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Coordinating Action and Language

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Coordinating Motor Actions and Language

The advent of the “visual world paradigm” (e.g. Cooper, 1974; Tanenhaus, Spivey-Knowlton, Eberhard, & Sedivy, 1995) provided an ecologically valid way to study spoken-language comprehension, and set the stage for indispensable insight into the processes that contribute to on-line comprehension in domains such as spoken word recognition (e.g. Allopenna, Magnuson, & Tanenhaus, 1998; McMurray, Tanenhaus, & Aslin, 2002), anticipatory processing (e.g. Altmann & Kamide, 1999), semantic interpretation (e.g. Sedivy, Tanenhaus, Chambers, & Carlson, 1999), and in populations from which it had historically been difficult to index on-line processing ability, such as young children who don’t yet read (e.g. Trueswell, Sekerina, Hill, & Logrip, 1999). In addition to these advances, eye-tracking in the visual world paradigm served another important role in the language sciences—it helped to emphasize the importance of the interaction between perceptual (visual) and cognitive processes. Given the other contributions to this volume, we won’t restate the merits of eye-tracking in the visual world with respect to issues bearing on the nature of language-vision interaction (see Spivey & Huettenlocher, 2015, and Pykkö & Crocker, 2015, this volume, for relevant discussions). Instead, the goal of this chapter is to provide a succinct overview of research that employs a much more recently developed use of the visual world paradigm—namely, the systematic examination of manual motor movement around a visual scene—as a way of providing additional (or complementary) insight into the dynamics underlying language processing across multiple domains.

Indeed, over the past decade, extensive analyses of action have opened new avenues of investigation into the dynamics underlying cognitive processing across a wide variety of domains. This work has most often made use of x,y pixel-coordinate trajectories of computer-mouse movement as the cursor is moved around a task-relevant visual scene in response to a

visually- or auditorily-presented stimulus, offering a rich time series of action data. Stated broadly, experimental results have consistently demonstrated that arm movement (as measured by the movement trajectories recorded from a computer mouse or other devices) systematically reflects ongoing cognitive processes in a wide range of tasks ranging from low-level perception to high-level reasoning (for reviews of this literature, see Freeman, Dale, & Farmer, 2011; Song & Nakayama, 2009): spoken-word recognition (Spivey, Grosjean, & Knoblich, 2005), speech sound categorization (Farmer, Liu, Mehta, & Zevin, 2009), syntactic processing (Farmer, Anderson, & Spivey, 2007; Farmer, Cargill, Hindy, Dale, & Spivey, 2007), semantic categorization (Dale, Kehoe, & Spivey, 2007), attention-related processes (Hindy, Hamilton, Houghtling, Coslett, & Thompson-Schill, 2009), response selection (Wifall, Buss, Farmer, Spencer, & Hazeltine, *submitted*), evaluative thinking (Dale & Duran, 2011; McKinsty, Dale, & Spivey, 2008), deceptive responding (Duran, Dale, & McNamara, 2010; Dale, Roche, Snyder, & McCall, 2008), social perception and judgment (e. g. Freeman & Ambady, 2009; Freeman, Ambady, Rule, & Johnson, 2008; Wojnowicz, Ferguson, Dale, & Spivey, 2008), and affective decision making with respect to clinically-relevant phenomena (Smith, Treat, McMurray, & Farmer, 2014; *in preparation*).

Traditional theories of information processing once viewed the mind's cognitive systems as functionally independent from the systems responsible for executing motor responses, such that motor movement was often characterized as the uninteresting end-result of cognitive processing. Just as tracking eye-movements around a visual display helped to illuminate the importance (or perhaps even existence) of language-vision interaction, however, the tracking of manual motor movements around similar visual displays has helped to foreground the oft-neglected interface between cognitive (for our purposes here, linguistic) and motor systems. The

net result of the recent investigations into the properties of overt motoric behavior recorded during the processing of linguistic stimuli (detailed throughout the remainder of this chapter) has been, we believe, a stronger appreciation for the co-extensive nature of linguistic and motor processes (e. g. Spivey et al., 2005), which has helped foster the development of meta-theoretical perspectives that embrace—instead of deny—the continuous inter-facing that exists among cognitive, perceptual, and motoric systems (Spivey, 2007).

Chapter Overview

In the text that follows, we provide a synthetic overview of evidence from multiple fields that, when considered together, is strongly suggestive of a co-extensive relationship between language and action, thus foregrounding an emphasis on action dynamics in the study of cognitive processing. First, we present a short summary of work conducted in the embodied cognition tradition, with a special emphasis on relatively recent work in the field of embodied sentence processing. Next, we provide an overview of work that has capitalized on manual motor movements in order to make inferences about linguistic processes and representations. In this section, we also review neuroscientific evidence that highlights the continuous interaction between cognitive processes and motor planning and execution. In the following section, we provide a case study involving a visual world task designed to address mechanistic debates about the systems that underlie on-line syntactic processing. Here, we demonstrate how tracking computer-mouse movements around a visual display can complement the eye-movement record, thus providing novel data that speak to the feasibility of various models of syntactic processing during comprehension. In a final section, we provide brief summaries of experiments that employ more novel uses of visual displays to address questions about the engagement of motor

systems during language processing. The data discussed in this chapter, taken together, support the claim that the mouse-tracking methodology can serve as one basis for insight into linguistic processes that are, in some cases, difficult to observe when more discrete and discontinuous dependent measures are recorded.

The Link Between Motor Planning and Language

Across the second half of the 20th century, models of information processing were dominated by modular views of cognition, and rested heavily upon the assumption that cognitive symbols were both amodal and arbitrary (Fodor, 1975; 1983; Pylyshyn, 1984). Under these modular frameworks, information processing was hypothesized to proceed in a stage-based manner, passing through a series of domain-specific, informationally-encapsulated modules. Only when an encapsulated processor completed its operations was it hypothesized to share its outputs with another encapsulated processor. Despite the predominance of these modular theories, other frameworks permitted stronger interaction between various stages of information processing. For example, Gibson (1979) proposed that a sensory analysis of the world generates not a copy of the world's structure, but instead a pragmatic mapping onto the action opportunities that the world's structure makes available. He called these pragmatic mappings "affordances," and suggested that the process of decision-making that underlies voluntary behavior is, at least in part, the process of selecting among the range of possible actions afforded by the environment to the organism. Because one of these possible actions must ultimately be selected and released into overt execution, Gibson's approach suggested that this process should be somewhat embedded within the neural systems associated with motor control.

Building upon Gibson's theory, adherents of embodied approaches to cognition have

argued that the cognitive abilities of an organism are grounded in an organism's experiences with the world. Specifically, higher-level cognitive processing is hypothesized to rely quite necessarily on perceptual and motor groundings in the environment, such that the systems contributing to language comprehension should be perceptually and motorically grounded in nature (Barsalou, 1999; Langacker, 1987). Indeed, evidence for the motor underpinnings of language is plentiful, even when a listener hears an individual word out of context. When comprehending action words, for example, similar patterns of activation are found in motor and pre-motor cortices when perceiving an action word and when performing that action (Hauk & Pulvermüller, 2004; Hauk, Johnsrude, & Pulvermüller, 2004; Pulvermüller, 1999; Pulvermüller, 2001). By exploring the time course of the spread of activity in motor cortex during word processing, it seems that this activity in motor cortex is not simply a by-product of the comprehension process, happening down-stream from processing the word. Instead, this information is immediately available to influence word comprehension. These and similar results are indicative not only of "spreading activation" from linguistic representations to motor representations, but also suggest a functional role for neural feedback from motor areas to language comprehension, a point on which we elaborate below.

To investigate the behavioral consequences of these multimodal neuronal ensembles, Boulenger and colleagues explored the effect of processing action words on the response dynamics of a reaching movement (Boulenger, Roy, Paulignan, Deprez, Jeannerod, & Nazir, 2006). In one experiment, participants moved their dominant hand from a central location when a fixation-cross appeared. Upon moving the hand from this home-pad, either a word or a pseudo-word replaced the fixation cross. If the letter string was a word, participants were instructed to continue the hand movement and grasp a cylinder located away from the home-pad, but were

required to return to the home-pad if the letter string was a pseudoword. The procedure of a second experiment was identical, except that the letter string was presented in place of the fixation cross before initiation of hand movement, thus serving as the go-signal. In this way, the experimenters were able to investigate the relative impact of the movement both during and after word comprehension. When the words appeared after the onset of the movement, the comprehension process seemed to *interfere* with the reaching movement. Specifically, the latency to reach to the cylinder was longer, and the amplitude of the wrist acceleration was smaller, when the word that appeared after the movement had been initiated was a verb relative to when it was a noun. However, when the word appeared as the go-signal itself, the verbs, but not the nouns or the pseudo-words, seemed to *facilitate* the response, with peak wrist acceleration occurring earlier. Hence, when primed with an action verb before initiating a movement, the movement is facilitated, but attempts to recruit motor neurons during action verb processing while they are already in use interferes with the movement. These findings are consistent with the notion that processing action words recruits the cortical regions that are also involved in programming and executing motion, and have been extended to show that even after the movement has been initiated, the reaching motion is disturbed by the visual presentation of a verb (Nazir, Boulenger, Roy, Silber, Jeannerod, & Paulignagn, 2007).

