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Gradiency and Visual Context in Syntactic Garden-Paths

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Abstract

Through recording the streaming x, y coordinates of computer-mouse movements, we report evidence that visual context provides an immediate constraint on the resolution of syntactic ambiguity in the visual-world paradigm. This finding converges with previous eye-tracking results that support a constraint-based account of sentence processing, in which multiple partially-active syntactic alternatives compete against one another with the help of not only syntactic, semantic, and statistical factors, but also nonlinguistic factors such as visual context. Eye-tracking results in the visual-world paradigm are consistent with theories that posit limited interaction between context and syntax, but they are still consistent with related theories that allow immediate interaction but require serial pursuit of syntactic structures, such as the unrestricted race model. To tease apart the constraint-based and unrestricted-race accounts of sentence processing, the distribution of computer-mouse trajectories was analyzed for evidence of two populations of trials: those where only the correct parse was pursued and those where only the incorrect parse was pursued. We found no evidence of bimodality in the distribution of trajectory curvatures. Simulations with a constraint-based model produced trajectories that matched the human data. A nonlinguistic control study demonstrated the mouse-tracking paradigm's ability to elicit bimodal distributions of trajectory curvatures in certain experimental conditions. With effects of context posing a challenge for syntax-first models, and the absence of bimodality in the distribution of garden-path magnitude posing a challenge for unrestricted-race models, these converging methods support the constraint-based theory's account that the reason diverse contextual factors are able to bias one or another parse at the point of ambiguity is because those syntactic alternatives are continually partially-active in parallel, not discretely winnowed.

Keywords

Syntax; Continuous; Dynamical; Language and Vision Interaction

What exactly is a garden-path? About three decades ago, the term was introduced to the psycholinguistic literature in describing what it feels like to have been led astray by syntactic preferences while reading a sentence. The reader reaches some later portion of the sentence, where the syntax and/or the semantics are no longer commensurate or sensible with how she's been parsing the sentence up to that point, and she feels as though she's has been "led down the garden-path." But is a garden-path due to the discrete computation of a mental representation that turns out to be inappropriate and must then be deleted and replaced by an alternative mental representation—as seen with discrete computing algorithms (e.g., Budiu & Anderson, 2004; Dietrich & Markman, 2003; Newell, 1990)? Or is a garden-path due to multiple partially-active mental representations simultaneously competing with one another—

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as seen with populations of neurons coalescing into a stable pattern over time (e.g., Desimone & Duncan, 1995; Rolls & Tovee, 1995; for review, see Spivey, 2007)?

Take, for example, Bever's (1970) famous garden-path sentence, "The horse raced past the barn fell." For novices, that sentence consistently elicits difficulty. They routinely conclude that the sentence is simply ungrammatical. Even once it is explained that the horse is not doing the racing independently, but is instead *being raced* by some unmentioned rider, and that it is the falling that the horse is doing independently, novices often protest that the sentence is still somewhat hard to process. But for the psycholinguistically trained, this sentence has become easy, indeed passé. Perhaps the novel sentences 1a–c can provide a little more freshness. These sentences use the very same syntactic structure as Bever's sentence about the horse. However, rather than causing the reader to exert equivalent amounts of effort in the pursuit of comprehension, they appear to span a continuum of difficulty in the degree to which the reader feels misled. Consider example sentences 1a–c below. Most readers tend to find example 1a to be the most problematic of these three for parsing as a reduced relative clause. In fact, for that sentence, 33 participants produced a mean acceptability rating (on a scale from 1 to 7) of 1.7 (Hare, Tanenhaus, & McRae, in press). The temptation to interpret the waiter as the agent of the serving event (which would force the reader down the path of constructing a simple main clause, and thus leave the verb *enjoyed* unattachable) is just too strong. In contrast, example 1c seems essentially unproblematic (as suspects are typically the logical objects of detaining events, and thus the reader is encouraged to pursue the relative clause construction). Its mean acceptability rating was 6.8 (Hare et al., in press). Crucial to our argument here, example 1b may feel somewhere in between these extremes. Indeed, Hare et al.'s participants gave this sentence a mean acceptability rating of 3.6. What does it mean for an individual garden-path effect to feel graded in its intensity?

1a) The waiter served a steak enjoyed it immensely.

1b) The lioness hunted throughout the night was pregnant with cubs.

1c) The suspect detained for questioning was later released.

Syntax-first models of sentence processing 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 (e.g., Ferreira & Clifton, 1986; Frazier, 1998; Frazier, & Rayner, 1982; Rayner, Carlson, & Frazier, 1983). Under such circumstances, either the initially-proposed structure was correct and a garden-path is not experienced, or it was incorrect and a garden-path is experienced while the recovery mechanism replaces the previous syntactic structure with a new one. As a result, one should expect that the reading of a sentence where a garden-path takes place and the reading of a sentence where one does not take place each belong to separate populations of events with different distributional properties.

Contrasting with that account, constraint-based approaches have proposed that statistical, semantic, and contextual biases converge the moment they become available in the input to bias multiple parallel syntactic structure alternatives, with a competition process adjudicating among the alternatives encountered at a point of syntactic ambiguity (e.g., Bates & MacWhinney, 1989; Elman, Hare, & McRae, 2004; MacDonald, Pearlmutter, & Seidenberg, 1994; McRae, Spivey-Knowlton, & Tanenhaus, 1998). 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. Thus, 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 single continuous distribution. Note that although syntax-first models do not predict the immediate effects of context that constraint-based models predict, they do readily accommodate this kind of gradiency in garden-path magnitude, attributing the varying difficulty to garden-path recovery processes in the re-analysis mechanism (e.g., Bornkessel, McElree, Schlesewsky, & Friederici, 2004; Fodor & Ferreira, 1998).

Recently, a sort of hybrid account has emerged that combines certain aspects of each of these theories. 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. Therefore, much like the syntax-first models, it 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. However, unlike syntax-first models, the unrestricted race model should also predict that roughly equi-biased syntactically ambiguous sentences will sometimes elicit a garden-path and sometimes not—thus producing two separate populations of events within the same experimental condition.

There is now a large body of research demonstrating rapid effects of biasing context on syntactic ambiguity resolution in reading (e.g., Altmann & Steedman, 1988; MacDonald et al., 1994; McRae et al., 1998; Spivey & Tanenhaus, 1998; Trueswell, Tanenhaus, & Garnsey, 1994). However, there is also considerable evidence supporting syntax-first models (e.g., Britt, Perfetti, Garrod, & Rayner, 1992; Clifton, Traxler, Mohamed, Williams, Morris, & Rayner, 2003; Ferreira & Clifton, 1986; Rayner, Garrod, & Perfetti, 1992). At the time of this writing, neither the data nor the computational models have succeeded in completely resolving the debate between constraint-based and syntax-first accounts. In the present context, we are more interested in discriminating between constraint-based models and unrestricted race models of language processing in the visual-world paradigm.

Recent research that is specifically aimed at teasing apart these two accounts has focused on showing that reading times for fully ambiguous sentences can be faster than those for disambiguated sentences (Traxler et al., 1998; van Gompel et al., 2001, 2005). This work has relied on the claim that constraint-based models could not accommodate such results, but this turns out to be an erroneous assumption (Green & Mitchell, 2006). Moreover, the reported ambiguity advantage is less apparent when end-of-trial questions encourage a more careful reading mode (Swets, Desmet, Clifton, & Ferreira, 2005).

The crucial distinction that does separate the constraint-based account from the unrestricted race account is the issue of gradiency in the garden-path itself. The constraint-based approach to sentence processing predicts that the full range of garden-path effects should belong to a single population with a unimodal distribution of “garden-path magnitude,” whereas the unrestricted race account (with its constrained probabilistic selection of a single syntactic structure) should predict a bimodal distribution of garden-path effects and non-garden-path effects. Since reading times of disambiguating regions in garden-path sentences constitute a continuous variable, one could, in principle, examine the histogram of reading times for garden-path sentences and test it for bimodality. However, one would need thousands of data points to provide an appropriate test of these alternative predictions, and most sentence processing

experiments involve about 30–40 participants each providing reading times for about 4–6 sentences in the ambiguous-sentence unsupportive-context condition.

Eye-movement data from the visual-world paradigm (e.g., Altmann & Kamide, 1999; Knoeferle & Crocker, 2006; Snedeker & Trueswell, 2004; Tanenhaus, Spivey-Knowlton, Eberhard, & Sedivy, 1995), which are typically interpreted as supporting constraint-based types of models, have not been able to directly address this gradiency issue because the analyses 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 can only either send 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, Riggio, & Rizzolatti, 1995). However, such subtly curved saccades and slightly deviated landing positions have not been measured in the visual-world paradigm.

What *can* readily show such a curved movement trajectory is a continuous reaching movement of the hand. 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, Péllisson, & Prablanc, 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; Tipper, Howard, & Jackson, 1997). Moreover, finger-pointing movements to colored targets show a temporally continuous graded influence from non-conscious color primes smoothly curving their trajectories (Schmidt, 2002).

Spivey, Grosjean, and Knoblich (2005) adapted this technique to record the streaming [x,y] coordinates of continuous computer-mouse movements for studying real-time 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 and 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. 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 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).¹

¹In eye-movement data from the visual-world paradigm, similar conclusions were made from the averaged curves of proportion of fixations over time of the target object and of the phonologically similar object (e.g., Allopenna, Magnuson, & Tanenhaus, 1998; Spivey-Knowlton, 1996).

With a similar visual display, this kind of continuous competition is also observed in computer-mouse trajectories toward semantic categories for taxonomic classes (e.g., Mammal and Fish), when participants are given atypical animal exemplars to classify (e.g., whale, seal) compared to typical members of those categories (e.g., horse and trout). Dale, Kehoe, and Spivey (in press) found that, in addition to greater overall curvature in trajectories for atypical animals, the very first time-step of mouse-cursor movement revealed a reliable angular difference between typical-animal responses and atypical-animal responses. Thus, in the atypical animal condition, the very onset of mouse movement was already exhibiting a mixture of spatial attraction toward both the competitor category and the correct category.

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). Moreover, Paninski et al. (2004) have demonstrated a tight link between the continuous dynamics of neuronal population codes in motor cortex and the continuous dynamics of hand movements. Thus, we suggest that, much like eye movements, continuous computer-mouse movements 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.

