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Keep Listening: Grammatical Context Reduces but Does Not Eliminate Activation of Unexpected Words

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To understand spoken language, listeners combine acoustic-phonetic input with expectations derived from context (Dahan & Magnuson, 2006). Eye-tracking studies on semantic context have demonstrated that the activation levels of competing lexical candidates depend on the relative strengths of the bottom-up input and top-down expectations (cf. Dahan & Tanenhaus, 2004). In the grammatical realm, however, graded effects of context on lexical competition have been predicted (Magnuson, Tanenhaus, & Aslin, 2008), but not demonstrated. In the current eye-tracking study, participants were presented with target words in grammatically unconstraining (e.g., "The word is . . . ") or constraining (e.g., "They thought about the . . .") contexts. In the grammatically constrained, identity-spliced trials, in which phonetic information from one token of the target was spliced into another token of the target, fixations to the competitor did not differ from those to distractors. However, in the grammatically constrained, cross-spliced trials, in which phonetic information from the competitor was cross-spliced into the target to increase bottom-up support for that competitor, participants fixated more on contextually inappropriate competitors than phonologically unrelated distractors, demonstrating that sufficiently strong acoustic-phonetic input can overcome contextual constraints. Thus, although grammatical context constrains lexical activation, listeners remain sensitive to the bottom-up input. Taken together, these results suggest that lexical activation is dependent upon the interplay of acoustic-phonetic input and top-down expectations derived from grammatical context.

Keywords: spoken word recognition, eye-tracking, grammatical context, continuous integration

A common assumption of models of spoken word recognition is that hearing a word simultaneously activates multiple lexical items in memory (Luce, Goldinger, Auer, & Vitevitch, 2000; Luce & Pisoni, 1998; McClelland & Elman, 1986; Norris, 1994). For example, hearing the word "card" activates perceptually similar lexical representations (called "competitors") such as "carve" and "cart." In everyday listening situations, word recognition rarely occurs in isolation; instead, listeners typically have access to a wealth of semantic (Dahan & Tanenhaus, 2004), pragmatic (Chambers, Tanenhaus, & Magnuson, 2004), and grammatical (Dahan, Swingley, Tanenhaus, & Magnuson, 2000) context that may help guide recognition. A long-standing area of research in this topic attempts to explain how listeners integrate multiple sources of information (e.g., bottom-up [acoustic-phonetic] input and top-down expectations) to resolve lexical competition (Dahan, 2010; Pirog-Revill, Tanenhaus, & Aslin, 2008). For example, when the word "card" is preceded by "her grandmother mailed her a birthday . . ." is the competitor "carve" activated, even though it is grammatically and semantically unlikely?

Strictly bottom-up accounts (referred to in the literature as exhaustive access, multiple access, or access-selection models) argue that lexical selections are initially made based solely on the goodness-of-fit between the auditory input and representations in memory, and information about context is integrated later (Marslen-Wilson, 1989, 1987; Zwitserlood, 1989). According to this view, when a listener hears "her grandmother mailed her a birthday *card*," "carve" would initially be activated, and context would influence the selection of the correct word following activation. In contrast, accounts that prioritize the effect of context (referred to as restrictive access or selective access frameworks) propose that sufficiently strong context limits activation to contextually appropriate competitors, completely excluding inappropriate words (like "carve" in the previous example) from lexical access (Glucksberg, Kreuz, & Rho, 1986; Shillcock & Bard, 1993; Simpson, 1981; Tabossi, 1988).

An alternative to the access-selection and restrictive access frameworks is *continuous integration,* which proposes that multiple sources of information (e.g., bottom-up input and contextual expectations) are integrated immediately and continuously over time (Dahan & Tanenhaus, 2004; Gaskell & Marslen-Wilson, 2002). When the signal is unambiguous and there is no constraining context, the word recognition system will show strong bottom-up preference and the activated representations may largely reflect the degree of match between representations and phonetic input. In contrast, if the signal is ambiguous or degraded, or the context is strongly predictive, top-down

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influences are likely to take precedence and benefit activation of contextually appropriate candidates. Indeed, Magnuson, Tanenhaus, and Aslin (2008) argue that "it is possible to observe extreme possibilities along an early–late impact continuum with endpoints that resemble selective access to context-appropriate items (early) and exhaustive (late) access" (p. 871).

