785-794.
Porter, R. & Lemon, R. N. (1993). *Corticospinal function and volunatry movement*. Oxford: Clarendon Press.
Postle, N., McMahon, K. L., Ashton, R., Meredith, M. & de Zubicaray, G. I. (in press) Action word meaning representations incytoarchitectonically defined primary and premotor cortices, *NeuroImage*.
Preissler, M. A. & Bloom, P. (2007). Two-year-olds appreciate the dual nature of pictures. *Psychological Science, 18(1)*, 1-2.
Prinz, W. (1997). Perception and action planning. *European Journal of Cognitive Psychology, 9,* 129–154.
Pulvermüller, F. (2004). Neurophysiological distinction of action words in the fronto-central cortex. *Human Brain Mapping, 21(3),* 191-204.
Pulvermüller, F. (2005). Brain mechanisms linking language and action. *Nature Reviews Neuroscience, 6*, 576-582.
Pulvermüller, F., Hauk, O., Nikulin, V. V., & Ilmoniemi, R. J. (2005). Functional links between motor and language systems. *European Journal of Neuroscience, 21*, 793–797.
Radvansky, G.A., Zwaan, R.A., Franklin, N., & Federico, T. (1998). Retrieval from temporally organized situation models. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 24,* 1224-1237.
Raposo, A., Moss, H. E., Stamatakis, E. A. & Tyler, L. K. (2009). Modulation of motor and premotor cortices by actions, action words and action sentences. *Neuropsychologia, 47(2)*, 388-396.
Rizzolatti, G., & Arbib, M. A. (1998). Language within our grasp. *Trends in Neurosciences, 21,* 188–194.
Rizzolatti, G., & Craighero, L. (2004). The mirror-neuron system. *Annual Review of Neuroscience, 27,* 169–172.
Rizzolatti, G., Fogassi, L., & Gallese, V. (2001). Neurophysiological mechanisms underlying the understanding and imitation of action. *Nature Reviews of Neuroscience, 2,* 661-670.

Rizzolatti, G., Matelli, M. (2003). Two different streams for the dorsal visual system: anatomy and functions. *Experimental Brain Research, 153*, 147-157.
Rosenbaum, D. A. (1980). Human movement initiation: specification of arm, direction, and extent. *Journal of Experimental Psychology: General, 109(4)*, 444-74.
Rosenbaum, D. A. (2005). The Cinderella of psychology: The neglect of motor control in the science of mental life and behavior. *American Psychologist, 60(4)*, 308-317.
Rüschemeyer, S., Brass, M. & Friederici, A. D. (2007). Comprehending prehending: Neural correlates of processing verbs with motor stems. *Journal of Cognitive Neuroscience, 19*, 855-865.
Sanford, A. J. & Graesser, A. C. (2009). Shallow processing and underspecification. *Discourse Processes, 42(2)*, 99-108.
Sato, M., Mengarelli, M., Riggio, L., Gallese, V. & Buccino, G. (2008). Task related modulation of the motor system during language processing. *Brain and Language, 105(2)*, 83-90.
Schmidt, R. A. (1975). A schema theory of discrete motor skill learning. *Psychological Review, 82 (4)*, 225-60.
Scorolli, C. Borghi, A. M., & Glenberg, A. M. (2008). Language-induced motor activity in bi-manual object lifting. *Experimental Brain Research, 193(1)*, 43-53.
Scorolli, C. & Borghi, A.M. (2007). Sentence comprehension and action: Effector specific modulation of the motor system. *Brain research, 1130,* 119-124.
Searle, J. R. (1980). Minds, brains, and programs. *Behavioral and Brain Sciences 3 (3):* 417-457.
Sebanz, N., Knoblich, G., Prinz, W. & Wascher, E. (2006). Twin peaks: An ERP study of action planning and control in coacting individuals. *Journal of Cognitive Neuroscience, 18(5)*, 859-870.
Simon, J. R. (1967). Choice reaction time as a function of auditory S-R correspondence, age and sex. *Ergonomics, 10*, 659–664
Taylor, L.J. & Zwaan, R.A. (2008). Motor resonance and linguistic focus. *Quarterly Journal of Experimental Psychology*, 61, 896-904.
Taylor, L. J. & Zwaan, R. A. (2009). Action in cognition: The case of language. *Language and Cognition, 1*, 45-58.
Taylor, L. J. & Zwaan, R. A. (submitted). Language modulates response force. Submitted to *Quarterly Journal of Experimental Psychology.*
Taylor, L.J., Lev Ari, S., & Zwaan, R.A. (2008). Inferences about action engage action systems. *Brain and Language, 107(1)*, 62-67.
Tettamanti, M., Buccino, G., Saccuman, M. C., Gallese, V., Danna, M., Scifo P., et al. (2005). Listening to action-related sentences activates frontoparietal motor circuits. *Journal of Cognitive Neuroscience, 17*, 273–281.
Tomasino, B., Werner, C. J., Weiss, P. H. & Fink, G. R. (2007). Stimulus properties matter more than perspective: An fMRI study of mental imagery and silent reading of action phrases. *Neuroimage*, *36*, T128-T141.
Tucker, M. & Ellis, R. (2001). The potentiation of grasp types during visual object categorization. *Visual Cognition, 8(6)*, 769-800.
Tucker, M. & Ellis, R. (2004). Action priming by briefly presented objects. *Acta Psychologica, 116*, 185-203.
Umiltà, M. A., Kohler, E., Gallese, V., Fogassi, L., Fadiga, L., Keysers, C., & Rizzolatti, G. (2001). "I know what you are doing": A neurophysiological study. *Neuron, 32*, 91–101.