The purpose of the present work is to marshal converging evidence that will speak to this question of whether syntactic garden-path phenomena manifest themselves as a single continuous unimodal distribution of graded investment in the incorrect parse, or as a bimodal distribution of full-investment and of non-investment in the incorrect parse. Our primary piece of evidence (Study 1) comes from novel experimental results that measure real-time language comprehension in a visual context using continuous motor action: computer-mouse movements. Study 2 provides simulation results from a localist attractor-network model of competition between syntactic alternatives that are commensurate with the data from Study 1. Study 3 provides a litmus test of the mouse-tracking paradigm's ability to reveal a bimodal distribution of trajectory curvatures when the initial portion of a stimulus sequence temporarily misleads the participant. Overall, results support constraint-based models of sentence processing, where contextual influences are immediately brought to bear in resolving syntactic ambiguities and simultaneous partial activation of the mutually exclusive syntactic alternatives results in continuous gradations of garden-path magnitude.

Study 1

In Experiment 1, we exploit the continuous nature of mouse-movement trajectories, in relation to the visual-world paradigm (Chambers, Tanenhaus, & Magnuson, 2004; Snedeker & Trueswell, 2004; Spivey, Tanenhaus, Eberhard, & Sedivy, 2002; Tanenhaus et al., 1995), in order to examine the nature of graded spatial attraction toward an object corresponding to a competing, but ultimately incorrect, syntactic representation. Preliminary findings in computer-mouse tracking of sentence processing (Farmer, Cargill, Hindy, Dale, & Spivey, 2006) have indeed shown effects similar to those found with eye-tracking (Spivey, et al., 2002; Tanenhaus, et al., 1995). When a participant is given an instruction like that in example 2a, and there is only one apple on the screen (one-referent condition), there exists a tendency to drag the apple slightly toward the towel on the way to dropping it in the box (Farmer et al.,

2006)—matching the high frequency of eye movements to the towel in that condition seen with eye-movement measures (Spivey, et al., 2002; Tanenhaus et al., 1995). This trajectory curvature toward the incorrect destination object (corresponding to an incorrect parse that attaches the first PP to the verb phrase) is essentially absent when the instruction is unambiguous, as in example 2b. (Since there is only one apple in this context, this PP-attachment amounts to an “over-specification” that does not conform well to Gricean maxims. However, this over-specification is held constant across ambiguous and unambiguous conditions, so it should not be responsible for any garden-path effects.) The role of visual/situational context is robustly demonstrated when the display contains two apples (two-referent condition). In this context, participants’ trajectories for ambiguous and unambiguous instructions are statistically indistinguishable, indicating that the visual context greatly reduced the activation of the incorrect syntactic structure.

2a) Put the apple on the towel in the box.

2b) Put the apple that’s on the towel in the box.

Although those preliminary data are promising, concerns remain with respect to the spatial and temporal comparisons of the x-pixel and y-pixel components of the trajectories in that initial experiment. In order to directly parallel the experimental trials from eye-tracking studies of the visual world, Farmer et al. (2006) placed the correct referent in the top left-hand portion of the screen, and the correct destination at the bottom right-hand portion of the screen. As a result, the diagonal downward-rightward movement conflates velocity toward the correct destination with spatial attraction toward the incorrect destination. That is, changes in x-coordinates do not only indicate velocity, and changes in y-coordinates do not only indicate attraction toward the incorrect destination. Thus, when a significant divergence between average ambiguous- and unambiguous sentence trajectories in the one-referent context is detected, it is unclear whether the divergence is caused by velocity differences between the two sentence conditions, or if genuine spatial attraction toward the incorrect destination is the source the statistically significant difference.

In the present study, a new version of the experiment involves a layout of objects where the correct mouse-movement is a purely horizontal trajectory, traversing from the left side of the screen to the right side, thereby allowing x-pixel analyses to solely reflect velocity. The incorrect destination was at the top center of the display. Therefore, any upward deflection from the horizontal movement plane reflects spatial attraction toward the incorrect object at the top of the screen, independent of velocity. Motivated by constraint-based accounts of sentence processing, we predicted the following: a) that the average ambiguous-sentence trajectory in the one-referent context would curve upward toward the incorrect destination, reliably more so than the average unambiguous-sentence trajectory, and b) that no such divergence would occur in the two-referent context. Additionally, and more important to the main goal of this present paper, we also predicted that the distribution of trajectory-curvatures in the one-referent ambiguous-sentence condition (the garden-path condition) would yield a unimodal distribution, underscoring the notion that the garden-path effect is a graded phenomenon.

Method

Participants

Thirty-three Cornell undergraduates ($M = 19.97$ years, $SD = 1.2$) participated in this experiment for extra-credit in a psychology course. All participants were native English-speakers and all were right-handed.

Materials

The stimuli were presented using Macromedia Director MX, and mouse movements were recorded at an average sampling rate of 40 Hz. The display resolution was set to 1024×768 . Sixteen experimental sentences, 104 filler sentences, and 40 visual contexts, adapted from Spivey et al. (2002), were combined to form 40 trials, each with one visual scene and three sentences. During an experimental trial, the experimental sentence preceded two filler sentences. In each of the 24 filler trials, three filler sentences were presented.

Spoken instructions were recorded from one male speaker using Mac-based digital-audio recording software. For the experimental sentences, the unambiguous versions (2b) were recorded, and the ambiguous versions (2a) were then created by editing out the word “that’s” from the unambiguous sentences. By creating the target sentences in this way, the resulting ambiguous and unambiguous versions of a sentence frame had nearly identical prosodies, eliminating the influence of prosodic cues to the attachment site of the ambiguous PP within each ambiguous-unambiguous sentence-pair. The sound files were proofed by two independent listeners and were re-recorded if there were any questions regarding accent, prosody, or the quality of the region in the sound file where “that’s” was removed.

Each visual context was composed of 4–6 objects, depending on the set of spoken instructions. A total of 52 objects were used in the visual scenes, and the images of these objects were created using a digital camera and were edited using Adobe Photoshop. Each object subtended an average of 6.5 degrees of visual angle in width by 5 degrees in height. The objects that could be used as a potential destination tended to be slightly larger (9.5 degrees in width by 6 degrees in height) than the potential referent objects (3.5 degrees in width by 4 degrees in height). All objects were again proofed by two other individuals and were reformulated if the image was ambiguous or distracting (due to loud colors or busy patterns).

Objects in each visual scene were presented in a diamond array (Figure 1). Objects on the left and right portions of the screen were positioned 14.6 degrees of visual angle from the center of the display, and objects in the upper and lower portions of the screen were positioned 10.6 degrees of visual angle from the center of the screen. Each version of the 16 experimental items required participants to move an object from the left-hand side of the display to the right-hand side of the display. As such, the exact center, in pixels, of each object appearing on the left- and right-handed portions of the screen always had the same y-coordinates, ensuring that no asymmetry existed in the alignment of the objects positioned on the horizontal movement plane.

Each of the sixteen experimental visual contexts was altered in order to produce a one-referent context and a two-referent context. For example, the one-referent visual context corresponding to sentences 2a and 2b consisted of a target referent (an apple on a towel) on the left side of the display, a correct destination (the box) on the right side of the display, an incorrect destination (an empty towel) at the top of the display, and a filler object (the flower) at the bottom of the display, as illustrated in Figure 1 (top panel). For the two-referent contexts, the locations of the target referent, the correct destination, and the incorrect destination were the same. However, instead of a distracter item appearing at the bottom center of the display, a second potential referent was included (an apple on a napkin), as illustrated in Figure 1 (bottom panel). In both visual contexts, the distance from the target referent to the incorrect destination was 16.1 degrees of visual angle, and to the correct destination was 25.7 degrees of visual angle.

Following Spivey, et al. (2002), the movements required to complete the remaining 104 filler commands were designed to avoid any movement-based statistical regularities. In addition to the movement used in the target commands, eleven distinct movements were possible in the visual context, and an approximately equal number of filler sentences (either eight or ten) were

assigned to each of these movements. For example, ten sentences required an object to be moved from the right-hand portion of the display to the bottom of the display, and eight sentences required an object to be moved from the top of the display to the bottom of the display, etc. Across the full set of instructions, we balanced the relative proportions of PPs attaching to the noun phrase and to the verb phrase, as well as the relative proportions of single-PP and double-PP sentences (for details, see Spivey et al., 2002).

Both levels of the Context variable were crossed with both levels of the Ambiguity variable, yielding four versions of each of the 16 experimental items. Four presentation lists were created, and the four versions of each experimental item were counterbalanced across those four lists such that each list contained four instances of each possible Context $\times$ Ambiguity combination, but only one version of each item. Participants were randomly assigned to one of the four possible presentation lists, and the order of filler- and experimental-sentence presentation occurring within a list was randomized per participant.

Procedure

Participants were asked to make themselves comfortable in front of the computer screen, adjusting the mouse and mouse-pad to a location on the right-hand side that suited them. First, participants read brief instructions, and upon signaling to the experimenter that they understood the task, were next presented with three practice trials (similar in form to the filler trials), followed by the experimental task. At the onset of each trial, participants were presented with the whole scene with the addition of a central cross. After a 500 ms preview period, participants heard the initial command, "Place the cursor at the center of the cross." One second after the offset of this command, the central cross disappeared and the first of the triplet of object-movement instructions began to play. Four seconds separated the offset of the each instruction from the onset of the next. At the end of the third instruction, a "Done" button appeared at the bottom of the screen, which participants clicked to signal that they were ready to move on the next trial. The entire experiment took approximately 25 minutes.

Results

Data Screening and Coding

Mouse movements were recorded during the grab-click, transferal, and drop-click of the referent object in the experimental trials. As a result of the large number of possible trajectory shapes, the x, y coordinates for each trajectory from each experimental trial were plotted in order to detect the presence of any aberrant movements. A trajectory was considered valid and submitted to further analysis if it was initiated at the center left region of the display and terminated in the center right region, indicating that the correct referent had been picked-up and then eventually placed at the correct destination. This screening procedure resulted in the exclusion of 28 trials, accounting for 5.3% of all experimental trials. A 2 (Context) $\times$ 2 (Ambiguity) ANOVA on the number of included trials per condition yielded no significant main effect of context, $F_1(1, 32) = .139$, n.s., $\min F'(1, 47) = .09$, n.s., or 2-way interaction, $F_1(1, 32) = .162$, n.s., $\min F'(1, 23) = .03$, n.s. There was, however, a significant main effect of ambiguity, $F_1(1, 32) = 13.91$, $p < .05$, $MSE = .218$, $\min F'(1, 35) = 5.56$, $p = .024$, with more trajectories included per participant in the unambiguous ($M = 7.88$, $SD = .33$) than in the ambiguous ($M = 7.27$, $SD = .80$) conditions. The fact that more trials were excluded in the ambiguous conditions is not surprising in light of the increased difficulty associated with the processing of these sentences. Importantly, a majority of the ambiguous-sentence trajectories that were excluded contained aberrant movements of the correct referent that can be characterized best as oscillating between rightward movement and leftward movement, with the correct referent either making it eventually to the correct destination or not. No participant

was excluded from subsequent analyses given that all participants produced at least 13 interpretable trajectories out of the 16 experimental trials ($M = 15.15$, $SD = .80$).