Motoric information also seems to play a role in the processing of sentences. Glenberg and Kaschak (2002) asked participants to judge whether or not sentences made sense by pressing a button that was either further from or closer to the participant. While all of the sentences required a “yes” response, they also implied directionality either away from or towards the participant. The results demonstrated that reaction times were significantly faster when the response movement matched the direction of motion implied by the sentence. For example,

participants responded faster to the sentence “Jay rolled the marble to you,” (implying movement towards the participant), if they were required to press the button that was closer to them (compatible movement) than if they had to press the button further away from them (incompatible movement). These data suggest that the action implied by an entire sentence primes and facilitates movements that are compatible with an action description.

Although the results of these studies are consistent with a perceptual-motor simulation account of language comprehension, it is possible that language-specific areas of the brain are responsible for language processing, and that activity in motor areas is simply peripheral and redundant. Following this line of argumentation, effects like those just described may not be indicative of a meaningful interaction between action and language processing. Determining whether action is central to language processing instead requires bi-directional influence between action and language processing. To explore the possibility of such bi-directionality, Pulvermüller and colleagues (Pulvermüller, Hauk, Nikulin, & Ilmoniemi, 2005) created temporary and reversible changes in an otherwise healthy brain through transcranial magnetic stimulation (TMS) and then observed its impact on language processing. They found that TMS of hand and leg areas in motor cortex differentially influenced the reaction time, derived from lip movement, to arm and to leg words. Applying TMS to effector-specific cortical areas resulted in differential responses to effector-specific words. This evidence suggests a functional and non-peripheral role for motor activity in the processing of language related to action words, demonstrating that motor activity influences language processing in a category-specific manner (see also Casasanto and Lozano, 2007; Havas, Glenberg, Gutowski, Lucarelli, & Davidson, 2010, for additional evidence in support of this bi-directional relationship).

Although space constraints preclude a more extensive review of this literature, evidence so far suggests that cortical areas devoted to action play a role in language processing. Not only are some of these neural architectures shared, language seems to influence execution of motor commands, and execution of a motor command seems to influence language comprehension. These relationships do not imply, however, that the locus of lexical access to a word is based only in the motor cortical areas of the brain. The evidence provided here suggests that motor planning is critically *involved* with language processing, but of course, many other brain areas are also involved (see Louwerse, 2008, for an account of the manner in which perceptuo-motor representations and linguistic representations may work together). Similarly, there are many outstanding questions regarding the nature of these interactions (Mahon & Caramazza, 2008) and the flexibility of embodiment (Markman & Brendl, 2005). Nevertheless, the work detailed in this section serves as an anchor for the foundational assumptions of the research presented in the remaining sections of this chapter. Not only does it highlight the degree to which perceptuomotor processes are engaged during language comprehension, it is highly suggestive of the possibility that recording and analyzing movement around a visual display can provide further, and novel, insight into the representational landscape that underlies language-related processes.

Mouse-Movements Around a Visual Scene as an Index of Linguistic Processing

If motor processing is involved in language processing, then the dynamic characteristics of motor responses during language tasks may reveal interesting aspects of that cognitive processing (as suggested by the work of Nazir et al., 2007, among others), even during language comprehension. In a seminal paper, Spivey, Grosjean, and Knoblich (2005) recorded the streaming x,y coordinates of continuous computer-mouse movements in a visual world task

designed to assess spoken word recognition. They presented pictures of objects on a computer screen and gave participants pre-recorded spoken instructions such as “Click the carriage,” and “Click the tower.” With the mouse cursor starting at the bottom center of the screen, and the objects displayed in the upper left and right corners, participants generally moved the mouse upward while also curving leftward or rightward. Interestingly, when the distractor object’s name shared phonetic features with the target object’s name (e.g., a carrot opposite the carriage, or a towel opposite the tower), the mouse-movement trajectory tended to be conspicuously curved toward the distractor, although participants did eventually click on the correct object. When the distractor object’s name did not share phonetic features with the target object’s name (e.g. a raccoon opposite the carriage, or a crayon opposite the tower), there was significantly less curvature toward the distractor in the mouse-movement trajectory. These results were interpreted as evidence for parallel partial activation of multiple lexical items competing over time (e.g. Gaskell & Marslen-Wilson, 1999; Luce, Goldinger, Auer, & Vitevitch, 1998; McClelland & Elman, 1986). The results of this experiment demonstrate that processes of spoken-word recognition are not confined purely to cognitive systems that are encapsulated from perceptuomotor processes. Instead, the spoken-word recognition process unfolds continuously into motor systems, and is thus reflected all the way into the computer-mouse trajectories.

Where Does This Curvature Come From?

Although individual saccadic eye movements can occasionally exhibit some curvature (Doyle & Walker, 2001; Port & Wurtz, 2003) and some informative variation with respect to landing position (Gold & Shadlen, 2000; Sheliga, Riggio, & Rizzolatti, 1994), individual movements of the arm and hand have the ability to demonstrate quite dramatic curvature

(Goodale, Péllisson, & Prablanc, 1986; Song & Nakayama, 2006), which can be interpreted as the dynamic blending of two mutually exclusive motor commands (Cisek & Kalaska, 2005). For example, when participants reach for a target object that shifts location while the arm is in motion, the arm smoothly adjusts its trajectory mid-flight in order to arrive at the target's new location (Goodale et al., 1986). Even the mere presence of a distractor object can attract the movement path toward the distractor or, in some cases, repel the movement path away from it (Song & Nakayama, 2006). Moreover, finger-pointing movements to colored targets show a temporally continuous graded influence from non-conscious color primes smoothly curving their trajectories (Schmidt, 2002).

These interesting properties of pointing and reaching have an elegant coherence when considered against the backdrop of extensive research on the neuroscience of motor control. The past several decades of research have revealed that even at the level of single-cell responses, motor regions are actively integrating and potentially influencing unfolding decision processes. The systems involved in motor control are anything but simple linear functions of endpoint cognitive decisions. This research on motor regions reveals that the neural processes leading to basic actions are complex and integrative. For example, when neurons underlying control systems are investigated, their response properties appear to exhibit multiple functions (Johnson, Ferraina, Bianchi, & Caminiti, 1996), and cells in premotor cortex may serve multiple, different roles in mediating between cognitive processing and bodily control (Ferraina, Johnson, et al., 1997). In addition, Shen and Alexander (1997) revealed that primary motor cortex activity is not just a reflection of the movement parameters in a reaching task. Instead, a substantial proportion of neurons recruited in the task were active during an “instructed” movement: They fired in trials with a spatial instruction cue that mismatched the limb movement required. Monkeys had to

learn to respond in such instructed trials, and primary motor cortex appears to be involved in accomplishing this. These early studies (see Kalaska, Scott, Cisek, & Sergio, 1997 for an early review) suggest that motor processes are active participants in the complex mediation between sensory and motor processes, and encourage the conceptualization of motor activity as a far more “intelligent” reflection of cognitive processes (e.g., Jeannerod, 2006).

Perhaps the most intuitive demonstration of motor output as a reflection of cognitive processes is the finding that competing motor programs simultaneously emerge during competing decisions. Essentially, when two motor commands are being generated at about the same time (Cisek & Kalaska, 2005), the motor movement produced can sometimes be a weighted combination of the two commands, resulting in an action that moves in the direction of a region *in between* the two intended movement destinations (Godijn & Theeuwes, 2002; Gold & Shadlen, 2000). These kinds of results have been interpreted as evidence that the real-time evolution of a perceptual and cognitive decision is coextensive with the real-time evolution of motor commands (Gold & Shadlen, 2001). Thus, we suggest that, much like eye movements, continuous hand movements may provide a real-time index of the activations of cognitive representations (especially when much of the arm’s inertial mass is supported by a table and most of the continuous movement is carried out by wrist and hand muscles). As a result, portions of trajectories that move toward regions in between two visual targets may be indicative of simultaneous partial activation of the two competing cognitive representations that correspond to those targets.

