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Streaming *x, y* Coordinates Imply Continuous Interaction During On-line Syntactic Processing

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Abstract

Although many theories of on-line syntactic processing invoke the parallel activation of multiple syntactic representations, evidence supporting simultaneous activation has been inconclusive. Here, we exploited the continuous and non-ballistic properties of computer mouse movements, identified by recording streaming *x, y* coordinates, in order to determine the validity of serial versus parallel accounts of sentence processing. Participants heard structurally ambiguous sentences while viewing scenes with properties either supporting or not supporting the difficult relative clause interpretation. The curvatures of the elicited mouse-movement trajectories revealed both an effect of visual scene, and competition between the simultaneously active syntactic representations.

Keywords: Sentence Processing; Language Comprehension; Mouse-Tracking; Multiple Constraints

Recently, it has been demonstrated that continuous nonlinear trajectories recorded from the streaming *x, y* coordinates of computer-mouse movements can serve as an informative indicator of the cognitive processes underlying both spoken word recognition (Spivey, Grosjean, & Knoblich, 2005), and categorization (Dale, Kehoe, & Spivey, in press). Unlike saccadic eye movements, mouse movements are generally smooth and continuous, and can curve substantially mid-flight. Additionally, whereas self-paced reading affords 2-3 data points (RTs) per second, and eye-movement data allow for approximately 2-4 data points (saccades) per second, "mouse-tracking" yields somewhere between 30-60 data points per second, depending on the sampling rate of the computer used. These properties of tracked mouse-movements are beneficial in that, crucially, they allow a truly graded stimulus-elicited response pattern to emerge within an individual trial. Here, we exploit the continuous nature of mouse-movement trajectories, in relation to the visual-world paradigm (Tanenhaus, Spivey-Knowlton, Eberhard, & Sedivy, 1995; Spivey, Tanenhaus, Eberhard, & Sedivy, 2002), in order to explore unresolved issues prevalent within the domain of syntactic processing.

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

In example (1), the prepositional phrase (PP) *on the towel* creates a syntactic ambiguity in that it can be initially interpreted as a destination (or Goal) for the referring expression *the apple*, thus attaching to the verb *Put* (VP-Attachment), or alternatively, could be interpreted as a modifier of the referring expression, such as ((*Put the apple on the towel*) in the box) (NP-attachment). In the absence of any contextual or other potentially influential information, there exists a strong and well-documented bias for VP-attachment (Britt, 1994; Spivey-Knowlton & Sedivy, 1995).

This VP-attachment bias can, however, be influenced by information contained within a visual scene presented in concert with the syntactically ambiguous spoken instruction (Tanenhaus et al., 1995; Trueswell, Sekerina, Hill, & Logrip, 1999; Spivey et al., 2002; Snedeker & Trueswell, 2004). When ambiguous sentences like (1a) are heard in the presence of visual scenes where only one possible referent is present (an apple already on a towel), along with an incorrect destination (an empty towel), and a correct destination (a box), participants often look to the incorrect destination until the second disambiguating PP is heard, upon which time eye-movements tend to be re-directed to the correct destination. The tendency in the one-referent context to look at the incorrect destination until the disambiguating second PP is heard is referred to as "the garden-path effect," and is indicative of initially attaching the PP to the VP.

The garden-path effect, however, can be dramatically attenuated when two possible referents (say, an apple on a towel and another apple on a napkin) are present. When hearing an ambiguous sentence like (1a) in a two-referent visual context, participants tend to look at the correct referent (the apple on the towel) and move it to the correct destination without looking very often at the incorrect destination. In accordance with various instantiations of referential theory (Altmann & Steedman, 1988; Spivey & Tanenhaus, 1998), thus, it seems that the when two possible referents are present, an expectation is created such that the two similar entities will be discriminated, thereby forcing a modifier interpretation of the initial PP.

Purpose

The purpose of this present study was two-fold. One goal was to determine the degree to which the mouse-tracking procedure reported initially by Spivey et al. (2005) can be used to illuminate the nature of the cognitive processes underlying the comprehension of complex syntactic structure. The context effect reported in relation to the visual world paradigm is highly replicable when tracking eye-movements. As such, recording mouse movements in this paradigm serves as a strong test case by which to evaluate the efficacy of the mouse-tracking procedure for the study of language processing in real-time.