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). As noted previously, due to the horizontal alignment of the target referent and the correct destination, the x-coordinates of the elicited trajectories are solely indicative of velocity toward the correct destination, and the y-coordinates are solely indicative of spatial attraction toward the incorrect destination. As such, x- and y-coordinates were analyzed separately. Importantly, given the spatial alignment of the trajectories to point (0, 0), y-coordinates falling below the horizontal plane at the center of the screen have negative values, whereas the coordinates recorded above the horizontal plane have positive values (see Figure 1).

It is worth noting that mouse movements tend to be initiated slightly later than eye movements. Therefore, there can be some concern regarding exactly when, with respect to the timing of the speech stream, the mouse began to move. In order to investigate this, we recorded the exact millisecond within each sound-file at which each trajectory was initiated. Across the four conditions, approximately 70–75% of the trials had their mice in motion while the speech file was still playing, and 85–95% of mouse movements were initiated within two seconds of the onset of the second PP (up to 750 ms after the end of the sentence). When the duration of the mouse-movement itself is included (about two seconds on average), this temporal range is about the same temporal range over which eye movements are typically analyzed for these kinds of sentences in the visual-world paradigm (Chambers et al., 2004; Spivey et al., 2002). Therefore, we conclude that these mouse-movement data are sufficiently on-line with respect to the delivery of the spoken instructions to provide evidence on par with the existing eye-movement data—corresponding approximately to the time range of the second, third, and fourth eye movements during task completion.

The Context and Garden-path Effects

Figure 1 illustrates the average ambiguous-sentence and unambiguous-sentence normalized trajectories in the one-referent (top panel) and two-referent (bottom panel) displays. In the one-referent context, there appears to be both a velocity and a spatial attraction difference between the average ambiguous and unambiguous trajectories. Notably, the unambiguous trajectories appear to arrive at the correct destination more quickly than the ambiguous trajectories, and the average ambiguous-sentence trajectory curves more toward the top of the screen (toward the incorrect destination) than its unambiguous counterpart. Both of these observations support the notion that participants were garden-pathed in the scenes where only one referent was present. In the two-referent scene, however, there is no evidence of spatial attraction when comparing the average ambiguous- and unambiguous-sentence trajectories, indicating an elimination of the garden-path effect by referential context.

To determine whether any divergences observed across the ambiguous- and unambiguous-sentence trajectories in the one- and two-referent contexts were statistically reliable, our initial analysis involved a series of paired-sample *t*-tests. The *t*-tests were conducted across the x-coordinates of each sentence condition, and across the y-coordinates of each sentence condition, separately, per context condition, at each of the 101 time-steps. In order to avoid the increased probability of a Type-1 error associated with multiple comparisons, and in keeping with Bootstrap simulations of such multiple *t*-tests on mouse-trajectories (Dale et al., in press), an observed divergence was not considered significant unless the coordinates between the ambiguous- and unambiguous-sentence trajectories elicited *p*-values $< .05$ for at least eight consecutive time-steps.

In the one-referent context, the x-coordinates of the average ambiguous- and unambiguous-sentence trajectories differed significantly from time-step 21 all the way to time-step 79, all t 's > 2.06 , all p 's $< .05$. The average effect size, indicated by Cohen's d , was .495, a medium-sized effect in the context of Cohen's benchmarks for effect size (Cohen, 1988). At each of the 59 time-steps in which a significant difference between the ambiguous- and unambiguous-sentence trajectories was observed, the x-coordinates for the unambiguous-sentence trajectories were always higher (that is, they were always further to the right of the screen where the correct destination was located) than they were for the ambiguous-sentence trajectories, indicating a higher velocity of movement, much like that seen with continuous motor responses to high and low frequency words (Abrams & Balota, 1991). Comparisons of the y-coordinates between the ambiguous- and unambiguous-sentence trajectories yielded significant differences from time-step 12 through time-step 72, all t 's > 2.043 , all p 's $< .05$, average effect size $d = .502$. Thus, very early on in the movement, participants began to exhibit significant spatial attraction toward the incorrect destination. At each of the 51 time-steps in which a significant difference was observed, the y-coordinates were always higher (closer to the location of the incorrect destination at the top of the screen) for the ambiguous-sentence trajectories, suggesting that significant activation of the competing syntactic structure was causing spatial attraction toward the garden-path object.

In the two-referent condition, comparisons of the y-coordinates from the ambiguous-versus unambiguous-sentence trajectories never yielded a single p -value $< .05$ across any of the 101 time-steps. Thus, it appears that in the two-referent context, there was little activation of the competing incorrect interpretation. Interestingly, there was an early but short-lived x-coordinate divergence from time-steps 8 through 21, all t 's > 2.06 , all p 's $< .05$, average effect size $d = .434$, with the x-coordinates in the ambiguous-sentence trajectories being closer to the correct destination than the unambiguous-sentence trajectories. This early x-coordinate differential may reflect the fact that in the unambiguous-sentence condition, the delivery of the goal PP in the speech stream is delayed slightly by the word "that's".

To assess directly the statistical reliability of the Context $\times$ Ambiguity interaction, we grouped the time-normalized trajectories into four time bins, time-steps 1–25, 26–50, 51–75, and 76–101, yielding a third independent variable of time segment. We then conducted two separate 2 (Context) $\times$ 2 (Ambiguity) $\times$ 4 (Segment) repeated-measures ANOVAs, one for velocity (x-coordinates) and one for spatial attraction (y-coordinates). The three-way interaction was significant for the x-coordinates, $F_1(3, 96) = 5.30$, $p = .002$, $MSE = 2661$, $\min F'(3, 135) = 3.10$, $p = .029$, and for the y-coordinates, $F_1(3, 96) = 2.89$, $p = .039$, $MSE = 128$, $\min F'(3, 68) = .57$, n.s. As is evident in Figures 1 and 2, and as demonstrated by the t -tests above, the effect is especially prevalent among the points comprising time-segments two and three. As such, only follow-up comparisons at time-segments two and three are considered in further detail here.

To assess the context effect, we compared each point in the one-referent context to its corresponding point in the two-referent context, in time-segments two and three. The means and standard errors associated with each data-point appear in Figure 2, and the confidence intervals reported with each pairwise comparison are the 95% confidence intervals for the mean difference. For the x-coordinates (indicating velocity toward the correct destination), unambiguous sentences showed no difference between the one-referent context and the two-referent context at segment two, $t(32) = .126$, n.s., 95% CI = 49.75, or segment three, $t(32) = .867$, n.s., 95% CI = 36.15. However, ambiguous sentences showed a significant velocity difference at segment two, $t(32) = 4.06$, $p < .0005$, $d = .707$, 95% CI = 54.33, and at segment three, $t(32) = 4.63$, $p < .0005$, $d = .798$, 95% CI = 35.20. As illustrated in Figure 2 (top panel), the x-coordinates for the ambiguous-sentence trajectories in the two-referent context were closer to the correct destination than they were in the one-referent context at each segment. For the y-coordinates (indicating spatial attraction toward the incorrect destination),

unambiguous sentences again showed no difference in average screen location between the one- versus two-referent context at segment 2, $t(32) = .99$, n.s., 95% CI = 7.50, or at segment 3, $t(32) = 1.22$, n.s., 95% CI = 9.93. However, ambiguous sentences did show a spatial attraction difference at segment two, $t(32) = 2.95$, $p = .006$, $d = .513$, 95% CI = 13.89, and at segment three, $t(32) = 2.56$, $p = .015$, $d = .460$, 95% CI = 13.24, with the y-coordinates in the one-referent condition being closer to the incorrect destination at each segment.

In assessing the ambiguity effect, for the x-coordinates, there was no significant difference between ambiguous- and unambiguous-sentence trajectories in the two-referent context at segments two or three, $t(32) = .90$, n.s., 95% CI = 45.44, and $t(32) = .38$, n.s., 95% CI = 24.32, respectively, but there was in the one-referent context at segments two, $t(32) = 3.39$, $p = .002$, $d = .590$, 95% CI = 51.16, and three, $t(32) = 2.96$, $p = .006$, $d = .513$, 95% CI = 41.36, with x-coordinates from the unambiguous-sentence trajectories being closer to the correct destination (Figure 2, top panel). For the y-coordinates, there was no significant difference in screen location between ambiguous- and unambiguous-sentence trajectories in the two-referent context at segments two and three, $t(32) = .49$, n.s., 95% CI = 10.74, and $t(32) = 1.21$, n.s., 95% CI = 12.78, respectively. However, in the one-referent context, the y-coordinates for the ambiguous-sentence trajectories were significantly closer to the incorrect destination (top of screen) than were the y-coordinates for the unambiguous-sentence trajectories at segment two, $t(32) = 3.53$, $p = .001$, $d = .613$, 95% CI = 10.98, and at segment three, $t(32) = 2.51$, $p = .017$, $d = .423$, n.s., 95% CI = 14.85.

Raw Time Analyses

Given that the trajectories above were time-normalized, the previous analyses do not provide information about when, in relation to the speech-stream, the x- and y-coordinates of the ambiguous-sentence trajectories diverged significantly from those of the unambiguous-sentence trajectories in the one-referent context. In eye-tracking studies that employ a similar manipulation, it has become customary to examine the percentage of looks to the incorrect destination that occur in each of a number of equally-spaced time-bins. Commensurate raw-time analyses are difficult here, however, because trajectory-initiation time varied considerably from trial to trial. A trajectory that was initiated in the one-referent ambiguous-sentence condition 200 milliseconds after the onset of the second PP, for example, is considerably misaligned with a trajectory that was initiated 1000 ms past the second PP onset. Because attraction toward the incorrect destination is not immediate, this misalignment exerts downstream effects whereby the coordinates of trajectories that are initiated in later time-bins (where little attraction has yet to occur) are averaged with the coordinates of earlier-initiated trajectories (where spatial attraction is currently occurring), thus dampening the effect of ambiguity in the one-referent context.