Researchers using the mouse-tracking methodology have typically assumed that the graded spatial differences in the mouse-movement trajectories index underlying continuous cognitive processing. The graded spatial attraction of these hand movements provides evidence

both of the continuous uptake and integration of visual and linguistic information, and of the dynamic competition between partially active alternatives made salient by this integration (e.g. Spivey et al., 2005; Magnuson, 2005). It has recently been suggested, however, that the signature curvatures in these mouse-movement trajectories can actually be explained, in principle, by a model in which cognitive processing is discrete and serial (considering a single symbolic representation at a time), but in which the motor output is produced by a continuous parallel processing system (van der Wel, Eder, Mitchel, Walsh, & Rosenbaum, 2009). In this model, two motor movements corresponding to a strategic upward movement and then to a perceptual decision movement are asynchronously averaged to produce a smoothly curved motor output (Henis & Flash, 1995). This distinction between perceptual processing and action planning provides an existence proof in which motor output may be continuous, but the underlying cognitive decisions are serial, creating obstacles for theories of embodied cognition that rest upon the assumption that cognition is dynamically coupled with action.

It seems unlikely, though, that one neural system (cognition) would behave in one way (i.e., using discrete representations in sequence), to then feed into a second system (action) that behaves in a qualitatively different way (i.e., using continuous representations in parallel). In their reply to van der Wel et al. (2009), Spivey and colleagues used the same equations that van der Wel et al. (2009) used for their model, adding a mechanism of dynamic competition between the multiple simultaneous cognitive representations that drive those motor commands (Spivey, Dale, Grosjean, & Knoblich, 2010). As there is nothing uniquely serial about the equations used by Henis and Flash (1995), the results of Spivey et al.'s model provide evidence that both perceptual and motor decisions can be made in a continuous, parallel fashion. For example, cognitive representations for two response options initiate motor commands for both potential

reach locations (Cisek and Kalaska, 2005), and the averaging weights for those two motor commands start out equal. This instigates motor output that is initially aimed at the midpoint between the two potential reach locations. As one cognitive representation receives increasing perceptual support, its weight ramps up, while the weight for the other cognitive representation ramps down. These changing weights are used to produce a dynamically averaged motor movement that smoothly curves in a manner identical to the human data. Hence, a dynamic and continuous cognitive task flows smoothly into a dynamic and continuous motor output. We return to this potential concern below after detailing a set of findings from experiments that have used computer mouse movement trajectories recorded in a visual scene to discriminate among models of syntactic processing. Properties of the data we present bear quite heavily on the validity of the assumptions that motivate dynamic competition-based interpretations of mouse-tracking experiments.

From Eye-Movements to Mouse-Movements Around the Visual World

As we have already noted, the purpose of tracking computer-mouse movements around a visual display is not just to replicate findings from previous eye-tracking experiments with a new, inexpensive, and easy to use methodology. Instead, we have argued that the continuity inherent to arm-movement trajectories can unmask the continuous dynamics of cognitive processes that, even on a trial-by-trial basis, are often occluded by discrete or discontinuous dependent measures. As a result, one has the ability to observe cognitive processing as it unfolds across time, potentially revealing a certain degree of gradedness in the amount of commitment to (or, activation of) a target versus its competitors. By obtaining a trial-by-trial index of cognitive processing that captures not only the end-result of a process, but also the intermediate portions of

it as it unfolds across time, one may have the opportunity to provide a more complete map of the representational landscape associated with processing in many different cognitive domains.

Being able to observe, index, and quantify gradedness in the competition dynamics of linguistic processing is particularly useful when different theoretical accounts of a phenomenon can be distinguished based on whether or not gradiency in the commitment to a potential target is predicted. Indeed, theories of on-line language comprehension, which have historically been demarcated along the lines of serial versus parallel weighted activation of syntactic alternatives, are an ideal arena in which to explore the degree to which data obtained by tracking computer-mouse trajectories can shed new light on existing theoretical debates. The purpose of this section is to highlight the manner in which eye- and mouse-movements around a relevant visual display, made in response to spoken instructions containing syntactic ambiguities, can together constrain the space of possible mechanistic models of on-line syntactic processing. Where appropriate, we emphasize the strengths of each methodology, noting that a combination of data from both methodologies provides stronger evidence for or against any group of theoretical accounts than evidence from either methodology when considered in isolation.

Syntactic Garden-Paths and Their Contribution to Models of On-line Language Comprehension

Sentences such as, “The adolescent hurried through the door tripped” are difficult to process because, at least temporarily, multiple possible structural representations exist (see Bever, 1970). In this example, *hurried* could either signal the onset of a reduced relative clause, equivalent in meaning to *The adolescent **who was** hurried through the door...*, or, *hurried* could be interpreted as the main verb of the sentence, such that the adolescent is the entity that willfully hurried. If *hurried* is initially interpreted as the main verb, then processing difficulty is

experienced upon encountering the word *tripped* because it requires the less- or non-active reduced relative clause interpretation. This kind of processing difficulty is classically referred to as the garden-path effect.

Contemporary accounts of how the comprehension system processes such syntactic ambiguity can be distinguished based on 1) the degree to which they rely on the activation of one versus multiple syntactic representations at any one time during the comprehension process, and 2) the time-frame in which non-syntactic information can influence interpretation. Syntax-first models (e.g., Ferreira & Clifton, 1986; Frazier & Fodor, 1978; Frazier & Clifton, 1996) have traditionally proposed that, at a point of syntactic ambiguity, syntactic heuristics alone select a single structure to pursue, and recovery from a misanalysis is achieved via a separate re-analysis mechanism that uses semantic and contextual information. Thus, these models propose that only one representation is active at any given time, and that non-syntactic information only influences interpretation at a later re-analysis stage.

Multiple-constraint based theories (e.g., Green & Mitchell, 2006; McRae, Spivey-Knowlton, & Tanenhaus, 1998; MacDonald, Pearlmutter, & Seidenberg, 1994; Trueswell, Tanenhaus, & Garnsey, 1994), on the other hand, describe language comprehension as an interactive process whereby all possible syntactic representations are simultaneously partially-active and competing for more activation across time. Unlike the syntax-first models, multiple sources of information, be they syntactic or non-syntactic, integrate *immediately* to determine the amount of activation provided to each of the competing alternatives. In this framework, what feel like garden-path effects are due to the incorrect syntactic alternative winning much of the competition during the early portion of the sentence, and then nonconforming information from the latter portion of the sentence inducing a laborious reversal of that activation pattern.

Importantly, the degree to which the incorrect alternative had been winning the competition early on affects the degree to which the reversal of that activation pattern will be protracted and difficult. As a result, one can expect that some garden-path events may be very mild, some moderate, and some extreme, such that a wide variety of sentence-readings should all belong to one population of events with a relatively continuous distribution.

Recently, a sort of hybrid account has emerged that combines properties of each of these two accounts. The unrestricted race model of van Gompel and colleagues (Traxler, Pickering, & Clifton, 1998; van Gompel, Pickering, Pearson, & Liversedge, 2005; van Gompel, Pickering, & Traxler, 2001) follows in the footsteps of constraint-based models in proposing simultaneous integration of multiple graded constraints from statistical, semantic, and contextual sources. However, rather than ambiguity resolution being based on a temporally dynamic competition process, the unrestricted race model posits an instantaneous probabilistic selection among the weighted alternatives of an ambiguity. The alternative most heavily supported by relevant information sources available to the listener upon encountering an ambiguity is the alternative that is discretely pursued by comprehension system. The non-selected alternative receives zero activation. Therefore, much like the syntax-first models, the unrestricted race account must hypothesize a separate reanalysis mechanism that is responsible for garden-path effects when the initial selected alternative turns out to be syntactically or semantically inappropriate (i.e. the incorrect interpretation was the one that was initially selected by the system). Unlike syntax-first models, however, the unrestricted race model also predicts that roughly equi-biased syntactically ambiguous sentences will sometimes elicit a garden-path and sometimes not (sometimes the ultimately correct alternative was initially selected, and sometime it was not)—thus producing two separate populations of events within the same experimental condition.

Distinguishing among these three accounts of garden-path resolution has traditionally been extremely difficult, although the visual world paradigm has contributed substantially to architectural specification in this domain. Here, we first review evidence from eye-tracking around the visual world that poses problems for a syntax-first account of syntactic processing, but doesn't bear directly on the distinction between constraint-based versus the unrestricted race accounts of the garden-pathing. We then review evidence gathered by tracking computer-mouse movements around the visual world that is difficult for an unrestricted race account to accommodate, but is instead entirely consistent with the predictions of a constraint-satisfaction model that handles syntactic ambiguity resolution by dynamic competition among simultaneously active alternatives.

Evidence from Eye-Movements Around a Visual Display

Some of the most compelling evidence in support of a constraint-based model has come from examining the pattern of eye-movements around a task-relevant visual display. For example, Tanenhaus et al. (1995) demonstrated that 1) patterns of eye-movements around a relevant visual display in response to an auditorally-presented sentence can accurately index the real-time interpretation of the sentence, and 2) a scene-based referential context manipulation was sufficient to eliminate the difficulty associated with sentences containing a "garden-path" manipulation. Participants heard instructions containing temporary syntactic ambiguities while looking at a visual display.