One method for assessing real-time lexical activation is the Visual World Paradigm (VWP), a technique that uses the tracking of eye fixations on a grid of images (or a display of real objects) to precisely determine when targets and competitors are activated. The VWP has been used widely in real-time psycholinguistic research and capitalizes on the assumed close alignment between estimates of lexical activation and proportion of fixations on visual elements (Brock & Nation, 2014; Cooper, 1974; Dahan & Tanenhaus, 2004; Huettig, Rommers, & Meyer, 2011; Tanenhaus, Spivey-Knowlton, Eberhard, & Sedivy, 1995). When the VWP is used to test the effects of semantic context on competitor activation, participants typically view a scene or set of images (the "visual world") including a target image to be selected (e.g., "bucket"), a cohort competitor (a competitor that shares onset with the target word, such as "buckle"; Marslen-Wilson, 1987), and two phonologically unrelated distractors. In one study, when participants were presented with a sentence without constraining semantic context like "click on the *bucket*," they fixated more on "buckle" than on distractors (Barr, 2008b). However, when the sentence provided strong semantic constraint, like "empty the *bucket*," fixations on "buckle" were significantly reduced, demonstrating early effects of semantic context on word activation.

Work using the VWP has highlighted the subtleties of how bottom-up and top-down information interact. In an initial experiment, Dahan and Tanenhaus (2004) presented participants with target words embedded in semantically constraining and unconstraining phrases and found that semantically inappropriate cohort competitors (referred to here simply as "competitors") were not fixated on more than distractors. However, in a second experiment, Dahan and Tanenhaus (2004) introduced a manipulation in which coarticulatory information from the competitor was cross-spliced into the target, increasing the phonetic similarity of the target and the competitor and thus pitting bottom-up input against top-down constraints. These stimuli were again presented in semantically constraining and unconstraining contexts. Following this subtle manipulation, participants fixated more on competitors than distractors in the constrained condition, despite poor semantic fit. This finding suggests that cross-spliced subphonemic and coarticulatory information from competitors can provide sufficient bottom-up support to overcome the effects of semantic context.

Partial activation of competitors has also been achieved by altering listener expectations using word frequency information. Weber and Crocker (2012) presented German participants with unconstrained sentences, such as "the woman finds the *Bluse* (blouse)," and constrained sentences, such as "the woman irons the *Bluse.*" The authors included competitors like "Blume" (flower) that had a higher frequency of occurrence in the language than the target word. Given that frequency modulates the extent to which lexical representations are activated (Dahan, Magnuson, & Tanenhaus, 2001), higher frequency competitors were expected to demonstrate activation despite poor semantic fit. In the critical constrained condition, participants fixated more on the higher frequency competitors ("Blume") than on unrelated distractors. These data demonstrate that semantic context downgraded but did not eliminate the activation of the contextually inappropriate competitor.

Other recent VWP research has provided further support for continuous integration accounts by demonstrating that listeners form expectations about likely lexical candidates prior to target onset while retaining sensitivity to the bottom-up signal (Altmann & Kamide, 1999; DeLong, Troyer, & Kutas, 2014; Kukona, Fang, Aicher, Chen, & Magnuson, 2011). In one study, participants heard sentences like "the boy will eat the white *cake*" while viewing four images: a white cake, a brown cake, a white car, and a brown car (Kukona, Cho, Magnuson, & Tabor, 2014). Prior to adjective onset, participants predominantly fixated on the images of the white cake and brown cake, demonstrating semantically driven anticipatory fixations to edible objects. As the adjective and noun unfolded, participants showed a higher proportion of fixations to "white car" than "brown car," indicating that they were still sensitive to the bottom-up phonological similarity between "white car" and the target "white cake," despite poor semantic fit.