Valyear, K. F., Culham, J. C., Sharif, N., Westwood, D. & Goodale, M. A. (2006). A double dissociation between sensitivity to changes in object identity and object orientation in the ventral and dorsal visual streams: A human fMRI study. *Neuropsychologia*, *44*, 218-228.

de Vega, M., Robertson, D. A., Glenberg, A. M., Kaschak, M. P., & Rinck, M. (2004). On doing two things at once: Temporal constraints on actions in language comprehension. *Memory & Cognition*, *32*, 1033-1043.

Vermeulen, N., Corneille, O., & Niedenthal, P. M. (2008). Sensory load incurs conceptual processing costs. *Cognition, 109*, 287-294.

Vingerhoets, G., Vandamme, K. & Vercammen, A. (in press). Conceptual and physical object qualities contribute differently to motor affordances. *Brain and Cognition*.

Volta, R. D., Gianelli, C., Campione, G. C., & Gentilucci, M. (in press). Action word understanding and overt motor behavior. *Experimental Brain Research.*

Waszak, F., Wascher, E., Keller, P., Koch, I., Aschersleben, G., Rosenbaum, D. A. & Prinz, W. (2005). Intention-based and stimulus-based mechanisms in action selection. *Experimental Brain Research*, *162*, 346-356.

Wilson, M., & Knoblich, G. (2005). The case for motor involvement in perceiving conspecifics. *Psychological Bulletin*, *131*, 460-473.

Wohlschläger, A. (2000). Visual motion priming by invisible actions. *Vision Research, 40*, 925-930.

Wolpert, D.M., Doya, K. & Kawato, M. (2003). A unifying computational framework for motor control and social interaction. *Philosophical Transactions of the Royal Society 358*, 593-602

Zwaan, R. A. (2004). The immersed experiencer: toward an embodied theory of language comprehension. In B.H. Ross (Ed.) The Psychology of Learning and Motivation (pp 35-62). Academic Press, New York.

Zwaan, R.A. (2008). Experiential traces and mental simulations in language comprehension. In DeVega, M., Glenberg, A.M., & Graesser, A.C. (Eds.) Symbols, embodiment, and meaning (pp 165-180). Oxford University Press, Oxford, UK.

Zwaan, R.A. & Kaschak, M.P. (2009). Language comprehension as a means of "re-situating" oneself. In Robbins, P. & Aydede, M. (Eds.) The Cambridge Handbook of Situated Cognition. (pp 368-381). Cambridge University Press, Cambridge, UK.

Zwaan, R.A. & Radvansky, G.A. (1998). Situation models in language and memory. *Psychological Bulletin*, *123*, 162-185.

Zwaan, R. A. & Singer, M. (2003). Text comprehension. *Handbook of Discourse Processes*, ed. Graesser et al., 83–121. Mahwah, N.J.: Lawrence Erlbaum.

Zwaan, R.A. & Taylor, L.J. (2006). Seeing, acting, understanding: motor resonance in language comprehension. *Journal of Experimental Psychology: General*, *135*, 1-11.

Zwaan, R.A., Taylor, L.J., & de Boer, M (in press). Motor resonance as a function of narrative time: further tests of the linguistic focus hypothesis. *Brain and Language*.

Summary

The sitcom “Perfect Strangers” explored the relationship between two cousins, Larry and Balki, who lived in Chicago. Cousin Balki came from the island nation of Mepos, a fictional country with ways much different than those of metropolitan Chicago in the late 1980s. Virtually every episode involved some misunderstanding that arose due to Balki’s lack of experience with the norms, situations, or objects that are common to most Americans. For example, when the cousins visit a hospital, Balki places a bedpan on his head and salutes Larry, because he’s mistaken it for an army helmet. Perfect Strangers and Balki’s persistent misadventures illustrate an important point. We constantly rely on our experience with the world and the background knowledge that it gives us in order to function appropriately in our environment.

This thesis has examined the conditions under which our motor experiences are activated during language understanding (Chapters 1-4) and how this sort of activation may influence object perception (Chapter 5). Chapter 1 is a literature review arguing that motor experiences are activated as a function of meaning and processing depth. Chapter 2 finds that these experiences are activated as a function of “linguistic focus,” or the degree to which a sentence guides a reader’s attention towards the action being described. Chapter 3 finds that a block of text that disambiguates information about an action activates these experiences as well. Chapter 4 finds that the effector (e.g. the hand) being described and the degree of force being used are among the action parameters that may be activated by language describing actions. Chapter 5 finds that a label describing an object as manipulable (“sphere”) or non-manipulable (“planet”) influences a person’s perception of the object. The final section (Chapter 6) embeds this research in the

existing literature in an effort to ascertain exactly what this activation does for people; it concludes that representations of motor experiences are neither necessary nor sufficient for language understanding because we have several other experiential modalities (e.g. vision) for representing the meanings of words. Instead, relevant motor experience enriches our understanding of language and contributes to our "fault-tolerant representations."