If the mouse-tracking technique can produce results from the visual-world paradigm commensurate with those obtained by tracking eye movements, we would predict that:

1) averaged trajectories recorded in response to ambiguous sentences in the one-referent context should show significantly more curvature toward the incorrect destination than the trajectories elicited by unambiguous sentences—a trend corresponding to the garden-path effect, and
2) the curvature of averaged trajectories in the two-referent condition should not differ between ambiguous and unambiguous sentences, thus demonstrating an effect of referential context.

Importantly, however, the goal of this study was not simply to replicate the context and garden-path effects with a new methodology, but also to demonstrate the ability of the mouse-tracking method to test distributional patterns in garden-path effects that can speak to the debate over serial versus parallel syntactic processing.

One dimension by which contemporary theories of syntactic processing can be distinguished is the degree to which they rely on the activation of one versus multiple syntactic representations at any given time during the sentence comprehension process. The *two-stage* theories (e.g. Frazier & Clifton, 1996; Ferreira & Clifton, 1986) posit that an initial first-pass analysis of a sentence, based largely upon syntactic information, is pursued. Should the initial syntactic analysis fail, other non-syntactic sources of information may be accessed during a revision stage in order to facilitate comprehension. Implicit in two-stage theories is the assumption that, at least initially, only one structural representation of an ambiguous sentence is represented.

Multiple constraint-based theories (e.g. McRae, Spivey-Knowlton, & Tanenhaus, 1998; Pearlmutter & MacDonald, 1995), on the other hand, describe language comprehension as an interactive process whereby multiple sources of information become accessible on-line and constrain possible interpretations of a sentence in real time. In contrast to the two-stage theories detailed above, the language comprehension system must engage in a process of rapidly evaluating multiple possible syntactic analyses in order to arrive at the (ultimately) correct interpretation of the sentence. As such, most constraint-based theories posit parallel partial activation of multiple syntactic representations.

Determining whether or not multiple structural representations are active during early on-line processing has proven to be an extremely difficult enterprise. Within the one-referent context, one might expect that if both possible representations of the ambiguous PP were active, participants might look back and forth between the correct and incorrect destinations until disambiguation occurs, and indeed, this kind of pattern has been observed (Tanenhaus et al,. 1995). However, due to the ballistic nature of saccadic eye movements, it is impossible to determine whether such vacillatory looking is indicative of simultaneous partial activation of both possible representations, or if it indicates an alternation between one complete representation and then the other. That is, distributions of eye movement patterns are almost always bimodal. There are saccades to the location of the incorrect destination and there are saccades to the location of the correct destination. Extremely rarely are there saccades to a blank location in between two potential targets.

In light of the ability to record many data points per second, and in light of their ability to curve mid-flight as a result of competition between multiple potential targets, however, mouse movements do have the ability to convey the continuity of processing. The second purpose of this study was to exploit this noted continuity with the goal of determining whether partial activation of each possible representation occurred. In order to do so, an area-based measure was used to determine the amount of curvature toward the incorrect destination that was exhibited by the ambiguous and unambiguous trajectories in the one-referent context. If only one representation were active at any one time, then the trial-by-trial distribution of trajectory curvatures, with the ambiguous instruction in the one-referent context, should be bimodal—comprised of highly curved "garden-path" movements and non-curved correct-interpretation movements. In contrast, if both representations were active and competing simultaneously, one should expect to see a unimodal distribution with a continuous range of less- and more-curved trajectories—that is, a gradation of "garden-pathing."

Method

Participants Forty right-handed native-English speaking undergraduates from Cornell University participated in the study for extra credit in psychology courses.

Materials and Procedure Sixteen experimental items, along with 102 filler sentences, were adapted from Spivey, et al. (2002) and digitally recorded. Each of the 16 experimental items was spliced in order to produce both an ambiguous sentence condition (1a), and an unambiguous sentence condition (1b). Each of the visual contexts corresponding to the 16 experimental items was varied to produce a one-referent condition and a two-referent condition. The one-referent visual context (illustrated in Figure 1) contained the target referent (an apple on a towel), an incorrect destination (a second towel), the correct destination (a box), and a distracter object (a flower). In the two-referent context, all items were the same except that the