In summary, there is broad support for continuous integration accounts of incorporating semantic context, indicating that competitor activation is affected by preceding context. Although the level of competitor activation is sometimes comparable to that of distractors (Barr, 2008b), it may be that context makes it difficult to distinguish low levels of activation from no activation at all. Indeed, two of the studies that have demonstrated weak activation of semantically inappropriate competitors were able to do so by employing cross-splicing manipulations (Dahan & Tanenhaus, 2004) or by choosing high-frequency competitors (Weber & Crocker, 2012) to increase competitor activation. Dahan and Tanenhaus (2004) demonstrated the subtlety of weak competitor activation by showing eliminated and reduced activation of competitors in the same paper; the two experiments used nearly identical word lists and only varied the bottom-up support for competitors.

In addition to semantic context, listeners have access to structural (grammatical) cues that may provide information about which words are likely to occur. For example, although the sentence "she thought about the *card*" provides minimal semantic context, given the syntactic rules of English, the word following "the" is most likely to be a noun (or a noun phrase initiated by an adjective). Listeners clearly make use of some types of grammatical cues; lexical decisions are faster when target words are preceded by a compatible gender-marked determiner (Colé & Segui, 1994; Jakubowicz & Faussart, 1998) or possessive adjective (Gurjanov, Lukatela, Lukatela, Savić, & Turvey, 1985) relative to an incompatible one, indicating that the grammatical markers activated lexical candidates that were consistent with the gender. Listeners also appear to be sensitive to the fact that words of different syntactic categories share form-based regularities, and use these for syntactic processing (Dikker, Rabagliati, Farmer, & Pylkkänen, 2010; Farmer, Christiansen, & Monaghan, 2006). Evidence from event-related brain potential (ERP) research suggests that listeners are sensitive to the proportion of grammatical and ungrammatical sentences in an experimental block (Coulson, King, & Kutas, 1998), and that they actively anticipate upcoming discourse based on grammatical context (Friederici, Hahne, & Mecklinger, 1996; Hagoort, 2003; Münte, Heinze, & Mangun, 1993).

Listeners also appear to use grammatical context very early in speech processing. Fox and Blumstein (2016) demonstrated that grammatical context can influence phoneme perception by varying the voice onset time of words starting with /b/ or /p/ (e.g., "bay" vs. "pay") in contexts ending in "to" or "the" (e.g., "She hated the *ay"). Following "the," participants were more likely to interpret an ambiguous string as a noun ("bay"), and vice versa for sentences ending in "to," a pattern that was apparent in the earliest moments of testing. Although this finding provides evidence that listeners use grammatical context to guide speech perception, it does not demonstrate how grammatical context influences the activation of lexical competitors. In other words, Fox and Blumstein (2016) showed that grammatical context can shift phoneme boundaries, but such a result does not address whether context affects the activation of the nonselected item (e.g., "pay" if the listener identified the ambiguous speech sound as "bay").

A relatively small body of VWP work using grammatical constraints has shown that grammatical context has strong and immediate effects on competitor activation. For instance, one study conducted in French found that presenting a gendered article (e.g., the masculine "le") before a noun eliminated activation of competitors that mismatched the gender of the article (e.g., grammatically feminine words, which require the article "la"; Dahan et al., 2000). Moreover, using an artificial lexicon in which words are associated with shapes (nouns) and textures (adjectives), Magnuson and colleagues (2008) demonstrated that the activation of grammatically inconsistent lexical candidates was eliminated. When presented with VWP displays that biased participants to expect words of one grammatical class, words of the unexpected grammatical class were not fixated on more than unrelated distractors. For example, given the pragmatic information that the situation did not require the use of an adjective (i.e., each of the four shapes was unique), objects with adjectives that sounded similar to the pictured nouns were not fixated on more than distractor items. Thus, measures relying on behavioral responses, ERPs, and eye-tracking have demonstrated that listeners often use grammatical context to guide their expectations about upcoming words.