1a) Put the apple on the towel in the box.

1b) Put the apple that's on the towel in the box.

In example (1a), the prepositional phrase (PP) *on the towel* creates a syntactic ambiguity in that it

could be initially interpreted as a destination (or Goal) for *the apple*, thus attaching to the verb phrase *Put*, or it could be interpreted as a modifier of *the apple*, and thus syntactically attached to that noun phrase. Although corpus analyses have shown that prepositional phrase attachment ambiguities are in general more frequently noun-phrase-attached than verb-phrase-attached (Hindle & Rooth, 1993), in the case of the verb *put* and the ambiguous preposition *with*, there exists a reliable lexically-motivated bias for verb-phrase-attachment (Britt, 1994; Spivey-Knowlton & Sedivy, 1995).

 Insert Figure 1 about here

When ambiguous sentences like (1a) are heard in the presence of visual scenes where only one possible referent is present (an apple already on a towel), along with an incorrect destination (an empty towel), and a correct destination (a box), as in the left panel of Figure 1, about 50% of the time participants fixate the incorrect destination after hearing the first PP. After the second disambiguating PP is heard, eye movements tend to be re-directed to the correct referent and then to the correct destination. When the unambiguous version of the sentence is heard (1b), participants do not look at the incorrect destination (e.g., the empty towel). The tendency in this one-referent context to look at the incorrect destination until the disambiguating second PP is heard provides evidence of the garden-path effect, and is indicative of initially preferring to attach the ambiguous PP to the verb phrase.

The garden-path effect, however, is frequently attenuated when two possible referents (say, an apple on a towel and another apple on a napkin) are present. When hearing an ambiguous sentence like (1a) in a two-referent visual context, participants tend to look at the correct referent

(the apple on the towel) and move it to the correct destination without looking very often at the incorrect destination. In accordance with various instantiations of referential theory (Altmann & Steedman, 1988; Spivey & Tanenhaus, 1998), thus, it seems that when two possible referents are present, an expectation is created such that they will be discriminated amongst, thereby biasing the system to favor a modifier interpretation of the initial PP.

The fact that a referential context manipulation is able to override looks to the incorrect destination—i.e. garden-pathing— is evidence for the non-modularity of syntactic processes, demonstrating that even non-linguistic information (in the form of objects in one's visual world) can attenuate the propensity to pursue the ultimately incorrect interpretation of a sentence (but cf. Engelhardt, Bailey, & Ferreira, 2006; Ferreira, Foucart, & Engelhardt, 2013, for articulations of methodological considerations that could, in principle, present problems for this interpretation). Indeed, this effect of referential context has become one of the most highly-replicated effects in the domain of sentence processing, replicating across language, ambiguity type, modality, and with a wide variety of psychological and psychophysiological testing methods (Altmann, Garnham & Dennis, 1992; Altmann, Garnham & Henstra, 1994; Altmann & Steedman, 1988; Altmann, van Nice, Garnham & Henstra, 1998; Brown, van Berkum, & Hagoort, 2000; Farmer et al., 2007a/b; Snedeker & Trueswell, 2004; Spivey & Tanenhaus, 1998; Trueswell et al., 1999; van Berkum, Brown, & Hagoort, 1999a; van Berkum, Brown, & Hagoort, 1999b; van Berkum, Brown, Hagoort & Zwitserlood, 2003; see Spivey, Anderson, & Farmer, 2013, for a review of context effects during on-line language comprehension). Although not predicted by a stage-based account of syntactic processing, the referential context effect detailed above is predicted by both constraint-based and unrestricted-race accounts of online comprehension. Under a constraint-based account, visual context acts as one of a set of information sources that work in concert to

bias the competition process over time, and under an unrestricted race account, where there is no competition among syntactic alternatives, the contextual information serves as one cue that helps push one of the alternatives over an activation threshold, at which point it receives 100% of the activation.

As noted above, what can discriminate between constraint-based and unrestricted race accounts of syntactic processing is an exploration of the degree to which garden-path behavior in the one-referent ambiguous-sentence condition (the “garden-path” condition) is graded (as predicted by a constraint-based account) versus all-or-none (as predicted by the unrestricted race account). To date, eye-movement data from the visual world paradigm (e.g., Altmann & Kamide, 1999; Knoeferle & Crocker, 2006; Snedeker & Trueswell, 2004; Tanenhaus et al., 1995) has not been used to directly address this gradiency issue. The analyses typically employed in eye-movement visual world experiments tend to rely on the frequency of discrete fixations of competitor objects in the visual display. That is, since the saccadic eye movement system is largely ballistic and only sends the eyes to fixate an object associated with a garden-path interpretation or not, the evidence from this paradigm is equally consistent with the unrestricted race model (where the various constraints are combined immediately, but on any given trial the reader is either garden-pathed or not). If the eyes were capable of regularly making substantially curved saccades, then one could imagine a mild garden-path effect manifesting itself as a subtly curved eye movement that went slightly in the direction of the garden-path object and then landed on the correct object. For example, a visual display with a saccade target and a distractor object (or even just the spatial memory of one) can induce a small landing-point deviation of about 8 minutes of arc (away from the distractor), accompanied by some slight curvature of about 8 minutes of arc, in a saccade that spans 7 degrees of visual angle (Doyle & Walker, 2001;

Theeuwes, Olivers, & Chizk, 2005; see also Sheliga et al., 1995). However, such subtly curved saccades and slightly deviated landing positions have not historically been reported in the types of visual world paradigm experiments reported above.

Given the fact that the arm is free to curve smoothly mid-flight, mouse-movement trajectories can, on a trial-by-trial basis, illuminate the degree to which a participant was garden-pathed during the processing of a syntactic ambiguity in the presence of a visual display. Below, we provide an integrative overview of the work detailed in Farmer et al., (2007a/b), in which trial-by-trial distributions of computer-mouse trajectory curvature in a garden-path condition were systematically examined. Unrestricted race accounts predict a bimodal distribution of garden-path magnitude values (either the correct analysis initially receives 100% of the activation based on the available information, or the incorrect analysis receives 100% of the activation and a separate reanalysis mechanism is engaged in response to disconfirming downstream information). Constraint-based models that rely on competition-integration as a mechanism of disambiguation, however, predict a continuous unimodal distribution of garden-path-magnitude values as a result of the trial-by-trial distribution of competition-based difficulty associated with the processing of a roughly equi-biased ambiguity.¹ The gradiency inherent to the movement-trajectories elicited in the “garden-path” one-referent ambiguous-sentence condition affords, on a trial-by-trial basis, the ability to examine that overall shape of a distribution of responses in the face of a syntactic ambiguity. And, it is this characteristic of computer-mouse movement trajectories that proffers the somewhat unique ability to discriminate different accounts where other more discrete and discontinuous dependent measures have been

¹ Due to space constraints, it is difficult to cover all of the information necessary to support the unimodal prediction that we argue is inherent to dynamic competition-based accounts of ambiguity resolution. The evidence supporting this claim comes primarily from a series of computational simulations, such as the one presented in study 2 of Farmer et al. (2007a).

less able to do so.

Experiments

In Farmer et al. (2007a/b), participants heard instructions containing temporary syntactic ambiguities (as in 1a) or unambiguous control sentences (1b), while looking at visual displays that contained either one (Figure 1, left) or two (Figure 1, right) referents for the referring expression (*the apple*), and arm movements were monitored via recording the streaming x,y coordinates of a computer mouse as they picked up an object and moved it to the destination corresponding to the ultimately correct interpretation of the ambiguity (see Farmer et al., 2007a/b for information about the details of the display layout, item information, and the presence of filler items). In critical trials for both the one- and two-referent conditions, the target referent (the apple on the towel, in example 1) always appeared in the top left corner of the screen, the incorrect destination (the empty towel) always appeared in the top right corner of the screen, and the ultimately correct destination (the box) was always located at the bottom right portion of the screen. The distracter object in the one-referent trials, and the second referent in the two-referent trials, always appeared in the bottom left corner of the screen.

Overall, the correct referent was almost always selected and moved to the ultimately correct destination. Each analyzable trajectory was time-normalized to 101 time-steps by interpolating the full set of recorded x,y coordinates spanning from its grab-click to its drop-click. All trajectories were then spatially aligned so that their first recorded point corresponded to x,y coordinates of (0, 0). Due to the horizontally elongated shape of the overall display, differences in x-coordinates of the mouse movements are somewhat more indicative of velocity differences, and differences in the y-coordinates are more indicative of genuine spatial attraction

toward the incorrect destination in the upper right corner (but see Farmer et al., 2007a for the details of a version of the experiment in which the movement on the target trials traversed a left-to-right horizontal movement plane, thus completely decoupling the effects of velocity and spatial attraction).