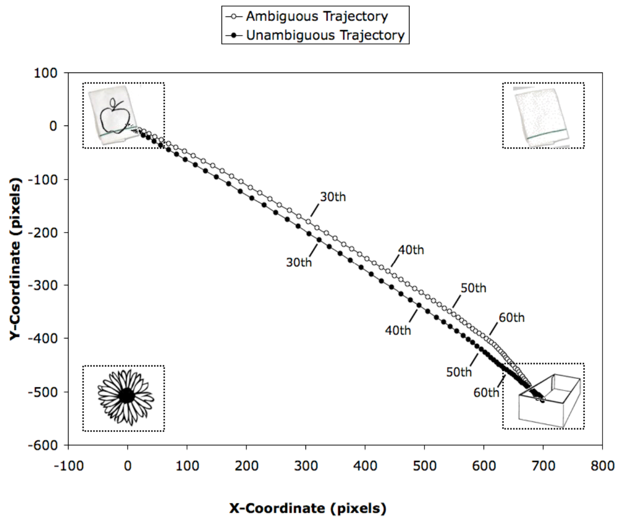

Figure 1. An example of a one-referent display for the instruction "Put the apple (that's) on the towel in the box." The trajectories plotted are the averaged trajectories elicited in this context.

distracter object was replaced with a second possible referent (such as an apple on a napkin). Twenty-four distracter scenes, designed to accompany filler sentences, were constructed by using different combinations of the objects presented in the experimental trials, in addition to a set of new and easily recognizable objects.

Spoken instructions were recorded using a Mac-based speech synthesizer program. At the beginning of each sound-file for every item, participants first heard "Place the cursor at the center of the cross." Then, for the sound-files accompanying experimental scenes, the experimental sentence always occurred second, followed by two additional filler instructions. Thus, for experimental items, participants viewed the appropriate scene while hearing, for example:

1) Place the cursor at the center of the cross.
2) Put the apple on the towel in the box (experimental trial).
3) Now put the apple beside the flower (filler sentence).
4) Now put the flower in the box (filler sentence).

For filler sentences presented with a distracter scene, participants heard three scene-appropriate unambiguous instructions. In all cases, two seconds separated the offset of one sentence from the onset of the next sentence within each trial.

In both the one- and two-referent conditions, the target referent always appeared in the top left corner of the screen, the incorrect destination always appeared in the top right corner of the screen, and the correct destination was always located at the bottom right portion of the screen. The distracter object in the one-referent trials, and the second referent in the two-referent trials, always appeared in the bottom left corner of the screen.

The filler sentences were constructed to prevent participants from detecting the regularity created by the object placements in the experimental trials. In addition to the movement used in the experimental instructions, eleven distinct movements were possible in the visual scene across trials, and an approximately equal number of filler sentences (either eight or ten) were assigned to each of these movements. Therefore, ten sentences required an object in the upper left-hand corner of the display be moved to the upper right corner of the display, eight sentences required an object in the upper left-hand corner of the display be moved to the bottom left-hand corner of the display, and so on.

In each scene, participants saw four to six color images, depending on how many objects were needed for the scene. The images were constructed from pictures of real objects taken by a digital camera and edited in Adobe Photoshop. The visual stimuli subtended an average of 5.96 X 4.35 degrees of visual angle, and were 14.38 degrees diagonally from the central cross. The mouse movements were recorded at an average sampling rate of approximately 40 Hz.

The experimental items were counterbalanced across four presentational lists. Each list contained four instances of each possible condition, but only one version of each sentence frame and corresponding visual context. Two filler sentences were included with the experimental items as described above, and three filler sentences were included with each of 24 distracter scenes. The presentation order was randomized for each participant. Three practice items were incorporated into the beginning of each list. Participants were randomly assigned to one of the four presentation lists.

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 mouse movements. A trajectory was considered valid and submitted to further analyses if it was initiated at the top left quadrant of the display and subsequently terminated in the bottom right quadrant, signaling that the correct referent had been picked-up and then placed at the correct destination. This screening procedure resulted in 29 trials being deleted from further analysis, accounting for less than 5% of all experimental trials. Table 2 displays the number of trials, per condition, included in the final dataset.

All analyzable trajectories were time-normalized to 101 time-steps by a procedure originally described in Spivey, Grosjean, and Knoblich (2005). All trajectories were aligned so that their first observation point corresponded to (0, 0) and their last recorded point to (1,1). Then, across 101 normalized time-steps, the corresponding x and y coordinates were computed using simple linear interpolation. In order to assess the statistical reliability of any observed ambiguous-unambiguous trajectory divergences, and in an attempt to extract as much valuable information from these rich trajectories as possible, we conducted several different sets of analyses.