In order to enforce some degree of temporal alignment among the raw-time trajectories, we examined only those trajectories that were initiated before the estimated end-of-sentence time for the longest instruction (2955 ms). By this inclusion criterion, 60% of all experimental trials were included, consisting of 73.11% of the trajectories in the one-referent ambiguous-sentence condition, 52.31% in the one-referent unambiguous condition, 76.47% in the two-referent ambiguous condition, and 36.72% in the two-referent unambiguous condition. To provide a time-course analysis of when during the speech stream the graded spatial attraction toward the garden-path destination emerged, we then examined each of the four 200-ms time-bins occurring between 600 and 1400 ms past the onset of the second PP. This range of time bins corresponds to the central portion of the period of time (during and shortly after the second PP) where previous eye-tracking results have shown the most fixations of the garden-path destination (e.g., Chambers et al., 2004; Spivey et al., 2002; Tanenhaus et al., 1995).

In the one-referent condition, although x-coordinate divergence between the ambiguous and unambiguous-sentence trajectories did not occur 600–800 ms past the onset of the second PP, there was significant divergence at the 800–1000 ms bin, $t(23) = 2.69$, $p = .013$, $d = .55$, 95% CI = 75.02, the 1000–1200 ms bin, $t(25) = 5.59$, $p < .0005$, $d = 1.08$, 95% CI = 73.75, and the 1200–1400 ms bin, $t(26) = 7.19$, $p < .0005$, $d = 1.38$, 95% CI = 72.65, with trajectories in the unambiguous-sentence condition being closer to the correct destination on the right than trajectories in the ambiguous-sentence condition. (The df values for each comparison differ because a participant could only be included in the analysis if they had initiated at least one trajectory in both the ambiguous- and unambiguous-sentence conditions at the time-bin of interest.) Marginally significant y-coordinate divergence occurred in the one-referent condition at the 600–800 ms time-bin, $t(18) = 1.97$, $p = .064$, $d = .45$, 95% CI = 17.11, and the 800–1000 ms bin, $t(23) = 1.99$, $p = .059$, $d = .405$, 95% CI = 16.95. Significant divergence did occur in the y-coordinates of the ambiguous- versus the unambiguous-sentence trajectories in the 1000–1200 ms time-bin, $t(25) = 2.31$, $p = .03$, $d = .453$, 95% CI = 18.67. In all cases, the y-coordinates were closer to the incorrect destination at the top of the screen in the ambiguous-sentence condition than in the unambiguous-sentence condition, and there was no significant y-coordinate divergence at the 1200–1400 ms time-bin.

In the two-referent condition, however, both the x- and y-coordinate comparisons between ambiguous- and unambiguous-sentence trajectories showed no significant divergence occurring at any of the four time-bins of interest. Within this subset of the data, then, it seems that the crucial spatial attraction effect (i.e., graded garden-path) is occurring in the one-referent ambiguous-sentence condition at around one second past the onset of the second PP. This result is commensurate with what has been seen with similar stimuli in the visual-world paradigm in previous eye-tracking studies (e.g., Chambers et al., 2004; Spivey et al., 2002), where a steady increased level of fixations of the incorrect destination is routinely observed from about 300 to 2000 milliseconds after the onset of the second prepositional phrase.

Distributional Analysis

In addition to demonstrating that mouse-tracking can reveal a visual context's modulation of syntactic garden-path effects, a principal goal of the present study was to examine the distribution of trajectory curvatures in the garden-path condition (one-referent context, ambiguous-sentence). Evidence for bimodality in the distribution of this critical garden-path condition would provide confirmation that some trials involved discrete selection of the incorrect syntactic structure while others involved discrete selection of the correct syntactic structure, as predicted by the unrestricted race account of syntactic ambiguity resolution (Traxler et al., 1998; van Gompel et al., 2001, 2005). In contrast, evidence that the distribution is unimodal would provide support for constraint-based models of sentence processing, where garden-path effects are the continuously graded results of simultaneously partially-active syntactic alternatives competing over time (Elman et al., 2004; Green & Mitchell, 2006; MacDonald et al., 1994; McRae et al., 1998; Tabor & Tanenhaus, 1999). Bimodality in this distribution was initially assessed by visually examining the trial-by-trial overlay of trajectory curvatures from the 119 trials in this garden-path condition. As evident in Figure 3, there is a small handful of extreme “garden-path” trials where the trajectory passed over the incorrect destination object before changing direction to move toward the correct destination. However, the vast majority of mouse trajectories that are responsible for moving the mean time-normalized trajectory into the upward bend seen in Figure 1 (upper panel) are quite subtle and graded in their curvature. Importantly, there does not appear to be two separate populations of trajectories (e.g., one sizeable group that is essentially straight and horizontal, and another sizeable group that exhibits initial movements toward the incorrect destination followed by corrective turns toward the correct one), as should be predicted by theories that posit immediate

probabilistic selection of a single syntactic alternative (Traxler et al., 1998; van Gompel et al., 2001, 2005).

In order to perform statistical tests for bimodality, it was necessary to quantify the magnitude of the garden-path effect within each trial of this one-referent ambiguous-sentence condition. Therefore, we calculated the signed maximum deviation value for each trial by first imposing a straight line from each trajectory's starting point to its endpoint, and then extracting the one point in the observed trajectory with the largest y-coordinate divergence from the straight line. Maximum deviation, in pixels, where the trajectory was above its straight line (tending toward the incorrect destination) was coded as positive, and deviation values produced by trajectories falling below their straight lines were coded as negative. This maximum deviation calculation produces a single value for each trial, indicating the degree of spatial attraction toward the incorrect destination. Using this maximum deviation value, we then plotted a histogram of garden-path-strength values in the 119 trials from this experimental condition and observed that there exists no immediately visible evidence of bimodality in the distribution (Figure 4a).

Darlington (1970) noted that an important index of possible bimodality in a distribution is kurtosis (a combination of "peakiness" and "heavy-tailedness" in a distribution). He suggested that a good rule of thumb is that when kurtosis < -1.2 , the distribution may have come from two different populations. For non-symmetric distributions, later work expanded this measure to include both skewness and kurtosis in the bimodality coefficient (DeCarlo, 1997; SAS Institute, 1989): $b = (\text{skewness}^2 + 1) / (\text{kurtosis} + (3 * ((n-1)^2) / ((n-2)*(n-3))))$, where n equals the number of observations in the distribution of interest. This bimodality coefficient has a standard cut-off value of $b = .555$, with values greater than $.555$ indicating bimodality in the distribution. Some caution is warranted when interpreting the b coefficient in relation to its cut-off value, as statisticians chose this threshold because a uniform (perfectly flat) distribution has a bimodality coefficient of $.555$. Therefore, distributions whose bimodality coefficients approach this threshold, but are below it, should not necessarily be treated as containing suggestive hints of bimodality, as they are clearly more unimodal than a uniform distribution.

Table 1 presents all the information needed to assess the presence of bimodality within a distribution. Examination of the bimodality coefficient b values indicates that no detectable bimodality exists in the distributions of any of the four conditions. Thus, especially in the experimental condition where garden-pathing was observed (one-referent ambiguous-sentence), there do not appear to be two separate populations of garden-path trajectories and non-garden-path trajectories. One might suggest that the few trials falling into the rightmost deviation bin in Figure 4a comprise a separate mode within the garden-path trial distribution. It is important to note, however, that even after removing all of the most extreme garden-path trials in the one-referent ambiguous ($n = 7$) and unambiguous ($n = 1$) conditions—the trials where the trajectory actually crossed over the location of the incorrect destination at some point during the trial—there is still substantial evidence for garden-pathing. With those extreme garden-paths removed, significant x-coordinate ambiguous-unambiguous divergence occurred from time-steps 21–79, all t 's > 2.07 , all p 's $< .05$, average $d = .524$ (unambiguous always further to the right), and significant y-coordinate divergence still occurred from time-steps 9–43, all t 's > 2.04 , all p 's $< .05$, average $d = .408$, with trajectories in the ambiguous-sentence condition being closer to the top of the screen.

Importantly, when comparing the one-referent ambiguous-sentence condition (where substantial garden-pathing is observed) to the one-referent unambiguous-sentence condition (where no garden-paths were expected in the first place), the Kolmogorov-Smirnov Goodness-of-Fit test revealed that the shapes of these two distributions did not differ, $p > .1$. Hence, we conclude that the distributional properties of a population of trials that should have *no* garden-paths and those of a population of trials that should have *many* garden-paths are not

distinguishable, suggesting that there is no greater evidence of bimodality in the garden-path condition (where certain theories predict it) than in the unambiguous control condition (where no theory predicts it). We interpret these results as indicating that there exists a continuum between motor movements elicited by smoothly parsed sentences and those elicited by garden-path sentences.

Discussion

The visual-world paradigm (Tanenhaus et al., 1995; Trueswell et al., 1999) allows a behaviorally relevant situational context to impose on-line constraints on real-time sentence comprehension. When adapted for recording the streaming [x,y] coordinates of continuous computer-mouse movements, instead of saccadic eye movements, many of the same findings are observed. The slight loss in immediacy with mouse movements is compensated for by the motor output being much less ballistic than saccadic eye movements, and thereby better able to reveal temporal continuity in the activation changes of mental representations. In our results, substantial evidence from multiple converging analyses supports the notion that both the garden-path effect and the contextual modulation of it were detected by investigating properties of the computer-mouse trajectories recorded in relation to the visual world. In the one-referent context, ambiguous-sentence trajectories took longer to reach the correct destination and were also more curved toward the incorrect destination than were their unambiguous counterparts. This garden-path curvature manifested itself as an average peak deviation (from a straight line) of about 1 degree of visual angle over the course of a 25-degree movement. In contrast, the two-referent context showed very little spatial attraction and no significant difference between the ambiguous-or unambiguous-sentence conditions.

The fact that most mouse trajectories began while the speech file was still being heard suggests that the effect of visual context modulating the garden-path took place during early moments of processing the linguistic input, not during a second stage of syntactic reanalysis. This result is problematic for syntax-first models of sentence processing, but does not distinguish between constraint-based and unrestricted race accounts. What does distinguish between these latter two accounts is the gradiency observed in the curvature of the trajectories in the garden-path condition (one-referent context, ambiguous sentence). If the unrestricted race model posits that only one syntactic representation is pursued at any one time, then one would expect it to predict mouse movements that generally move either in the direction of the correct destination or in the direction of the incorrect destination. In contrast, since the constraint-based account posits simultaneous graded activation of multiple syntactic alternatives, it predicts that mouse movements can move in directions that are essentially weighted combinations of the two competing destinations. Figure 3 shows that, although 7 of the trajectories moved all the way to the incorrect destination before changing direction, the vast majority of the trajectories responsible for the mean curvature were unmistakably graded in their spatial attraction toward the incorrect destination.