These conclusions are supported by additional evidence from expert populations, who understand language about their area of expertise better than non-experts, and patients with motor neuron disease, whose impaired motor neurons result in an impaired ability to perform and understand actions. This research from special populations sheds light on the data from normal undergraduate participants. When a person turns a knob faster while reading about someone opening a pickle jar, they are not merely activating a stored association between "open the jar" and twisting off lids; instead (or in addition to this), the reader is relying on his own experience with opening jars in order to make sense of what the writer is communicating.

That a person's experience with the world has an influence on his understanding of language should be obvious. I know that I could speak to each of you about the feel of the paper in an old novel with yellowed, musty pages because I can be confident that we share similar experiences with aged books. Conversely, asking you to describe the inside of the flying apartment with glass walls from my dream last night wouldn't make sense, as I can be quite sure that you haven't shared my experience with that dream.

Language allows us to relate novel ideas and events to each other even if the ideas are unfamiliar or the events are not in the here and now. Our ability to do so relies on common experience. Describing the atmosphere at a wedding reception as being “as festive as Queen’s Day without all the orange” will be more informative to a Dutch audience than to an American audience, for whom a reference to Super Sunday might be more fitting. That language routinely activates our experiences and that we rely on our experience in order to understand language are two major claims to fall out of the embodied approach to cognition. This thesis has examined the degree to which and the circumstances under which we recruit our motor experience to understand language and perceive objects.

Acknowledgements

Rolf: I can't thank you enough for everything. The more formal things like introducing me to the field and teaching me how to conduct research are typically expected of an academic advisor and prove that you're an excellent mentor. Like you, I hope to realize some degree of success in life while keeping a sense of humor and a twinkle in my eye. You also have the ability to keep interesting ideas floating around while tolerating my often embarrassingly unprofessional behaviour; this indicates that you're secretly some kind of superhuman.

Heiko: You've been a good friend and welcomed me into your family during my time in Rotterdam. I don't know how many hours we spent discussing pedantic theological theories and just shooting the breeze, but I'll always be grateful for every one of them.

Katinka: You helped to shepherd me from the US to a strange country that I could barely locate on a map. I've never known anyone who manages to have both strength and grace to the degree that you do.

Lisa: Zillions of thanks for helping me to put this entire book together at the last minute. The original Awesome Day shall never be forgot.

Ivo: You prove that there's no such thing as being too cool.

Benjamin (AKA Ben C Hammer): Do you remember throwing paper airplanes out of our thirteenth floor office window? I don't think I'll ever have that much fun again.

René and Diane: Simply by doing what you do, you each stand as excellent examples of how to be a solid young researcher.

Bruno and Marianne: We all know that when you have cigarette breaks with someone over the course of many months, you form a special bond with that person. I guess that's about where we are.

Xkcd.com: Thanks for letting me use your art on my back cover!

Lauren: You've been my closest and most supportive friend for quite some time now. You know... thanks.

Curriculum vitae

Larry Taylor is currently a lecturer in the Department of Psychology at Northumbria University and works with the Cognition and Communication Research Centre. He completed a BS at Baylor University in 2004, a MS at Florida State University in 2007, and doctoral research at Erasmus University in Rotterdam before moving to Northumbria University in Newcastle in 2009.

Larry is interested in a variety of topics within cognitive science, evolutionary psychology, and philosophy of mind. His primary contribution to the field has involved fleshing out the functional contribution of one's own motor experience to understanding actions. Larry currently enjoys teaching advanced cognitive psychology and psychobiology, sensation and perception.

Papers

Taylor, L.J. & Zwaan, R.A. (2010). Grasping spheres, not planets. *Cognition, 115*, 39-45.

Zwaan, R.A., Taylor, L.J., & de Boer, M (2010). Motor resonance as a function of narrative time: further tests of the linguistic focus hypothesis. *Brain and Language.*
112, 143-149.

Taylor, L. J. & Zwaan, R. A. (2009). Action in cognition: The case of language. *Language and Cognition*, 1, 45-58.

Taylor, L.J. & Zwaan, R.A. (2008). Motor resonance and linguistic focus. *Quarterly Journal of Experimental Psychology*, 61, 896-904.

Taylor, L.J., Lev Ari, S., & Zwaan, R.A. (2008). Inferences about action engage action systems. *Brain and Language*, 107, 62-67.

Zwaan, R.A. & Taylor, L.J. (2006). Seeing, acting, understanding: motor resonance in language comprehension. *Journal of Experimental Psychology: General*, 135, 1-11.