When only one referent was present (as in Figure 1, left), the average trajectory elicited by the sentences containing the temporary ambiguity curved significantly more toward the location on the screen consistent with the garden-path interpretation of the ambiguity (the empty towel at the top right corner of the display) than did the average trajectory in the unambiguous-sentence condition. Thus, in the one-referent ambiguous-sentence condition, the interpretation of the instruction associated with the incorrect destination was active enough to cause the average trajectory to veer toward it on the way to the ultimately correct destination, relative to the average trajectory produced in response to a baseline unambiguous control instruction (see Figure 2). This result is commensurate with the large increase in the number of looks to the incorrect destination when participants heard sentences containing a temporary ambiguity in the one-referent condition (Spivey, Tanenhaus, Eberhard, & Sedivy, 2002; Tanenhaus et al., 1995). No significant divergence between the ambiguous- and unambiguous- sentence trajectories, however, was detected when two potential referents were present, providing even more evidence that the presence of two potential referents in the visual context strongly reduces the tendency to garden-path when a temporary ambiguity is present. This result is consistent with the lack of any significant difference in looks to the incorrect destination in the ambiguous- versus the unambiguous-sentence condition in the two-referent context (Spivey et al., 2002; Tanenhaus et al., 1995).

Insert Figure 2 about here

Examination of the properties of the average movement-trajectories across the four conditions, then, highlights the fact that the garden-path effect and the referential context effect elicited by tracking eye-movements around a visual scene do replicate when tracking mouse-movements. But, the continuous, non-ballistic nature of arm-movements can provide information about the graded nature of underlying cognitive processes that often appear discrete when studied using methodologies that produce more discrete dependent measures. Accordingly, zooming in on the one-referent ambiguous-sentence condition, Figure 3 (top) displays each trajectory elicited in this condition (from Farmer et al., 2007b). Examination of Figure 3 reveals that although there are some trials where no garden-pathing occurred, and some trials where the incorrect analysis was strongly preferred but ultimately reversed (a strong garden-path), a majority of the trials elicited an intermediary graded amount of garden-pathing, as evident by various degrees of curvature toward the incorrect destination on the way to the ultimately correct destination.

Insert Figure 3 about here

On a trial-by-trial basis, we calculated the strength of a garden-path (or, the amount of manual attraction toward the incorrect destination in the one-referent ambiguous-sentence condition) by deriving a trajectory's area-under-the-curve value (or alternatively, each trajectory's maximum deviation from an idealized straight line, see Freeman & Ambady, 2010 for a comparison of the two values). When examining the area-under-the-curve (garden-path-

magnitude) values in a histogram (Figure 3, bottom), a continuous roughly normal distribution of garden-path values is evident. Visual inspection of the histogram reveals that the distribution of garden-path-magnitude values is not bimodal, although truly assessing a distribution for the presence of bimodality is quite difficult. Across Farmer et al. (2007a/b), however, a series of possibilities for such assessment are described. In each case, no bimodality was detected in the distribution of garden-path values in the garden-path condition. The shape of this distribution is what would be predicted by a constraint-based account of ambiguity resolution where parallel competition between simultaneously active representations takes place. The lack of bimodality in the distribution of trial-by-trial trajectory curvatures suggests that the garden-path effect is not an all-or-none phenomenon—the activation of one structural representation does not forbid simultaneous activation of other possible representations. Instead, the garden-path effect is graded, meaning that although sometimes one syntactic alternative may have greater activation than another, it is also the case that, until disambiguating information is presented, both can be considered in parallel, and the simultaneously active representations compete for activation over time.

Can Mouse-Movement Trajectories Even Pick Up a Discrete Representational Flip?

The results detailed above suggest that syntactic ambiguity resolution is a temporally dynamic parallel competition process, rather than a sequential selection-and-correction process. One potential criticism of the mouse-tracking methodology as implemented here, however, is that the continuous nature of goal-directed arm movement may be causing a discrete representational flip to appear continuous. That is, just as much as one might argue that discrete and discontinuous dependent measures such as saccades and button presses may have the ability

to make a continuous cognitive process appear discontinuous, it could be argued that a continuous dependent measure, such as a computer-mouse movement trajectory, may instead be masking a discrete cognitive process (sentiments of this argument are echoed in van der Wel, et al., 2009, addressed above). In a control experiment (Farmer et al., 2007a, Study 3), we investigated what average movement trajectories, and trial-by-trial distributions of them, should look like when a very obvious representational flip occurred versus a situation where a competitor was present. Participants were presented with three colored squares (see Figure 4) and were simply asked to “click on the green square.” In one condition, the top and bottom squares were red and the right-ward square was green. This condition is akin to an unambiguous sentence condition where no competition should occur. Coincidentally, average trajectories in this condition transcended the horizontal movement plane in a relatively straight (non-curved) manner.

 Insert Figure 4 about here

In another condition, the green square originally appeared at the top center of the screen, with the other two squares being red. However, as soon as the cursor exited the left-ward “Start” box, the green square turned red, and the left-ward square that was originally red became green. This condition corresponds to a situation where a strong discrete representational flip occurred, with participants initially committing to the ultimately incorrect movement and having to make a strong revision. In Figure 4, the average trajectories in this “garden-path” condition show a very strong initial movement to the original location of the green square, followed by a sharp re-direction toward the ultimate location of the green square. This movement pattern provides

compelling evidence that should a representational flip occur, as would be predicted by the unrestricted-race account on a certain proportion of trials, continuous arm-movement tracking can detect it. And, in a final condition, the bottom square was red, the right-ward square was green, and the top center square was a blue-green. Here, the blue-green square served the role of a competitor. In this “competition” condition, the average trajectory was smooth and curved toward the location of the competitor, providing an example of what the average trajectory shape should look like when there is a salient competitor in the visual display.

The results of this control study highlight the robust nature of the mouse-tracking methodology. The movement patterns (and corresponding trial-by-trial distributions) elicited by the competition, no competition, and the representational flip conditions reveal what types of movement patterns should be present under different models of language comprehension. And, when comparing these results to the movement patterns identified in the syntactic ambiguity studies, it is strikingly evident that the average movements elicited in one-referent ambiguous-sentence do not mirror that of the representational flip condition (as would be predicted by stage-based models of language comprehension), but instead appear identical to the condition where parallel competition between a target and distractor occurs (see Farmer et al., 2007a, for a discussion of the distributional analyses of the trajectory curvatures in each condition). By way of this relatively simple experiment, we have been able to demonstrate that computer-mouse movements can detect discrete representational flips should they be present (see Freeman et al., 2008 for another example of this type of control experiment), providing additional support for the role of a dynamic competition process, instead of a discrete serial selection-and-replace-when-needed process, as a mechanism of disambiguation during language comprehension.

Manual Motor Movement and Higher-Level Linguistic Processes:

Path Aspect Experiments

More recently, the mouse-tracking methodology has been extended beyond the two- and three-forced choice visual scenes used in previous research, providing a new way of investigating other higher-level language tasks within the visual world paradigm. Specifically, mouse-tracking has recently been used to examine the processing of different grammatical aspectual forms, a phenomenon that has proven difficult to examine using other methodologies (Madden & Zwaan, 2003). Grammatical aspect provides information about how events unfold in time. It provides information about the completion, duration, or repetition of actions or situations expressed by the verb (Comrie, 1976; Frawley, 1992). Take, for example, the following sentences: “David ran to the university,” and “David was running to the university.” Both convey information about a past event but they use different aspectual forms. The first sentence uses the perfective form, specifically simple past, of the verb “ran” to emphasize the completion of the action. The second uses the imperfective form, specifically past progressive, to emphasize the ongoing nature of that past event. Hereafter, we will refer to these as simple past and past progressive sentences, respectively. Even though aspect is known to shape the temporal “coloring” of a verb’s information, little is known about the dynamics of cognitive processing during comprehension of different aspectual forms.

Although grammatical aspect has been described very thoroughly in linguistics, it has been more difficult to assess how it is processed. One way of examining how different aspectual forms are processed differently has been to look at off-line responses (Matlock, Fausey, Cargill,

& Spivey, 2007). Participants read a sentence like “This morning David walked to the university” (simple past) or “This morning David was walking to the university” (past progressive), and saw a schematic drawing that showed a path leading to the destination described in the sentence and ten unevenly spaced identical silhouette characters on the path (e.g., pedestrian with leg extended forward and arms bent as if in motion). Participants were instructed to “circle the man that the sentence is most naturally referring to.” They were more likely to circle a character in the middle region of the path with sentences containing past progressive verbs (e.g., *was walking*), and more likely to circle a character in the latter region of the path in response to sentences containing a simple past verb (e.g., *walked*). A similar pattern emerged in a subsequent experiment where participants were asked to indicate where along the path an object had been dropped after reading simple past or past progressive sentences. These results demonstrate that when participants read simple past sentences, they focus on the end of the path, or the location of the completed action in the scene. In contrast, when participants read past progressive sentences, they focus on the middle section of the path, where the ongoing action would have taken place. These data indicate that different aspectual forms have consequences for thinking about motion events, but questions about processing remain.