Study 2

To further explore this distinction between the predictions of a constraint-based model and those of the unrestricted race account, we designed a competition-integration simulation using the normalized recurrence competition algorithm (Green & Mitchell, 2006; McRae et al., 1998; Spivey & Tanenhaus, 1998). See Figure 5. This localist attractor network forces each information source (constraint vector) to provide evidence for the alternatives of an ambiguity in the form of graded support distributed across the alternatives. These constraint vectors send feedforward activation to an integration vector, which then sends feedback to the constraints, gradually biasing them toward the consensually favored alternative. Previous simulations of sentence processing have recorded how long the integration vector takes to settle (with the

winning node exceeding an activation threshold), as a measure of reading times. However, the present simulation instead includes a visuomotor constraint vector and converts its dynamic activation patterns into cascaded [x,y] coordinate movements (see Spivey et al., 2005). Therefore, the network actually has three alternatives being competed over: movement toward the correct destination (right side), the incorrect destination (top), and the irrelevant location (bottom), in that order. In the critical target sentences being tested, the first alternative corresponds to attaching a PP to the NP, the second corresponds to attaching a PP to the VP, and the third corresponds to a viable visuomotor option that is not consistent with the linguistic input on the current trial.

As in previous simulations of garden-path effects, groups of constraint vectors were added to the network in sequence, as the relevant information sources became available in the speech stream (see Figure 5). Therefore, the first set of constraint vectors that became active (e.g., for the “Put the apple” phase) were: a) a referential context vector, with the one-referent context moderately supporting verb-phrase-attachment and thus movement toward the incorrect destination [.33 .67 0], and with the two-referent context supporting noun-phrase-attachment and thus movement toward the correct destination [.67 .33 0], and b) a verb-bias vector coding for the fact that “put” has a strong preference to attach any PP to itself (Britt, 1994), supporting movement toward the incorrect destination [.1 .9 0], and c) a visuomotor vector for guiding x,y movements that starts out with uniform random activations between 0 and 1 for each of the three destinations [rand rand rand] to reflect a participant’s unpredictable anticipation of where the next instruction might lead them. (This initial random activation pattern in the visuomotor vector is the only non-deterministic aspect of these simulations.) In the ambiguous condition, this first phase of constraints was allowed to compete for three time-steps. In the unambiguous condition, this phase lasted five time-steps (to allow for the duration of the additional word “that’s”) and also included a constraint vector for hearing the disambiguating “that’s” [1 0 0]. The weight for each constraint in this first phase was $1/n$, where n is the number of constraints (Spivey & Tanenhaus, 1998). In the second phase, activation patterns from the previous phase carried over and a constraint for the first prepositional phrase (“on the towel”) was added, consisting of a moderate statistical bias toward NP-attachment [.67 .33 0], based on the corpus analysis by Hindle and Rooth (1993). As in previous competition-integration simulations, this newly added constraint was given a weight of 0.5, and weights for the other constraints were halved. After five time-steps (for the duration of that phrase), the activation patterns were carried over to the third phase of speech delivery, adding a constraint for the second PP (e.g., “in the box.”) with discrete support for noun-phrase-attachment and movement toward the correct destination [1 0 0]. As before, this constraint was given a weight of 0.5, and the weights of the others were halved.

At each time-step, the normalized recurrence competition algorithm combines the constraint vector activations in a weighted average to compute the integration vector’s activation pattern, which then returns cumulative multiplicative feedback to the constraint vectors (for details, see Green & Mitchell, 2006; McRae et al., 1998). The feedback from an integration node to a constraint node multiplies the weighted constraint activation that had traveled up that connection by the net activation of that integration node, and adds that product to the constraint node’s current activation. Every new time-step begins with the constraint vectors each re-normalizing themselves to sum to 1.0 (applying a form of implicit competition), before being averaged to re-compute the integration vector’s new activation pattern.

A key property of this competition algorithm is that the integration and feedback process facilitates a kind of indirect crosstalk whereby the consensus of bias among the majority of constraint vectors can sway any equibaised constraint vectors to follow suit. Recall that the visuomotor constraint vector starts out uniformly random for motor commands toward each of the three locations on the screen, since a participant’s initial movement biases are

unpredictable. However, as the linguistic and contextual biases exert their influence on the visuomotor vector (as well as on one another), its activation pattern changes gradually and nonlinearly over time to conform to those biases. Since we treat evolving motor commands and evolving cognitive decisions as coextensive with one another (Cisek & Kalaska, 2005; Gold & Shadlen, 2000, 2001), we allow this visuomotor vector to send its biases to the integration vector just like all the other constraint vectors do. Therefore, an initially random motoric bias toward moving to the upper square can cooperate with a linguistic bias toward that same garden-path interpretation and result in a temporary “gang effect” whereby the simulated mouse trajectory curves upward before the disambiguating second PP vector eventually pulls everything its way. Following previous simulations of continuous motor movements (Spivey et al., 2005; see also Godijn and Theeuwes’s, 2002, competitive integration model), it is directly from this visuomotor vector that we sampled a cascaded blend of the three motor commands. The distance (in x and y pixels) from the current simulated mouse location to each of the three potential destinations was calculated, and weighted by their corresponding activation values. The resulting [x,y] vector was scaled by one tenth of the activation of the most active visuomotor node to produce the direction and magnitude of the coordinate transition for that time-step. Thus, an uncertain visuomotor vector, with near equal activations, would make a small movement on that time step, whereas a confident visuomotor vector, with only one substantially active node, would make a more sizeable movement on that time step.

Figure 6 shows the mean simulated computer-mouse movements from 100 runs of the model in each experimental condition. Only 50 time steps are plotted because some of the simulated trajectories took no more than 50 time steps. Closely matching the human data (Figure 1), the one-referent context simulation (Figure 6, upper panel) shows considerable divergence between the ambiguous- and unambiguous-sentence conditions, with the ambiguous-sentence resulting in a prolonged spatial attraction toward the incorrect destination. The two-referent context simulation (Figure 6, lower panel) shows no divergence between the ambiguous- and unambiguous-sentence conditions. These simulation results stand as an existence proof that a constraint-based model using dynamic competition between simultaneously partially-active representations (and continuous flow of those biases onto weighted-average motor commands) is able to account for the garden-path effect and its contextual modulation in this task.

However, since the unrestricted race model also combines multiple information sources (Traxler et al., 1998; van Gompel, 2001, 2005), it should also be able to account for the garden-path effect and its contextual modulation. In fact, the present simulation arrangement provides an opportunity to construct a version of the model that adheres to the claims of the unrestricted race account. Although the unrestricted race model of syntactic ambiguity resolution has yet to be explicitly implemented computationally for producing quantitative predictions, the present model architecture actually allows one to forgo the dynamic competition altogether and simply immediately select one or another alternative, depending on its activation—as posited by the unrestricted race account. Under these circumstances, only one of the visuomotor nodes will ever be allowed to drive the [x,y] coordinate changes during any phase of the spoken input. The resulting mouse-movements from such a simulation are mostly horizontal trajectories in the unambiguous conditions, and a combination of horizontal trajectories and quite angular trajectories in the ambiguous conditions, because movement will often be initially directed solely to the incorrect destination and then corrected to move toward the correct destination. When 100 simulations are averaged for each condition, as before, the results do a reasonable job of approximating the human data (Figure 7). (As before, only 50 time steps are plotted because some of the simulated trajectories took no more than 50 time steps.) Thus, it would appear that the unrestricted race account can produce an existence proof of about equal quality to that of the constraint-based model.

However, as noted in the introduction, the key differentiation between constraint-based models and the unrestricted race account is that the latter predicts a bimodal distribution of garden-path magnitude because some trials involve a discrete commitment to an incorrect parse (thus requiring re-analysis) and others involve a discrete commitment to the correct parse from the beginning. As long as a significant garden-path effect is being observed across ambiguous and unambiguous conditions, then the distribution of garden-path magnitudes among the garden-path trials must be clearly shifted substantially away from that of the non-garden-path trials. Thus, if an ambiguous condition were composed of a combination of some of those garden-path trials and some of those non-garden-path trials, as predicted by the unrestricted race account, then it should exhibit a bimodal distribution of garden-path magnitude. Figure 8 examines this distribution by plotting the set of 100 simulated trajectories in the one-referent ambiguous-sentence condition. Since the unrestricted race simulation (lower panel) can only direct mouse movements toward one target location at a time (not toward weighted averages of target locations), it produces many perfectly horizontal trajectories and many quite angular trajectories that do not mimic well those of the human data (compare to Figure 3). The constraint-based simulation, by contrast, produces smoothly curved trajectories with a variety of shapes that closely resemble those of the human data.

When maximum deviation is calculated for each simulated trajectory in Figure 8, the distribution of curvature magnitudes is radically different for the two simulations. The constraint-based simulation produces a unimodal distribution of maximum deviation (Figure 9, upper panel) similar to that in the human data (Figure 4a), with kurtosis= 0.120, skewness= 0.030, and the bimodality coefficient, $b = 0.311$. In contrast, the unrestricted race simulation (Figure 9, lower panel) produces a clearly bimodal distribution of maximum deviation that does not fit the human data, with kurtosis= -0.995, skewness= -0.48, and the bimodality coefficient, $b = 0.587$. Thus, while the averaged-trajectory results (Figures 6 and 7) could perhaps not unequivocally adjudicate between constraint-based and unrestricted race models, these distributional analyses show that the constraint-based model clearly outperforms the unrestricted race model in simulating the temporal dynamics of computer-mouse movements during spoken language comprehension in a visual context. It is possible that additional parameters could be added to the unrestricted race simulation to smooth out its individual trajectories, and perhaps even reduce the bimodality in its distribution of curvature magnitudes. For that theoretical position to maintain its viability in the face of present findings, explicit quantitative simulations like these, with fits to human data, will be necessary to demonstrate how such modifications could be successful.