In contrast, Riordan, Dye, and Jones (2015) demonstrated that listeners do not make use of all grammatical cues present in spoken language. The authors found that presenting morphosyntactic information about grammatical number (e.g., the word "are," indicating plurality in "Where are the lions?") did not cause listeners to fixate more quickly on numerically consistent items (like a picture of two lions). The authors suggest that this may be because number has low cue validity—although information about number may have been helpful in the study, this may not be true of language more generally (e.g., in cases such as "There are some tongs" or "She saw a herd of sheep"). Thus, the extent to which listeners use grammatical context to guide their expectations may be a function of the informativeness of the context. This is in line with the predictions of continuous integration accounts; it may be that grammatical number is a form of context that has sufficiently low predictive value that the speech recognition system prioritizes bottom-up input even when clues about grammatical number are provided (but see Brown, Dilley, & Tanenhaus, (2014) for evidence suggesting that listeners are quite sensitive to subtle changes in bottom-up information that may provide numerical clues about upcoming words).

Thus, research to date has demonstrated that listeners use grammatical context to guide word recognition in some, but not all, situations. Although this is consistent with the predictions of the continuous integration view, more compelling evidence for continuous integration would be to demonstrate in a single experimental paradigm that varying the strength of the bottom-up and top-down inputs affects activation of lexical competitors. Showing that competitor effects can be decreased by including grammatically constraining context and increased with additional bottom-up support would provide strong evidence for continuous integration accounts. Although graded effects of grammatical context on lexical activation (consistent with continuous integration) have been predicted (Magnuson et al., 2008), they have not been demonstrated empirically within a single study. The goal of the reported experiment was to evaluate how grammatical context affects competitor activation and assess whether additional bottom-up support for competitors can increase their activation even when grammatical context makes them unlikely.

The present experiment sought to test how grammatical constraints affect the processing of real English words by conceptually replicating and extending the findings of Dahan et al. (2000) and Magnuson et al. (2008). In the current experiment, participants viewed VWP displays with four pictures, such as "rug" (target), "run" (competitor), "bench," and "pray" (phonologically unrelated distractors), while their eye movements were monitored (see Figure 1). The task was presented in two forms: grammatically unconstrained (e.g., "The word is *rug*") and grammatically constrained (e.g., "They thought about **the** *rug*"). We predicted that the proportion of fixations to the grammatically inconsistent competitor (e.g., the verb competitor "run" for the target noun "rug") should be significantly reduced when the determiner is included in

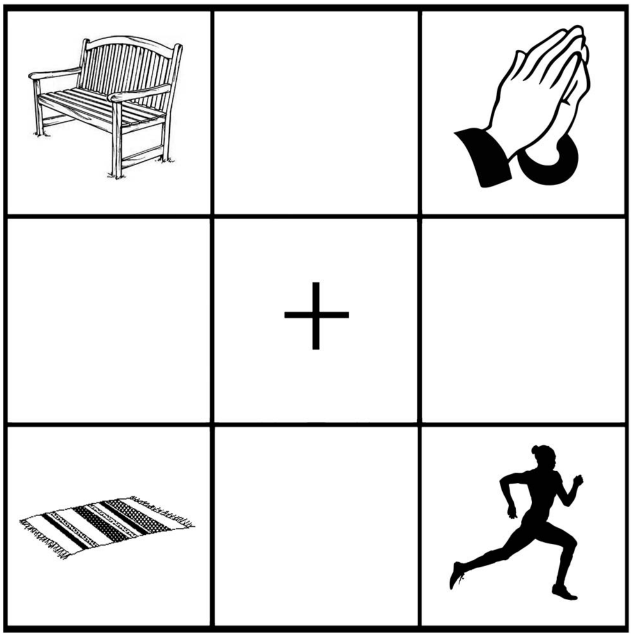

Figure 1. Sample Visual World Paradigm (VWP) display including the words "rug" (noun target), "run" (verb competitor), "bench," and "pray" (noun and verb phonologically unrelated distractors).

the carrier phrase, relative to when it is not included. We also expected that fixations to the grammatically inconsistent competitor would be greater if the target word contained acoustic-phonetic information consistent with the competitor than if it did not, in line with prior work (Dahan & Tanenhaus, 2004; Salverda, Dahan, & McQueen, 2003).