Madden and Zwaan (2003) addressed the on-line processing of verbal aspect, showing that simple past and past progressive sentences create reaction time differences in narrative reading. In one experiment, participants were quicker to respond to pictures showing a completed action after they had read a simple past sentence (e.g., The car sped through the intersection) versus a past progressive sentence (e.g., The car was speeding through the intersection). However, no such latency differences arose when participants read sentences containing past progressive verbs and saw pictures of intermediate action. The authors suggest

that the effect was not significant in the past progressive condition because readers represented the ongoing action at different stages of completion. In other words, past progressive sentences could potentially correspond to any of a number of intermediate actions, and these diffuse possibilities were not captured by static visual stimuli used in the picture verification and reaction time tasks. These results suggest that different aspectual forms lead to processing differences in real time (for other work on aspect and spatial representation, see Ferretti, Kutas, & McRae, 2007; Magliano & Schleich, 2000; Morrow, 1985).

 Insert Figure 5 about here

Although the diffuse number of perceptual simulations corresponding to past progressive sentences have been difficult to detect with reaction time tasks, mouse-tracking easily allows researchers to examine how their processing differs from processing simple past sentences (e.g. Anderson, Matlock, & Spivey, 2013; see also Anderson, Matlock, Fausey, & Spivey, 2008). In one experiment, participants listened to sentences like, “Tom jogged to the woods and then stretched when he got there,” or “Tom was jogging to the woods and then stretched when he got there.” While participants heard these sentences, they saw scenes consisting of a path curving upwards from left to right, and terminating at the destination described in the sentence. A character was located to the right of the beginning of the path and under the destination, separated from the scene by a black box framing the destination and path (see Figure 5). The two aspectual forms elicited significantly different movement durations: participants spent a longer period of time moving the character into the scene with past progressive sentences than when they heard sentences containing simple past verbs. Additionally, the trajectories produced in

response to the simple past sentences were significantly smoother, and the x,y coordinates of the drop location were closer to the location consistent with the completed action. These data converge with earlier research, further supporting the idea that past progressive aspect focuses attention on the on-going nature of the action while simple past aspect focuses attention on the end state of that action, even during on-line processing.

Conclusion

The embodied cognition literature has emphasized the engagement of motor systems during linguistic processing, and the motor systems literature has helped to solidify claims about the co-extensive nature of cognition, on the one hand, and motor planning and execution on the other. Together these findings predict what has been borne out in action dynamics experiments: The more recent mouse-tracking literature has demonstrated the continuous interfacing that exists between cognitive processing and motoric behavior. By considering these literatures together, it has become increasingly clear that the dynamics of action do not simply reside in the aftermath of cognition. Rather, they are part and parcel with cognition, and the cognitive and motor systems are far more coextensive than previously imagined.

In light of all of the discussion about the benefits associated with the mouse-tracking methodology, it is important to note that there are also several drawbacks that deserve to be addressed when comparing mouse-movement trajectories to patterns of saccades to objects in the visual world. One concern is that the competition effects that are often observed in mouse-tracking tasks are dependent upon instructions to move. As a result, competition effects in mouse-tracking tasks are dependent upon response decisions (as sanctioned by task demands) whereas in experiments that examine eye-movements around a visual scene, the same types of

effects can be elicited without movement instructions (although we note that many eye-tracking visual world experiments do contain instructions to move). Another concern is that arm movements take longer to initiate and execute than do saccades, although just how much longer is not well documented. As a result, a sacrifice of time-course information—especially with respect to the immediacy of an effect of some variable on processing—is probably an inherent limitation of the dependent measure, relative to saccades. In the syntactic ambiguity experiments of Farmer et al. (2007a/b), for example, it wasn't possible to make strong claims about the immediacy of the visual context effect. Proponents of stage-based models, which typically propose syntactic heuristics as the sole guiding force in the initial interpretation of an incoming sequence, would simply argue that due to the delayed initiation time of an arm-movement, we have missed out on the early important cognition, and instead have picked up on gradiency that can be attributed to a later-stage re-analysis mechanism. In order to address this concern, we can only defer to the eye-movement data from studies such as Tanenhaus et al. (1995). In terms of time-course, the context effect in the two-referent condition is much more compelling when examining patterns of eye-movements around the visual world, providing data that are suggestive of an early effect of visual context.

In the same vein, given the quick programming time and low threshold for activation, saccades are likely to be less susceptible to strategic effects than are computer-mouse movements. In some tasks, especially ones that involve responding to a temporal stimulus that unfolds over time, participants may develop strategies whereby they slow down or delay movement until they are more certain about the correct target on which they are to click. Such a trend is problematic because after a strong decision about where to move has been made, one is substantially less likely to pick up on the activation of a distractor in a display. These issues are

more easily addressed in that mouse-tracking tasks can be programmed to discourage or forbid these types of strategic response patterns (see Farmer, Mehta, Liu, & Zevin, 2009, for an example of how to modify the design of an experiment to attenuate this concern, and also Freeman & Ambady, 2009, as an example of how to encourage participants to quickly initiate movement). We note that in some cases, the drawbacks associated with strategy-related concerns can be offset by the fact that mouse-movements can be tracked without a participant's explicit awareness. In eye-tracking tasks, on the other hand, participants are usually keenly aware that their eye-movements are being tracked.

As a result, we believe that eye-movements and mouse-movements around the visual world complement each other. Mouse-movements are, on a trial-by-trial basis, more continuous and thus afford a more straightforward depiction of gradiency in processing should it exist. Eye-movements may not be able to bring out this type of gradiency on a trial-by-trial basis very easily, but they probably provide a more immediate index of cognitive processing and are less susceptible to strategic effects. As such, researchers have typically conducted a thorough comparison between the mouse-movement record and the eye-movement record in order to gain the most detailed insight into processing in some domain. It may be the case, though, that tracking both eye- and hand-movements at the same time will be the best way to exploit the complementary aspects of the two dependent measures, and there are some recent attempts to time-lock both eye- and hand-movements to the time-course of an unfolding stimulus for this purpose (e.g. Farmer, Davidow, & McCandliss, 2009; Huette, Kello, Rhodes, & Spivey, 2013; Levy & Staub, 2012).

Although mouse-tracking experiments have become more and more common since Spivey et al. (2005), many domains are wide-open with respect to the potential usefulness of the

paradigm. One domain where this is particularly true is within the domain of cognitive development. Trueswell et al. (1999) documented the feasibility of using a head-mounted eye-tracker to investigate on-line language comprehension, and since then, many studies have used eye-movements around a visual display to explore multiple aspects of language processing in younger non-reading populations (e. g. Snedeker & Trueswell, 2004; Thothathiri & Snedeker, 2008). But, tracking eye-movements with younger children is not always an easy task. Head-mounted eye-trackers sometimes incur objections from parents, the equipment is not always easily portable, the data sometimes require slow hand-coding, and systems can be quite costly. Children are becoming more and more computer-literate at earlier and earlier ages. Evidence suggests that they can use a computer mouse at 3;6 years, on average, and that the onset of autonomous computer use is approximately 3;8 years (Calvert et al. 2005). This raises the possibility that recording computer-mouse movements around a visual display can serve as a cheap, portable, and accessible methodology that can be used to study complex cognitive phenomena in young children. Anderson, Farmer, Schwade, Goldstein, & Spivey (2011) recorded mouse-movements made by 5-year-olds in relation to sentences containing syntactic ambiguities (basically, the same visual world manipulation detailed above). They found that the same effects that had been identified in the same age group when tracking eye-movements (basically, a strong garden-path effect and no visual context effect) also manifested themselves in the movement trajectories elicited by the younger children. The fact that the trajectory data of Anderson et al. are commensurate with previously reported eye-tracking data lends support to the notion that the mouse-tracking method is feasible and reliable for documenting cognitive processing in young children.

In summary, tracking manual action during language processing is not just methodologically accessible, but also offers novel empirical discoveries of theoretical importance. Recently, a user-friendly software package—MouseTracker—was developed, allowing researchers to easily harness the power of the mouse-tracking methodology. A full outline and description of the software, as well as studies validating the accuracy and reliability of its data, are provided in Freeman and Ambady (2010). The software allows researchers to design and run experiments, and subsequently analyze the mouse-movement data in an intuitive, graphics-based manner. It supports many sophisticated forms of analysis and both simple and complex experimental designs, making mouse-tracking experiments easier than ever to conduct.