Study 3

The distribution of trajectory-curvature elicited in the garden-path condition in Study 1 provides support for gradation in the magnitude of the garden-path effect and is consistent with graded competition between two simultaneously active representations. Moreover, Study 2 illustrates that a computational implementation of the constraint-based account is capable of producing smoothly curved trajectories mirroring those found in Study 1. The combined results of these two studies provide support for a model of syntactic processing whereby multiple representations of an ambiguity are simultaneously active and compete for activation across time based on the information available to the system. Importantly, the distribution of maximum deviation values in Study 1 (an index of garden-path magnitude) is unimodal and is thus difficult to reconcile with the unrestricted race model which predicts a bimodal distribution of garden-path magnitudes that would correspond to one population of trials where participants were garden-pathed and a separate population of trials where they were not.

Although the syntactic ambiguity manipulation in which we are primarily interested did not appear to produce a bimodal distribution of garden-path magnitudes, it is possible that the

mouse-tracking paradigm and/or the bimodality coefficient are not sensitive enough to illuminate an underlying bimodal distribution of responses to garden-path sentences. That is, perhaps factors that are unrelated to language, such as the kinematics of wrist and/or hand movements along the horizontal movement plane, may be limiting the motor output in a way that prevents a bimodal distribution of trajectory curvatures from emerging. Additionally, assessing the number of modes within a distribution is difficult given the current statistical techniques available, and one concern is that the methods we used to assess the number of modes in the garden-path distribution (all of which support the conclusion that the distribution of garden-path magnitudes is unimodal) were not sensitive enough to detect bimodality in the distribution should it actually exist. In order to allay such concerns, we created a purely visuomotor experimental task with conditions that should produce mouse movements that are consistent with the various parsing models discussed above. Should the conditions employed here actually produce such mouse movements, it will then be possible to compare their distributions to the previously observed distributions of mouse movements in order to determine which parsing model best characterizes the distribution of responses to garden-path sentences.

In this control study, participants were presented with a scene consisting of four squares corresponding to each of the four possible object locations in Study 1. After being instructed to “Click on the green square,” participants clicked on the square located in the center of the left edge of the display to begin a trial. They were subsequently presented with another green square to move to and click, in one of the three remaining object locations. For “garden-path” trials, the target green square appeared at the top-center of the display, and red squares appeared at the right- and bottom-centers of the screen. However, once the participant’s mouse moved outside of the start box in pursuit of a click on that upper green square, the green square changed to a red square and the red square located at the right-center of the display changed to a green square. This switch required the participant to alter an initial up-rightward diagonal movement toward the top-center of the screen (just like toward the incorrect destination in Study 1) to a rightward (and somewhat downward) movement directed at the green square in its new location (the same location as the correct destination in Study 1). This color-switch thus simulated a situation whereby one discrete representation was initially active, issuing a motor command to move to the upper square, followed by a separate discrete representation issuing a command to move to the right square. A baseline “no-switch” condition was included in which the green square appeared at the right of the display, with red squares appearing in the other two locations and no switch ever occurring. This condition mirrored the unambiguous-sentence conditions in Study 1, requiring a simple left-to-right movement with no activation of any analysis corresponding to the incorrect destination. In a third condition, participants were presented with a set of “competition” trials in which a red square appeared at the bottom-center location, a green square at the right-center location, and a greenish-blue square at the top-center location. This condition corresponds to the constraint-based prediction that multiple syntactic representations may be partially active at the same time (McRae et al., 1998), and issuing multiple motor commands at the same time (Cisek & Kalaska, 2005), which result in a continuously updated movement vector that is an average of the multiple motor commands, dynamically weighted by the changing activations of their corresponding linguistic representations.

The distribution of garden-path (switch) trials combined with baseline (no-switch) trials should produce the response distribution that the unrestricted race account predicts for syntactically ambiguous sentences—one in which a garden-path would either occur due to the discrete selection of the ultimately incorrect representation, or would not occur, due to the discrete selection of the ultimately correct alternative. By examining the distributional properties of the maximum deviation values produced by the garden-path and non-garden-path trials, together, we can thus determine whether or not the statistical techniques we used to assess the bimodality

of the garden-path distribution in Study 1 are capable of detecting bimodality in a case where the response distribution should clearly be bimodal (as it should be if the unrestricted race account were accurate). Moreover, because we also included a condition that should induce graded-competition similar in nature to the competition between syntactic alternatives posited in Study 1, it is possible to compare the properties of the garden-path distribution in Study 1 to the properties of both the unrestricted race distribution and the competition distributions in this study to determine which distribution best characterizes the garden-path distribution created by the presence of syntactic ambiguity.

Predictions

In relation to the actual shapes of the trajectories, it was predicted first that movement in the baseline no-switch condition would mirror the average rightward horizontal movement produced by the unambiguous-sentence conditions in Study 1, and that significant y-coordinate divergence would be seen between the baseline (no-switch) trials and both the competition and garden-path (switch) trials. It was also predicted that the presence of a color-switch would induce a strong garden-path effect not unlike the most extreme garden-path trials in the garden-path condition from Study 1 (most evident on Figure 3). In relation to the distribution of maximum deviation values, it was predicted that the combined switch and no-switch distribution would be bimodal, as indexed by the bimodality coefficient (b should be $> .555$), whereas the competition distribution would be unimodal. Most importantly, based on the results of Studies 1 and 2, we also predicted that the garden-path distribution from Study 1 would have properties roughly identical to the competition condition in this present study and that the shapes of the two distributions would be indistinguishable as determined by the Kolmogorov-Smirnov test. Such a result would suggest that the garden-path trajectories in Study 1 arise from a highly-active signal to move rightward (such as a green target square in that location) *accompanied simultaneously* by a partially-active signal to move upward (such as a greenish blue square in that location).

Method

Participants

A separate group of 26 right-handed Cornell undergraduates ($M = 19.6$ years, $SD = 1.1$) participated in this study for extra course credit.

Materials

As in Study 1, all stimuli were presented using Macromedia Director MX (display resolution = 1024×768), and mouse movements were recorded at an average sampling rate of 40 Hz. All 24 experimental trials and 48 filler trials involved the presentation of three 1.5×1.5 inch squares that were either red, green, or greenish-blue, depending on the experimental condition or type of filler trial. For all trials, experimental and filler alike, one square always appeared at the top-center of the display, another at the center of the right side of the display, and another at the bottom-center. For all trials, a 1.5×1.5 inch start-box appeared at the center of the left side of the screen and contained the words "Click Here to Begin." Each square subtended an average of 4.64 degrees in width by 4.64 degrees in height of visual angle. The start-box, located on the far left of the screen, subtended 12.69 degrees of visual angle from the center of the screen, the square on the far right of the screen subtended 12.69 degrees of visual angle from the center of the screen, and the squares in the bottom- and top-center positions each subtended 10.37 degrees of visual angle from the center of the screen. Figure 10 illustrates the relative locations of the squares.

On all trials, the green square was always the target square on which participants were to click. For 24 of the filler trials, the green square appeared at the top-center of the screen, with red

squares occupying the right- and bottom-center square locations, and for the other 24 filler trials, the green square appeared at the bottom-center of the display, with red squares occupying the right- and top-center square locations. Given that the goal of this study was to examine mouse-movements that are analogous in nature to the movements produced during the processing of the experimental sentences in Study 1, on the 24 experimental items, the green square appeared initially, or ended-up, at the right-center location of the display—a location that corresponds to the location of the correct destination in Study 1. As in Study 1, then, the movement always initiated at the left-center of the display (at the start-box in this study or at the target referent-object in Study 1) and progressed rightward, terminating at the right-center of the display.

Of the 24 experimental items, eight were garden-path (switch) trials, eight were baseline (no switch) trials, and the remaining eight were competition trials. The characteristics of these trial-types are described in the introduction to this study.

Procedure

Participants were instructed simply to “click on the green square with as much accuracy as possible.” At the beginning of each trial the start-box appeared, and upon clicking on it, three 1.5×1.5 inch white boxes, demarcated by black dotted lines on all four sides (as in Figure 10), subsequently appeared. Participants were thus informed of exactly where the colored squares were about to appear, but were prevented from planning any course of action because they did not know the location of the green square. After one second, the empty boxes were replaced with three colored squares corresponding to one of the trial-types listed above. The cursor was frozen at the exact location in the start-box where the trial-initiating click occurred, and remained frozen throughout the one-second delay up until the colored squares appeared, at which point the participant was able to move the cursor with the mouse to click on the green square. This delay of movement functioned to prevent any anticipatory movement. Once the participant clicked on the green square, the current display disappeared and participants were presented with the start-box for the next trial. The 72 items were presented in one experimental block, and the order of item presentation was randomized per participant.

Results and Discussion

Trajectory Analyses

Mouse movements were recorded throughout the duration of the trial, beginning with the point at which the colored squares appeared up until the point at which the green square was clicked. The x,y coordinates from the trajectories of each experimental trial were graphed individually in order to identify any aberrant movements or any trials on which participants clicked one of the incorrect (non-green) squares before ultimately clicking on the green square. No trial contained an aberrant or nonsensical movement, and only 1.4% of the experimental trials were excluded from the analyses presented below because they involved a mouse-click of a non-green square. Each analyzable trajectory was time-normalized to 101 time-steps as in Study 1.

Figure 10 displays the averaged time-normalized trajectories produced by each experimental condition. The average movement produced by the baseline no-switch condition corresponds to the average movement on the unambiguous-sentence conditions in Study 1, with a rather straight horizontal movement from left to right. It also appears that the switch condition produced a large number of extreme garden-paths, with trajectories initially traveling toward the upper square (corresponding to the incorrect destination in Study 1) before being redirected to the ultimately correct destination after the color-switch occurred. Moreover, it appears that the competition condition produced, on average, a more subtle graded curvature toward the

location of the greenish-blue square, as is the case for the garden-path condition in Study 1 (compare to Figure 1, upper panel).

In order to assess the degree to which the x,y coordinates of the trajectories produced in the garden-path and competition conditions diverged significantly from the baseline (no-switch) condition, we conducted a *t*-test at each of the 101 time-steps for the x- and y-coordinates, separately. As in Study 1, an observed divergence was not considered significant unless the coordinates between the baseline condition and the competition or garden-path conditions elicited *p*-values < .05 for at least eight consecutive time-steps. Also as in Study 1, the x-coordinates of the elicited trajectories are solely indicative of velocity toward the correct destination, and the y-coordinates are solely indicative of spatial attraction toward the ultimately incorrect destination.