Method

Participants

We recruited 136 college-aged native English speakers with self-reported normal hearing and normal or corrected-to-normal vision from the Carleton College community. Data from one participant was lost due to experimental error, so the results below are based on 135 participants (note that data loss from one participant means the stimulus lists are not fully balanced). Carleton College's Institutional Review Board approved the research procedures. The study took approximately one hour and participants were compensated $10 for their time.

Selecting and Generating Stimuli

To select the target words, we first identified all nouns and present-tense verbs that contained five or fewer phonemes in an online dictionary containing phonological transcriptions (Balota et al., 2007). Of those, we searched for word pairs that share all but their final phoneme, and excluded potentially offensive words and stimuli that would be difficult to represent with pictures (e.g., *lore*). Although perceptually similar words that differ from the target at onset also provide lexical competition (Allopenna, Magnuson, & Tanenhaus, 1998), the time course of competition differs from that of cohort competitors. Therefore, the current study included only competitors that overlapped at onset with the target word.

Speech stimuli were recorded at 16-bit, 44100 Hz using a Shure KSM-32 microphone with a plosive screen by a female speaker with a standard Midwestern accent, and were equalized on root-mean-square (RMS) amplitude using Adobe Audition (Version 9.2.0). Cross-spliced sentences were created by splicing the initial portion of a sentence containing the competitor into the final portion of the target word (following the procedures of Dahan, Magnuson, Tanenhaus, & Hogan, 2001; Dahan & Tanenhaus, 2004). The splicing occurred after the vowel for the majority of words, but for 10 of the stimuli the target word was fully embedded within the competitor word or vice versa (e.g., target "boy" and competitor "boil" or target "hold" and competitor "hole"). In these cases, a portion of the final phoneme from a recording of the target sentence was added to the end of the cross-spliced token if that token sounded abrupt and unnatural. For example, the cross-spliced token of the target word "boy" (competitor: "boil") was created by splicing the end of the "oy" sound in "boy" into the end of the sentence "they thought about the boi(l)," after the "l" had been removed. We also constructed an identity-spliced version of each sentence, in which one token of the target sentence was spliced into another token of the same sentence (see Table 1 for examples of cross-spliced and identity-spliced stimuli). This was done to ensure that all words were spliced, so that any differences in cross-spliced and identity-spliced trials were not a function of the splicing itself (Dahan & Tanenhaus, 2004; Salverda et al., 2003). Filler trials (see below) were all identity-spliced, since competitors of the targets in filler trials were not included in the experiment. In a pilot test, two naïve listeners were asked to transcribe the cross-spliced and identity-spliced sentences to ensure intelligibility. Incorrectly perceived tokens (i.e., those that deviated in any way from the intended target for either listener) were re-spliced to include more of the target word.

The visual stimuli were 520 black and white line drawings (4 images for each of 128 critical trials, plus 8 images used in 2 practice trials) selected from Cycowicz, Friedman, Rothstein, and Snodgrass (1997) and Duñabeitia et al. (2017), and were supplemented with line drawings from online sources. The VWP displays were created with Adobe Photoshop CS5, and included a 3 × 3 grid with one drawing in each corner cell and a fixation cross in the center. The individual images were approximately 7.5 cm square on the screen, filling approximately eight degrees of the visual field for participants seated a comfortable distance from the screen. Targets and competitors appeared equally often in each position within the grid. The grids were combined with the prerecorded sentences to create videos for each trial using Final Cut Pro X.

Design

In each of the 128 trials, participants were presented with a VWP display and were instructed to click on one of the images by a prerecorded voice. Participants were randomly assigned to receive instructions in either a grammatically unconstraining context ("The word is [*target*]") or a grammatically constraining context

Table 1
Examples of Critical, Grammatically Constrained Trials

Condition	Noun target, noun competitor (NN)	Noun target, verb competitor (NV)	Verb target, noun competitor (VN)	Verb target, verb competitor (VV)
Target	BRICK	KNOT	CARVE	SHAKE
Competitor	bridge	knock	card	shave
Identity-spliced	THEY FIXATED ON THE BRICK	THEY CAME UPON THE KNOT	THEY PREPARED TO CARVE	THEY WERE REQUIRED TO SHAKE
Cross-spliced	they fixated on the briCK	they came upon the knoT	they prepared to carVE	they were required to shaKE