Context and Garden-Path Effects The mean ambiguous and unambiguous trajectories illustrated in Figure 1 demonstrate that, as hypothesized, in the one-referent context, the average ambiguous trajectory was more curved toward the incorrect destination and had lower velocity than did the average trajectory elicited by the unambiguous sentences. Noteworthy also is the fact that the average trajectory for the unambiguous sentences traveled to the correct destination much more quickly than did the average trajectory elicited by the ambiguous sentence. Both of these trends support the notion that participants were garden-pathed by the syntactic ambiguity manipulation.

In a preliminary attempt to discern whether or not the divergences observed across the ambiguous and unambiguous trajectories in the one-referent context were statistically reliable, we conducted a series of t-tests. Given the differences in velocity between the trajectories across the two sentence conditions, the t-tests were conducted across the x-coordinates of each sentence condition, and the y-coordinates of each sentence condition, separately, at each of the 101 time-steps. In order to avoid the increased probability of a Type-1 error associated with multiple t-tests, and in keeping with Bootstrap simulations of such multiple t-tests on mouse-trajectories (Dale, Kehoe, & Spivey, in press), an observed divergence was not considered significant unless the coordinates between the ambiguous and unambiguous sentences elicited p-values < .05 for at least eight consecutive time-steps.

In the one-referent context, two significant divergences were found when comparing the x-coordinates from the ambiguous and unambiguous trajectories at each time-step. The comparisons between sentence conditions from time-step 41 to time-step 54 all elicited p-values < .05 (all t's > 2.057). The average effect size, computed by Cohen's d, was .348, a medium-sized effect in the context of Cohen's benchmarks for effect size (Cohen, 1988). There were also significant differences (p's < .05) in x-coordinates from time-steps 64 to 79 (all t's > 2.057), with a medium-sized effect (average d=.347). The y-coordinates at each time-step were compared in the same manner for the ambiguous and unambiguous trajectories in the one-referent context. The t-tests revealed differences in y-coordinates from time-steps 29 through 82 (all p's < .05, all t's > 2.068), and the average d was .433, also a medium-sized effect. The same analyses were conducted on the x and y coordinates from the ambiguous and unambiguous trajectories at each time-step in the two-referent condition. For both the x-coordinate and y-coordinate comparisons, no single t-test yielded a p-value < .05 at any of the 101 time-steps.

In order to avoid concerns associated with multiple comparisons in the t-tests above, and to assess directly the statistical reliability of the context X ambiguity status interaction, we conducted two separate 2 X 2 X 3 ANOVAs, one for x-coordinates and one for y-coordinates. Based on time-steps, x and y-coordinates were grouped into three time-bins: 1-33, 34-67, and 68-101, yielding a third independent variable of segment. The three-way interaction was significant for the x-coordinates, $F(2, 78) = 5.06$, p=.009, and for the y-coordinates, $F(2, 78) = 48.75$, p < .0005. As illustrated, indirectly, in Figure 1, and demonstrated by the t-tests above, the effect is especially prevalent among the points comprising segment two. As such, only the context x ambiguity interaction at segment two will be considered in further detail here.

In the middle time segment, the context X sentence type interaction was significant for both the x-, $F(1, 39) = 7.15$, p = .011, and the y-coordinates, $F(1. 39) = 8.13$, p = .007. The means and standard errors for all possible combinations of the independent variables in the x- and the y-coordinate analyses appear in Table 1. To assess the context effect, we compared each point in the one-referent context to its commensurate point in the two-referent context. For the x-coordinates, there was no difference between coordinates in the one-referent context versus the two-referent context for the unambiguous sentences, $t(39) = .99$, n.s., but there was for the ambiguous sentences, $t(39) = 4.14$, p < .0005, d = .655, with the x-coordinates for the one-referent context being closer to the right side of the screen. For the y-coordinates, there was no difference in average screen location for the unambiguous sentences in the one- versus two-referent context, $t(39) = 1.26$, n. s., but there was for the ambiguous sentences, $t(39) = 3.71$, p = .001, d = .586, with the y-coordinates in the one-referent condition being closer to the top of the display.