Average trajectories in the garden-path condition traveled rightward significantly faster than they did in the baseline no-switch condition from time-steps 18–45, as indexed by the x-coordinate comparisons, all *t*'s > 2.14, all *p*'s < .05, average *d* = 1.43. However, from time-steps 50–85, this difference reversed, with the average trajectory in the baseline condition traveling rightward toward the location of the ultimately correct destination more quickly than did the average trajectory in the garden-path condition, all *t*'s > 2.07, all *p*'s < .05, average *d* = 1.67. As is evident in Figure 10, there was also significantly more spatial attraction toward the top of the screen, corresponding to the location of the incorrect destination in Study 1, in the garden-path condition than there was in the baseline condition, as indexed by the significant y-coordinate comparisons from time-steps 19–101, all *t*'s > 2.57, all *p*'s < .05, average *d* = 2.17. When considering the x- and y-coordinate analyses together, then, it appears that for the first half of the average trial in the garden-path condition, participants made a quick movement upward toward the initial location of the green square, but after the switch occurred, the movement was redirected toward the new location of the green square at the right-center of the display. On average, these re-directed trajectories arrived at the ultimately correct destination later than the average baseline no-switch trajectories. These results support the presence of a clear garden-path effect in the switch condition, consisting of one discrete motor command to move the cursor to the upper square, quickly replaced by a different motor command to move the cursor to the rightmost square.

Substantial x-coordinate divergence also occurred between the average trajectories in the baseline condition and in the competition condition from time-steps 47 to 82, all *t*'s > 2.10, all *p*'s < .05, average *d* = .451, with trajectories in the baseline condition being closer to the correct destination (green square) than the competition condition trajectories at each of those time-steps. Substantial y-coordinate divergence was observed as well between the average trajectories in the baseline condition and the competition condition trajectories from time-steps 28–78, all *t*'s > 2.16, all *p*'s < .05, average *d* = .744. At each of those time-steps, the trajectories in the competition condition were significantly closer to the location of the competing greenish-blue square at the top of the screen than were trajectories in the baseline condition.

Comparisons between the x-coordinates of the competition and garden-path conditions revealed that from time-steps 20–49, all *t*'s > 2.08, all *p*'s < .05, average *d* = 1.272, the garden-path condition elicited trajectories that traveled rightward more quickly than did the competition condition. As was the case with the x-coordinate comparisons between the averaged baseline and garden-path condition trajectories, however, from time-steps 53–81, the trajectories in the garden-path condition traveled rightward toward the ultimately correct destination more slowly than did the average trajectories in the competition condition, all *t*'s > 2.32, all *p*'s < .05, average *d* = 1.264. Additionally, the y-coordinate comparisons revealed that the average trajectories in the garden-path condition were significantly closer to the top

of the screen than were the average trajectories in the competition condition for time-steps 19–101, all t 's > 2.09 , all p 's $< .05$, average $d = 1.779$.

The results of these analyses confirm that the mouse-tracking paradigm is capable of producing average movements that correspond to the predictions of various models of syntactic processing. First, the average movement in the baseline (no-switch) condition is one characterized by a rightward movement traversing the horizontal movement plane between the start- and end-points. Such a movement is consistent with what was observed for the unambiguous-sentence conditions in Study 1, in which the absence of a syntactic ambiguity prevented any noteworthy spatial attraction toward any other location in the display. This movement pattern also corresponds to the portion of syntactically ambiguous trials that the unrestricted race model predicts would not need reanalysis because the ultimately correct representation of a sentence's syntactic structure was initially discretely selected. Secondly, the garden-path condition produced trajectories that moved up and rightward more quickly than either of the other two conditions for the first half of the trial, but not for the second half. Such a trend suggests that, relative to the competition condition, participants were initially strongly biased toward the top-center of the screen and moved accordingly, but that upon processing the color switch, redirected their movement toward the new location of the green square. This pattern is consistent with the portion of syntactically ambiguous trials that the unrestricted race model predicts would need reanalysis because the incorrect representation of a sentence's syntactic structure was initially selected.

Most interesting, however, is that the average movement in the garden-path condition of Study 1 (Figure 1, upper panel) does not resemble the average movement in either the garden-path switch or the baseline no-switch conditions here. Instead, the average movement in the presence of a syntactically ambiguous sentence in Study 1 looks a lot like the competition condition in this study, where a more subtle upward curvature toward the competing location occurs, and where the velocity of the trajectory toward the ultimately correct location is slower when competition occurs than when the sentence is unambiguous (thus involving little or no competition). Of course, these across-study comparisons are qualitative in nature, but given that the average movements across each of the three conditions in this study map onto the predictions of various parsing models, cross-study quantitative comparisons of the distributions of mouse movements in the various conditions are warranted.

Distributional Analyses

Figure 11 displays the distributions of curvature magnitudes for each of the three conditions employed here, along with a fourth distribution that was created by combining the distributions of the baseline no-switch and garden-path switch trials. The descriptive statistics associated with each of the four distributions can be found in Table 2. The distribution produced by the baseline no-switch condition is unimodal, bimodality coefficient $b < .555$, and appears to vary normally around the mean. By contrast, the garden-path trial distribution elicited a $b > .555$. This distribution, alone, has a shape that would be predicted by the unrestricted race model in the presence of a syntactic ambiguity with constraints that relatively strongly bias the system toward the ultimately incorrect syntactic alternative. The large rightmost mode corresponds to a majority of trials on which reanalysis is needed due to a garden-path, and the much smaller leftmost mode corresponds to the proportion of trials in which participants discretely selected the ultimately correct alternative from the beginning. That is, when participants are faced with a situation that corresponds to a true garden-path where basically only one representation can be discretely considered at a time, distributions of mouse-movements are still bimodal. Given the disparity in the descriptive properties between the distributions of garden-path-strength values in the one-referent ambiguous-sentence condition in Study 1 and the garden-path switch distribution here, however, it is safe to say that the distribution that would be predicted by the

unrestricted race account is an inappropriate characterization of the language-related garden-path phenomenon. Furthermore, the Kolmogorov-Smirnov test demonstrates that the shapes of those two distributions are significantly different, $p < .0005$.

We combined the baseline and garden-path switch trials into one distribution in order to approximate a distribution comprising some trials that required a re-analysis and some trials that did not require a re-analysis. The unrestricted race model would predict such a distribution in the presence of an ambiguity with constraints that support each of the alternatives roughly equally. The combined distribution is clearly bimodal, as evident from visual inspection of Figure 10d, and by the fact that it elicited a b -value $> .555$ (Table 2). As was the case with the distribution of garden-path magnitudes in the switch condition alone, the properties of this combined distribution also do not align well with the properties of the distribution produced by the presence of syntactic ambiguity in Study 1. Moreover, a Kolmogorov-Smirnov test found that the shape of the Study 1 garden-path distribution (Figure 4a) is significantly different from the shape of the Study 3 combined distribution (Figure 10d); $p < .0005$.

In contrast, the properties of the Study 3 competition distribution (Figure 10b) closely mirror those of the distribution of curvature magnitudes in the garden-path condition of Study 1 (Figure 4a). As was the case with the garden-path distribution in Study 1, bimodality was not detected in the competition condition here, $b < .555$. The means of the garden-path distribution in Study 1 ($M = 23.82$) and the competition distribution here ($M = 19.96$), along with the standard deviations (Study 1 $SD = 91.87$, Study 3 $SD = 90.88$), are almost identical, and the shapes of the distributions are statistically indistinguishable by the Kolmogorov-Smirnov test, $p > .1$. Unlike the distributions that are predicted by the unrestricted race model, then, the distribution that actually does accommodate garden-path effects on syntactically ambiguous sentences is one produced by continuously graded competition.

The results of this study demonstrate that the mouse-tracking technique employed here can produce average movements that correspond to what would be predicted by various parsing models. The presence of bimodal distributions of movements in the garden-path switch and combination distributions demonstrates not only that the mouse-tracking technique can produce a bimodal distribution when one is expected, but also that the statistics we employed to assess the number of modes within the various distributions are sensitive enough to detect bimodality when it is present. Therefore, the conspicuous absence of evidence for bimodality in the distribution of garden-path magnitudes in Study 1 (Figure 4a) is likely due to there not being any bimodality in the way that garden-path sentences are processed.

General Discussion

We have presented converging evidence from computer-mouse movements and model simulations in the visual-world paradigm that provide evidence in favor of the constraint-based account of sentence processing, in which multiple partially-active syntactic alternatives compete with one another via support from a variety of information sources (e.g., Elman et al., 2004; MacDonald et al., 1994; Spivey & Tanenhaus, 1998; Trueswell et al., 1994). Interestingly, it is a *visual* context that is influencing this linguistic competition process. The real-time information flow between visual and linguistic information is particularly well illustrated in the continuous trajectories of computer-mouse movements in Study 1. Although these movements of the hand are initiated slightly later than the first eye movement of a scan path, they are considerably smoother and less ballistic than saccades, and they are typically revealing their graded spatial attraction around the same period of time (relative to the spoken sentence) as many of the critical fixations of competing objects are occurring in the visual world paradigm (Chambers et al., 2004; Spivey et al., 2002; Tanenhaus et al., 1995; Trueswell et al., 1999). Our results clearly demonstrate that, while a participant drags an object toward

its syntactically-correct destination, variation of the visual context modulates the tendency to move that object partly in the direction of its garden-path destination as well (Figures 1 and 2).

According to constraint-based accounts of sentence processing, part of why visual context is able to immediately influence the resolution process is precisely because the correct alternative was never summarily discarded during the comprehension system's partial foray down the garden path. In fact, van Gompel himself reports evidence that activation of the *inappropriate* parse of a temporary syntactic ambiguity lingers for long enough after the sentence to exert syntactic priming on the production of a subsequent sentence (van Gompel, Pickering, Pearson, & Jacob, 2006). If statistical, semantic, and structural biases were to persuade the processing system to *eliminate* the syntactic alternative that would have turned out to be the correct one, then new information that supported that now-absent alternative would have no available representation to receive said support. However, if those other constraints merely *inhibited* the graded activation of that alternative, then a strongly supportive new constraint could perhaps be influential enough to bring that suppressed (but not eliminated) alternative back to a prominent activation level. For example, look at what the integration-competition model does when it displays a substantial garden-path effect. Initially, the incorrect alternative prevails over the correct alternative by a substantial margin of activation. During that portion of the sentence, there is little competition and hence little processing difficulty, as the whole system settles on the wrong parse. However, when disambiguating information, such as the second PP in example 2a, provides evidence discretely in favor of the correct alternative, the overturning of that incorrect activation pattern involves a laborious and time-consuming competition process (see Green & Mitchell, 2006). Now compare that to what the model does when something like visual context prevents a substantial garden-path. Some local constraints support the wrong syntactic alternative and the contextual constraint supports the correct one, so the early portion of the sentence now exhibits a moderate amount of competition and processing difficulty, which does *not* get fully resolved before later portions of the sentence are heard or read. As a result, the model has not dug in its heels to defend either alternative, and when the disambiguating portion of the sentence is encountered, those new biases can now take over relatively smoothly.