In this chapter, we have highlighted those theoretical insights in the domain of language processing, where the gradedness of action dynamics may help mitigate long-standing theoretical debates. We have argued that these data support continuous and interactive accounts of language processing. Certainly, debate on these issues will continue beyond this chapter, but we hope to have convinced readers that studying the coordination of manual action and language can play an important role in these continuing discussions. In fact, beyond language processing, Rosenbaum (2005) argues that closely investigating action and integrating it more fully with cognition (traditionally construed) will shed light on theoretical and practical issues across a broad swath of the psychological sciences.

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Figure Captions

Figure 1. An example of a one-referent (top) and a two-referent (bottom) display for the instruction “Put the apple (that’s) on the towel in the box.”

Figure 2. The averaged trajectories elicited by the ambiguous and unambiguous instructions. Substantial statistically reliable x- and y-coordinate divergence existed between the two sentence conditions in the one-referent context, but both the x- and the y-coordinates for the ambiguous- and unambiguous-sentence trajectories were statistically indistinguishable in the two-referent context.

Figure 3. Distributions of trajectory curvature in the ambiguous sentence conditions. Raw trajectories are on the top and a distribution of area-under-the-curve values are on the right.

Figure 4. Visuomotor Control study. The mean mouse-movement trajectory for the “Garden-path” condition shows a sharply-angled curvature, while the “Competition” condition shows subtle graded curvature, and the “Baseline” condition shows a genuinely flat trajectory.

Figure 5. Visual scene accompanying sound files in Anderson, Fausey, Matlock, & Spivey (2008).

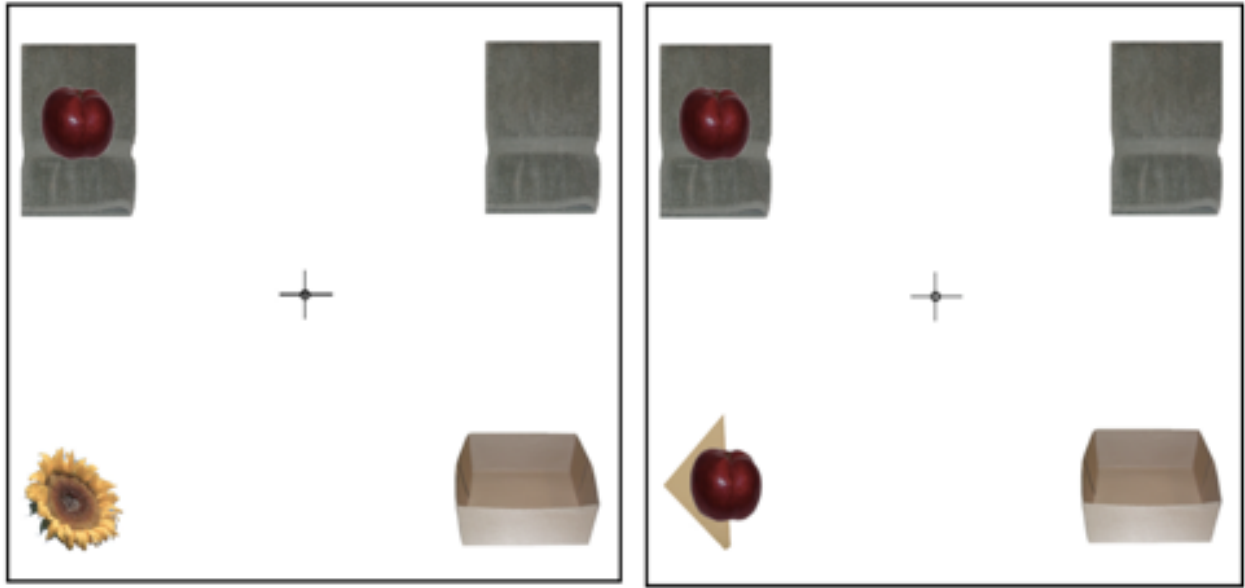


Figure 1.

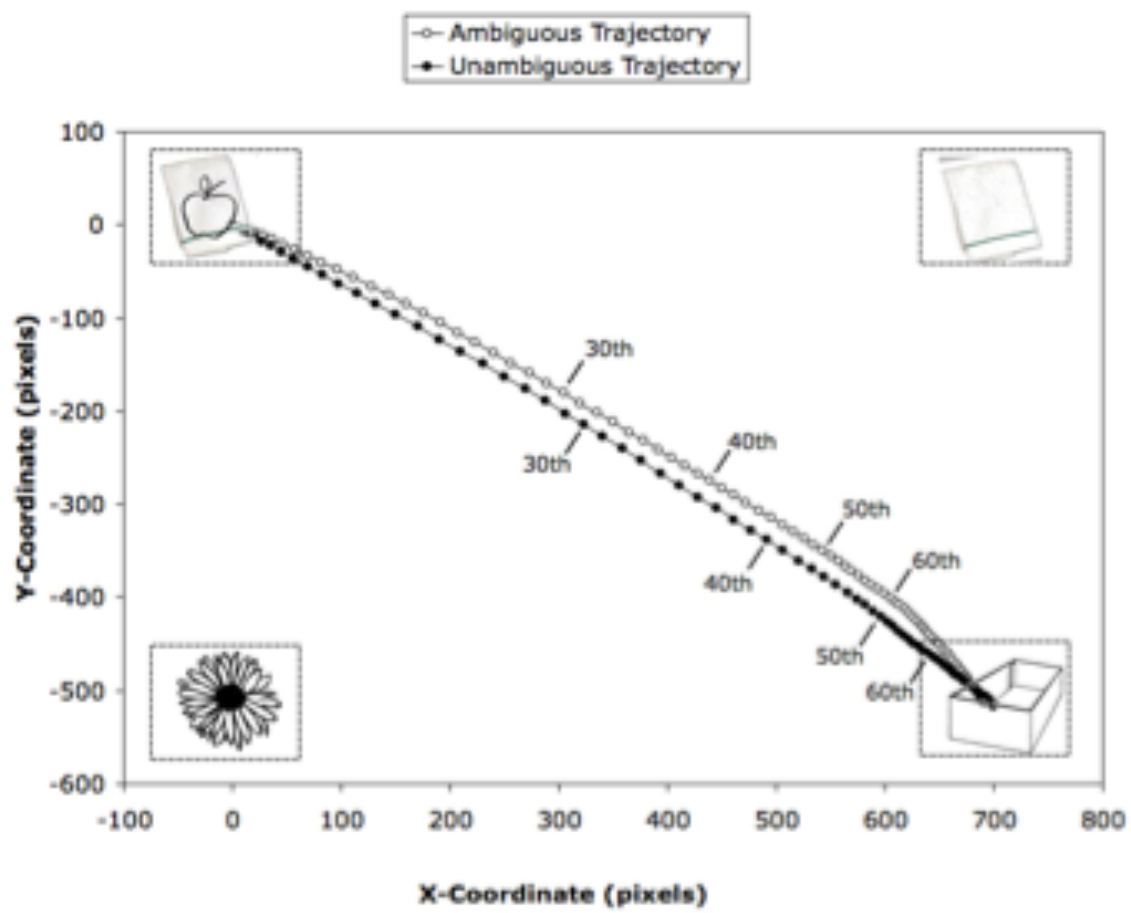
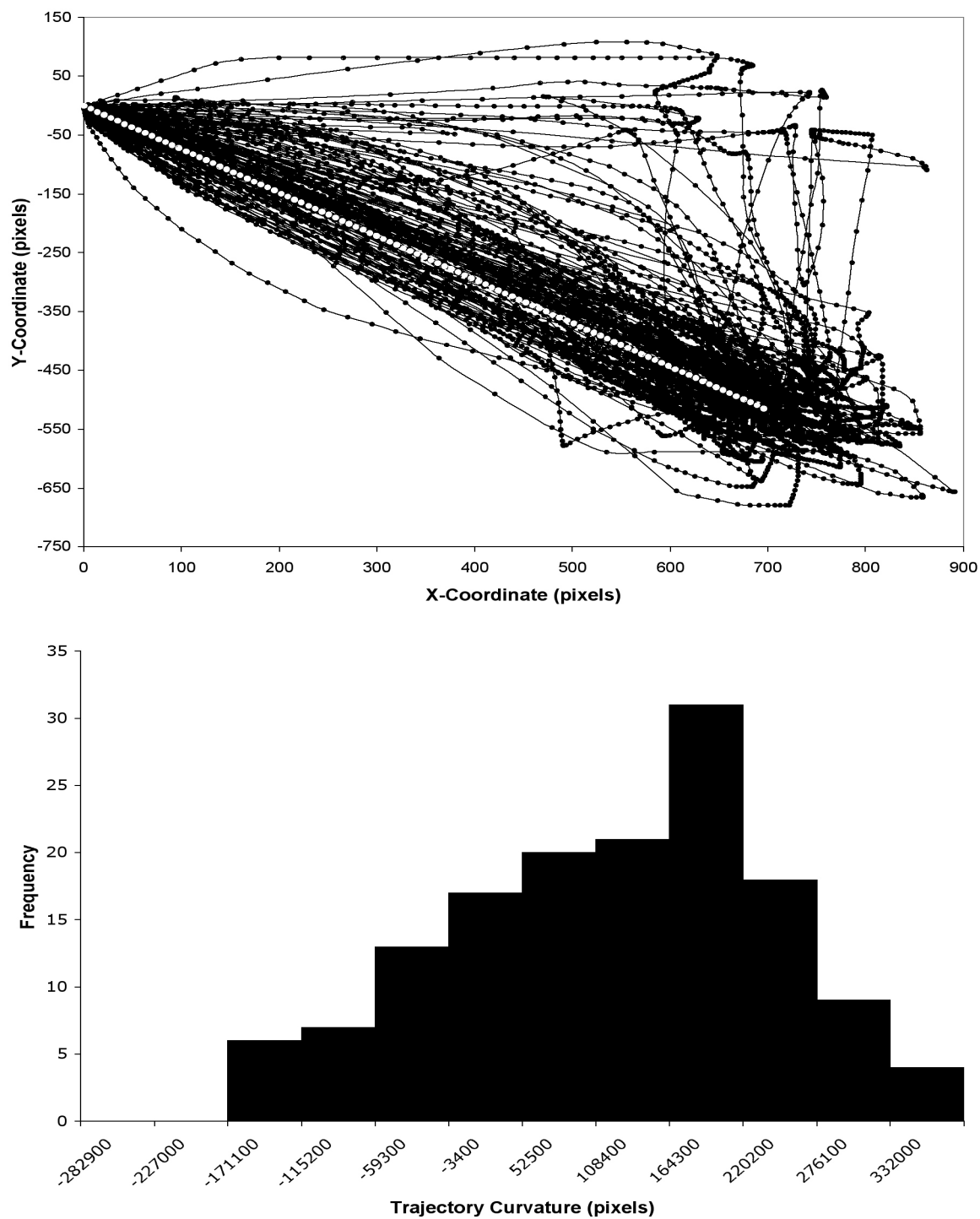