Table 1: Means (SEs) for the middle-segment ANOVAs

Set	Context	Sentence Type	Mean Coordinate (SE)
X	One Referent	Ambiguous	527.02 (22.47)
		Unambiguous	575.95 (18.26)
	Two Referent	Ambiguous	613.15 (11.70)
		Unambiguous	592.14 (14.01)
Y	One Referent	Ambiguous	-340.06 (19.79)
		Unambiguous	-406.12 (13.81)
	Two Referent	Ambiguous	-416.47 (11.13)
		Unambiguous	-419.95 (9.84)

Finally, in order to account for both the x- and y-coordinates in one analysis, we computed the average Euclidean distance at each time-step between points in the ambiguous and unambiguous sentence conditions, per context. Figure 2 illustrates that the distance between the ambiguous and unambiguous trajectories in the one-referent context is similar during the beginning of the trial but then diverges such that the distance between the conditions is larger in the one-referent than in the two-referent context.

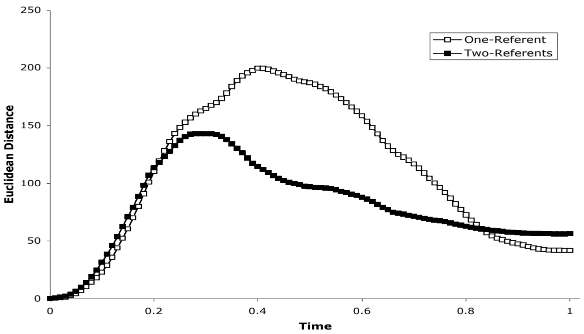

Figure 2. The Euclidean distance between the ambiguous and unambiguous sentence conditions, per context.

Paired-samples *t*-tests, conducted at each time-step as those above, revealed differences in the Euclidean distance between ambiguous and unambiguous sentence in the one versus two-referent context from time-steps 37 through 73, all p's $< .05$ (all t's > 2.107), with an average effect size of $d = .459$. In Figure 1, it is evident that in the one-referent context the average ambiguous trajectory is closer to the incorrect destination than the average trajectory at all of these time-steps. Thus, in the presence of the garden-path effect, it seems clear that there exists more attraction to the incorrect destination for the ambiguous sentences.

Serial versus Parallel Activation In order to assess whether or not the distribution of responses in the ambiguous conditions was bimodal (thus indicating only discrete garden-paths and discrete non-garden-paths), we computed the area under the curve on a trial-by-trial basis. First, a time-normalized straight line from the coordinates (0, 0) to (1, 1) of the observed trajectory from the trial was computed. Then the area (in pixels) between the straight line and the observed trajectory was calculated, thus resulting in an index of trajectory curvature. Area subtending toward the incorrect destination was coded as positive area, and area subtending in the opposite direction from the straight line was coded as negative.

Figure 3 illustrates the shape of the distribution of trajectory curvatures for the one-referent ambiguous trials (top panel) and the two-referent ambiguous trials (bottom panel). As an index of bimodality, we calculated the bimodality coefficient *b* (SAS Institute, 1989, based on work by Darlington (1970)—see DeCarlo (1997) for a discussion), which has a standard cut-off value of b=.555, whereby values greater than .555 indicate the presence of bimodality. Although we focus on the one-referent ambiguous response distribution here, Table 2 presents the descriptive statistics for each distribution, along with each distribution's corresponding bimodality statistic value. The b value for each distribution is less than .555, indicating no presence of bimodality within the distributions. Notably, with regard to the distribution of responses in the one-referent ambiguous condition, b < .555 indicates that the graded spatial attraction effects elicited in this condition came not from two different types of trials but from a single population of trials.

Table 2. Statistics necessary for the assessment of bimodality in distributions

Condition	n	Variance	Skewness	Kurtosis	Bimodality (*b*)
1 Referent Ambiguous	146	1.477E+10	-.289	-.535	.429
1 Referent Unambiguous	157	1.699E+10	-.126	-1.141	.529
2 Referents Ambiguous	150	1.629E+10	-.387	-.731	.493
2 Referents Unambiguous	159	1.647E+10	-.545	-.533	.514