This gradiency in the simultaneous activation of syntactic alternatives may provide a turning point in the debate between re-analysis theories (whether of the syntax-first variety or the unrestricted race variety) and competition theories (typically, constraint-based). Previous work has shown that in a one-referent visual context, it is about half of the time that participants fixate that incorrect destination, and the other half of the time they look only at the correct destination (Spivey et al., 2002; Tanenhaus et al., 1995). Therefore, this would appear to be the ideal case where the two syntactic alternatives are near 50/50 in their salience. Hence, the unrestricted race theory should predict a clearly bimodal distribution, with about half of the trials exhibiting dramatic spatial attraction to the incorrect destination, and the other half showing none at all. In fact, that pattern is exactly what the eye-tracking data show, because saccadic eye movements tend to be quite ballistic. However, in Study 1, our distribution of continuous computer-mouse trajectories in the one-referent ambiguous-sentence condition showed no evidence of such a bimodal distribution (Figure 3). The degree of curvature among the trajectories was distributed in a clearly unimodal fashion (Figure 4a). That is, the graded spatial attraction effects elicited in this condition came not from two different types of trials (some engaging a re-analysis mechanism and some not doing so) but from a single population of trials (all engaging the same competition process). Moreover, the shape of the distribution was not significantly different from that of a distribution of curvature values elicited by control sentences (a condition where no theory would predict a bimodal distribution).

Furthermore, in Study 2, an integration-competition simulation of continuously emitted [x,y] coordinate changes (inspired by constraint-based accounts of sentence processing), using a weighted combination of the active alternatives to produce a blend of movements, provided a close fit to the actual mouse-movement trajectories (compare Figures 3 and 8a). Much like the distribution of curvature magnitudes from the human data (Figure 4a), these simulated trajectories exhibited curvature magnitudes that formed a unimodal distribution (Figure 9a). In contrast, when the same model used only one syntactic alternative at a time to drive [x,y] movements, corresponding to the unrestricted race theory, the pattern of simulated trajectories did not match well with the human data (Figure 8b), and its curvature magnitudes formed a clearly bimodal distribution (Figure 9b).

Finally, in Study 3, a visuomotor control task demonstrated that when a signal is initially misleading about where to move the mouse, our mouse-tracking paradigm is able to reveal the dramatically curved trajectories that result. And when a distribution of curvature magnitudes contains some of those dramatically curved trajectories and also some very straight trajectories, our tests for bimodality can detect the presence of two separate populations of trials. Therefore, the fact that we did not find evidence for bimodality in Study 1 is indeed informative. It suggests that the garden-path trajectories in the one-referent ambiguous-sentence condition come from a single population of sentence processing events. Also, the competition condition in Study 3, where the upper distractor square was similar in color to the target square, exhibited a unimodal distribution of graded curvature magnitudes (Figure 11b) that was not statistically different from the distribution of curvature magnitudes in the garden-path condition of Study 1 (Figure 4a). This observation lends further support to conceiving of these garden-path effects as resulting from competition between simultaneously partially-active representations.

Overall, the results described here tie in nicely with converging evidence for a close-knit relationship between language processing, visual perception, and motor action (e.g., Barsalou, 1999; Chambers et al., 2004; Glenberg & Kaschak, 2002; Pulvermüller, 1999; Spivey et al., 2005; Zwaan & Taylor, 2006). And if perceptual and motor processes rely on distributed graded activations of multiple representations evolving in real-time (e.g., Paninski et al., 2004; Rolls & Tovee, 1995), perhaps it should not be surprising that tightly-yoked linguistic processes would follow suit. This, of course, would not be the first time that cognitive psychology has witnessed the gradual blurring of a historical dichotomy between two categorically different perceptual processes (e.g., a garden-path event and a non-garden-path event). For example, in the 1970's, necessary and sufficient conditions for discretely defining an exemplar as either a member or a non-member of a category gave way to the concept of prototype-based *graded membership* in a category (Rosch, 1973; Zadeh, 1975). And in the 1990's, the categorical distinction between parallel and serial visual search gave way to a *continuum* of search efficiency (Duncan & Humphreys, 1989; Wolfe, 1998).

In fact, hints of this kind of gradiency have been showing up in a number of recent approaches to syntax, in the form of either probabilistic or underspecified representations (e.g., Bod, Hay, & Jannedy, 2003; Ferreira, Bailey, & Ferraro, 2002; Hale, 2006; Jurafsky, 1996; Levy, 2006; Weinberg, 1993; see also Tabor, Galantucci, & Richardson, 2004). This departure from traditional frameworks (which required a discrete commitment to a determinate parse), and the present gravitation toward continuous dynamical frameworks for syntax (Culicover & Nowak, 2003; Tabor & Hutchins, 2004), are bringing the field of sentence processing in line with the growing successes of dynamical-systems accounts of cognition in general (e.g., Port & Van Gelder, 1995; Spivey, 2007; Ward, 2002). As a result, the theoretical treatment of syntactic garden-path effects is likely to require something of a reformulation. Rather than conceiving of the pursuit of a syntactic structure as an all-or-nothing process, on which a discrete re-analysis either will or will not be required (Traxler et al., 1998; van Gompel et al., 2001, 2005), the results we report point to a gradiency in the degree to which an incorrect syntactic

structure is pursued in conjunction with the correct syntactic structure, which is consistent with competition-based accounts of constraint-based sentence processing (e.g., Elman et al., 2004; Green & Mitchell, 2006; MacDonald et al., 1994; McRae et al., 1998; Tabor & Tanenhaus, 1999).

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Figure 1.

A depiction of the typical visual scene, along with the average normalized ambiguous-and unambiguous-sentence trajectories, in the one-referent (top panel) and two-referent (bottom panel) visual-context conditions. There was substantial y-coordinate divergence between the ambiguous- and unambiguous-sentence trajectories in the one-referent context, with ambiguous-sentence trajectories showing more curvature toward the incorrect destination. Additionally, there was absolutely no commensurate divergence in the two-referent context.

Figure 2.

Average x-coordinate (top panel) and y-coordinate (bottom panel) locations across each of four time-bins. In the one-referent condition, there was significant x- and y-coordinate divergence between the ambiguous- and unambiguous-sentence conditions at segments 2 and 3, but no such divergence in the two-referent context.

Figure 3.

The trial-by-trial ($n = 120$) overlay of trajectories in the one-referent ambiguous-sentence (garden-path) condition. Although a few extreme garden-path trials exist, most trajectories in this condition pass through some intermediate point between the horizontal movement plane and the location of the incorrect destination (top-center) before landing at the correct destination (right-center).

Figure 4.

The distributions of trajectory curvature magnitudes in the four experimental conditions, calculated as the maximum deviation (in y-pixels) from a straight line. All the distributions are unimodal, indicating that that trajectories elicited in the garden-path condition (panel A) come from one population of garden-path magnitudes, not two.

Figure 5.

In this integration-competition simulation of the one-referent ambiguous-sentence condition, partway through the first time-step, the initial activations of three constraint vectors (verb, context, and visuomotor) produce a weighted average at the integration vector (hexagon nodes). In the second phase of competition, hearing the first prepositional phrase activates the First PP vector (dashed lines). In the third phase of competition, hearing the disambiguating prepositional phrase activates the Second PP vector (dotted lines). At every time-step, the activation pattern on the visuomotor vector is converted into a change in [x,y] coordinates by several pixels.

Figure 6.

Constraint-based version of simulation. Trajectories are averaged from 100 runs of the integration-competition model, corresponding to each of the four cells in the Context × Ambiguity interaction. For the one-referent condition, as with the human data, substantial divergence between the ambiguous- and unambiguous-sentence conditions was observed (top panel). No substantial divergence occurred in the two-referent condition (bottom panel).

Figure 7.

Unrestricted Race version of the simulation. Trajectories are averaged from 100 runs of the integration-competition model in which only one visuomotor node was allowed to drive motor behavior at any one time. The averaged results are not substantially different from those of the constraint-based model or from the human data, although the ambiguity effect in the two-referent context is still somewhat present.

Figure 8.

The trial-by-trial ($n = 100$) overlay of trajectories in the one-referent ambiguous-sentence (garden-path) condition, for the constraint-based and unrestricted-race versions of the simulation. Only the constraint-based simulation (upper panel) produces individual trajectories that resemble those of the human data (Figure 3).

Figure 9.

The distributions of simulated trajectory curvature magnitudes from Figure 8, calculated as maximum deviation (in y-pixels) from a straight line. The constraint-based simulation produces a unimodal distribution much like that in the human data (Figure 4A), whereas the unrestricted race simulation produces a clearly bimodal distribution of many flat non-garden-path trajectories and many upwardly-angled garden-path trajectories.

Figure 10.

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 11.

In the visuomotor control study, the distributions of maximum deviation (in y-pixels) from a straight line reveal bimodal distributions when baseline non-garden-path trials are combined with garden-path trials (Panel D), as well as in the garden-path condition alone (Panel A). In the competition condition alone, corresponding to a constraint-based account of multiple representations being partially active at the same time, the distribution is unimodal with a mean slightly greater than zero. In the baseline condition alone (Panel C), corresponding to an unambiguous-sentence condition, the distribution is unimodal with a mean of zero.

Table 1
Maximum deviation statistics for the four distributions of trials in Study 1.

Condition	n	Mean	SD	Skewness	Kurtosis	Bimodality (<i>b</i>)
1 Referent Ambiguous	119	23.82	91.87	1.40	4.34	.399
1 Referent Unambiguous	130	9.3	50.30	.24	1.26	.244
2 Referents Ambiguous	119	5.24	73.73	.76	6.69	.161
2 Referents Unambiguous	128	-2.5	53.80	-.39	2.59	.203

Table 2
Maximum deviation statistics for the four distributions of trials in Study 3.

Condition	n	Mean	SD	Skewness	Kurtosis	Bimodality (<i>b</i>)
Baseline (No Switch)	206	-24.43	56.93	-.01	.71	.267
Garden-path (Switch)	202	214.35	85.99	-2.72	9.27	.680
Competition (Bluish-green)	205	19.96	90.88	.39	.90	.292
Combination (GP + Baseline)	408	94.18	140.40	-.02	-1.43	.630