Figure 2.

*Figure 3.*

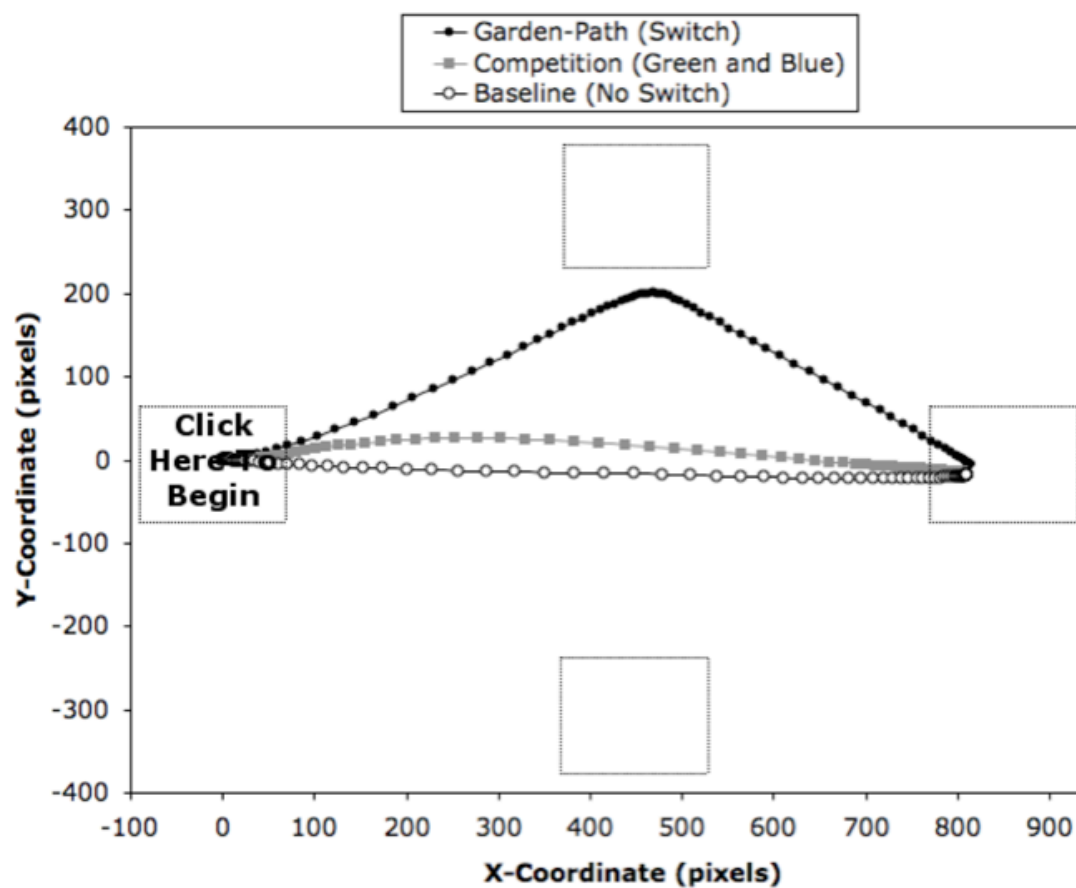


Figure 4.

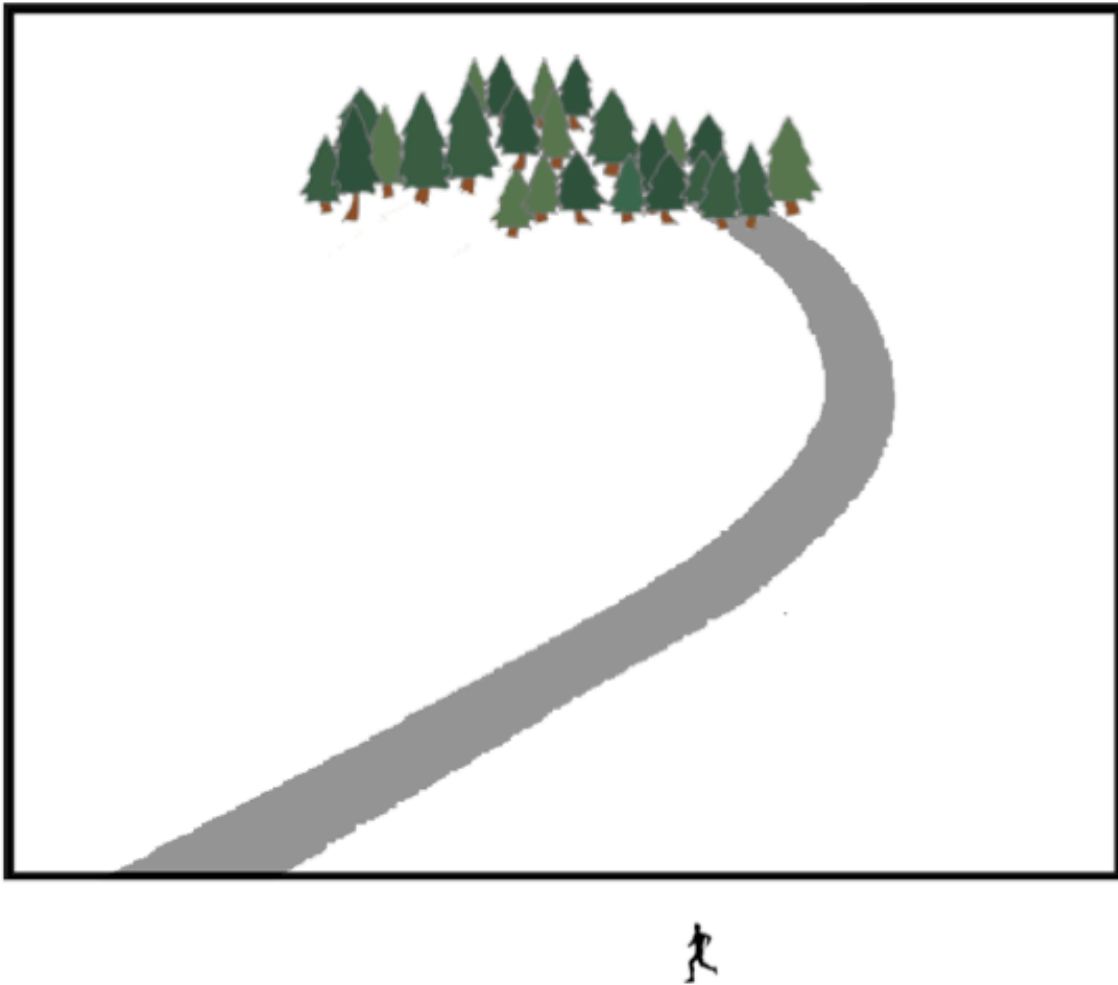


Figure 5.