Note. Sentences were also presented in a grammatically unconstrained context ("The word is [*target*]") that followed the same splicing protocol. Articulatory information from the target word is shown in capital letters, and information from the competitor is shown in lowercase letters. In the identity-spliced trials, one token of the target sentence was spliced into a different token of the same sentence. See the Appendix for a full list of stimuli.

that included the word “the” (for nouns) or “to” (for verbs) prior to the target (e.g., “They thought about **the** [*target*]” or “They began **to** [*target*]”). The constrained sentences were constructed to provide grammatical context that biased the final word to be either a noun or a verb, while avoiding the use of constraining semantic context. For each participant, half the words were cross-spliced and half were identity-spliced. For each target word, the constraint condition was counterbalanced across participants using lists such that half of the participants heard a given target word in the constrained context and the other half heard the same target in the unconstrained context. For example, every participant was presented with the word “card” in the same visual display but it was preceded by “The word is . . . ” for half of the participants and by “They discussed the . . . ” for the other half, and the word was cross-spliced for half of the participants and identity-spliced for half (balanced across constraint condition).

Each display contained one noun and one verb distractor. This arrangement was used to ensure that participants could not use any strategic processing to determine which words were likely to be targets based on the composition of the distractors. Each participant saw each grid once, presented in a pseudorandomized order. Each of the 128 trials and two practice trials contained unique images that only appeared in that trial. Half the trials were critical items used in the analyses and half were fillers.

Critical Trials

Of the 64 critical trials, half included a target and competitor that were the same part of speech (*congruent* trials): either a noun target with a noun competitor (NN) or a verb target with a verb competitor (VV). The other half (*incongruent* trials) had either a noun target with verb competitor (NV) or a verb target with a noun competitor (VN). Within each trial type (16 trials for each of the four types NN, VV, NV, VN), targets and competitors were matched on frequency (Brysbaert & New, 2009), number of phonological neighbors (Balota et al., 2007), number of cohort competitors (see Appendix), phonological length, and orthographic length ($p > .20$ for all). As is typical with short English words, some target words could function as a noun or a verb (e.g., “ring”), but stimuli had an average part of speech dominance of .92, indicating that they appeared as the intended part of speech in 92% of instances in the SUBTLEX-US Database (Brysbaert, New, & Keuleers, 2012). See Appendix for a full stimulus list.

The other two images in each grid were a phonologically unrelated noun and a phonologically unrelated verb. Distractor images were matched to the target and competitor lists on frequency and number of neighbors. We avoided target words that began with /t/, /θ/, or /ð/ to ensure that participants would not be led to fixate on those when hearing the words “to” or “the” in the carrier phrase.

Filler Trials

Sixty-four filler trials were constructed in a similar manner to critical trials. However, given the large number of unique images required for the study, we exhausted the supply of imageable, present tense words that serve primarily as verbs. Thus, some filler trials included items that occur more commonly as other parts of speech but can also function as verbs. For example, “tug” was included as a verb distractor item even though it occurs as a verb in only 39% of instances according to the SUBTLEX-US norms. The images selected for these low part of speech dominance items were strongly biased to indicate the verb interpretation of the word (e.g., people playing tug-of-war) rather than another interpretation (e.g., a tug boat).

Forty trials included a target (half nouns, half verbs) and three phonologically unrelated distractors. An additional 24 trials included a target (half nouns, half verbs), a phonologically unrelated distractor, and two distractors that were phonologically unrelated to the target but competitors of one another (e.g., target “drill” with competitors “sway,” “path,” and “pack”). These were included to prevent participants from assuming that similar sounding words presented in the same grid were more likely to be targets (Dahan et al., 2000; Dahan & Tanenhaus, 2004).

Apparatus

Participants sat a comfortable distance away from a 24-inch PC monitor. Stimulus presentation and participant responses were controlled with Tobii Studio (Version 3.2) and auditory materials were presented at approximately 65 dB SPL via Sennheiser HD-280 Pro headphones. Participants’ fixation data were collected at 60 Hz with the Tobii ×2-60 eye-tracking system. A custom script was used to return the cursor to the center of the display at the beginning of each trial. Participants’ eye movements were calibrated using Tobii Studio’s 9-point calibration pattern.