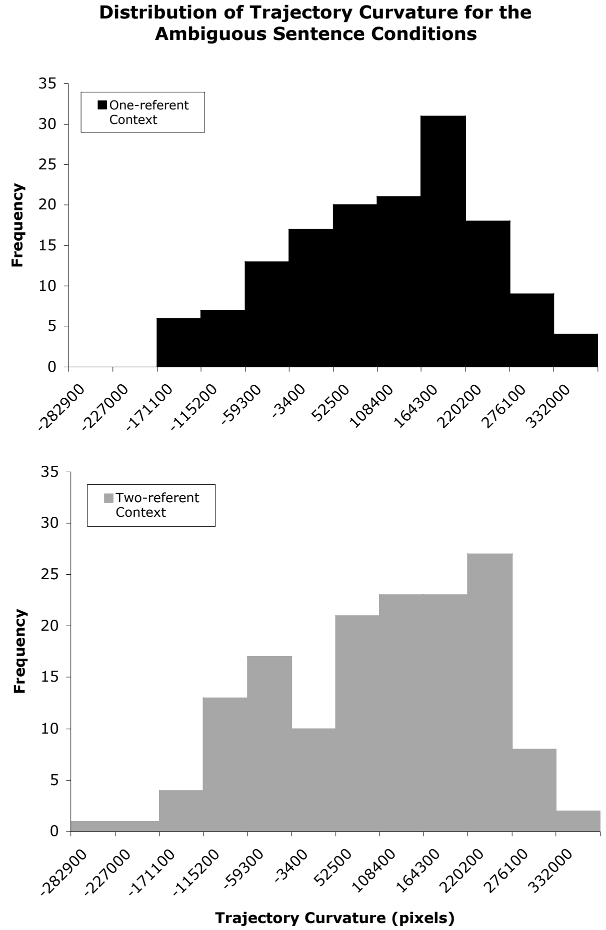

Figure 3. Distributions of trajectory curvature in the ambiguous sentence conditions. There is no evidence of a bimodal distribution in the one-referent context.

General Discussion

Converging evidence from the statistical analyses presented above shows that the effects traditionally associated with the visual-world paradigm are replicable with the mouse-tracking methodology. In the one-referent scene, participants' mouse movements in response to the ambiguous sentences curved significantly closer to the top-right of the screen (toward the incorrect destination) than in response to unambiguous sentences. Thus, it would seem that when only one referent was present, the incorrect destination (the towel) was partially considered relevant, until disambiguating information was processed — a trend corresponding to the garden-path effect associated with this condition. Importantly, the divergence between the x- and y-coordinates of the trajectories in the ambiguous and unambiguous conditions was completely absent in the two-referent context.

Additionally, by capitalizing on the continuous, non-linear, and non-ballistic properties of trajectories produced by mouse movements, mouse-tracking has the potential to answer questions that have traditionally been difficult to answer with more traditional methodologies. The lack of bimodality in the distribution of trajectory curvature in the one-referent ambiguous sentence condition suggests that the garden-path effect so frequently associated with this manipulation is not an all-or-none phenomenon. That is, the activation of one structural representation does not forbid simultaneous activation of other possible representations. Instead, the garden-path effect is graded, meaning that although sometimes one syntactic alternative may be strongly considered over another, it is also the case that, until disambiguating information is presented, both can be considered, in parallel – and the simultaneously active representations may compete over time. Moreover, the lack of bimodality in this condition alleviates the concern that the mean curvature found in the one-referent ambiguous condition is a result of collapsing across discrete movements to the correct destination and discrete movements to the incorrect destination that were followed quickly by movements to the correct destination.

The results presented here support multiple-constraint-based accounts of real-time language comprehension in two respects. As discussed above, the curvature-distribution analyses indicate graded sensitivity to syntactic ambiguity, thus denoting parallel partial activation. Additionally, the replication of the context effect demonstrates that non-syntactic, and indeed even non-linguistic, information can exert an early influence on syntactic processing.

More broadly, the results presented here demonstrate that the mouse-tracking technique can be used with tasks that involve complex and highly interactive displays. The results of this study also serve to attenuate worries that, given the large space of possible movements, data collected through the tracking of mouse movements might be too noisy to yield interesting and statistically reliable results. Finally, it is important to note that we do not advocate, or foresee, the usurping of eye-tracking data in light of the advantages of mouse-tracking enumerated here. Instead, we believe that the two techniques can be used in a complementary (even simultaneous) fashion in order to more fully unlock the nature of the complex interactions associated with high-level cognitive processes.

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