Procedure

Prior to beginning the eye-tracking task, participants were trained on the names of the images using a custom computer script. First, participants saw each of the 520 images along with its name in a random order, at self-paced intervals. Next, they saw each picture in a different randomized order and were asked to verbally provide its name. An experimenter coded their responses for accuracy and the written name was presented again for incorrect guesses. Images that were identified incorrectly were repeated again at the end of training until participants could correctly identify each image. All participants were able to successfully learn all the images.

After the image training, participants completed the eye-tracking task. Each trial began with a blank grid for one second, followed by the addition of the visual world for 500 ms before the audio was presented. Participants were told to click on the picture indicated by the instructions. Participants completed two practice trials prior to the start of the experiment.

Results

All raw data and code for analyses and figures are publicly available at http://osf.io/8hv7a. Given the common assumption that it takes approximately 200 ms (Rayner, Slowiaczek, Clifton, & Bertera, 1983) to program and launch an eye movement (Fischer, 1992), the window of analysis started 200 ms after the onset of each target word and ended 530 ms later (the average length of the target words). Thus, the window of analysis was offset 200 ms from the start and average end of the target words, for a total of 32 frames of data for each trial. Trials in which participants clicked on the inappropriate object (5% of trials, all of which involved the participant clicking the competitor rather than the target) were excluded from analysis. Unsurprisingly, accuracy was numerically higher in identity-spliced than cross-spliced trials (98% and 92%, respectively). Accuracy was also slightly higher in constrained than unconstrained trials (98% and 95%), but quite similar in congruent and incongruent trials (96% and 95%). Participants showed relatively typical patterns of VWP data, with fixation proportions to targets rising steadily, brief increases in fixation rates to competitors, and relatively low levels of fixations to distractors throughout (see Figure 2).

Following the procedures of Fine and Jaeger (2013) and Thothathiri and Snedeker (2008), the dependent variable in our analyses was the number of frames with fixations to the competitor minus the number of frames with fixations to the averaged distractors during the critical time region (referred to here as the "competitor preference"). This enabled us to evaluate the extent to which participants preferentially looked at competitors relative to distractor objects on the screen. In line with the recommendations of Barr (2008a), counts were empirical logit-transformed before the difference scores were calculated (see also Kukona et al., 2014 for use of empirical logit-transformations in the VWP). Figure 3 shows mean competitor preference scores by condition. Note that although the analyses included logit-transformed counts of frames with fixations, the line graph (see Figure 2) shows untransformed proportions of fixations over time, as is customary in the literature.

Eye movements were analyzed using linear mixed-effects models via the lmer4, languageR, and lmerTest R packages (R Core Team, 2016), version 3.4.0 (see Baayen, Davidson, & Bates, 2008; Jaeger, 2008 for arguments about the benefits of mixed effects models over analyses of variance; ANOVAs). We used sum contrasts to make the model intercept equivalent to the grand mean and variables were coded as follows: for the splicing variable, cross-splicing = 1, identity-splicing = −1; for the constraint variable, constrained = 1, unconstrained = −1; and for the target/competitor congruence variable, congruent (NN & VV) = 1, incongruent (NV & VN) = −1. We employed the maximal random effect structure justified by sample (Barr, Levy, Scheepers, & Tily, 2013). In cases of nonconvergence, the summaries of partially converged models were examined and random slopes with the smallest variance were removed until the model converged.

Participants and items were entered into the model as random effects, and between-subjects constraint condition (constrained vs. unconstrained) and within-subjects splicing (cross- vs. identity-spliced), and within-subjects trial congruence (congruent vs. incongruent) were entered as fixed effects, along with the crucial constraint-by-trial congruence interaction. The effect of splicing was significant ($\beta = .17$, $SE = .05$, $t = 3.78$, $p < .001$), and the positive sign indicates that competitor preference was higher in cross-spliced than identity-spliced conditions. This indicates that the splicing manipulation was successful in increasing bottom-up support for the competitor. The effect of congruence was significant ($\beta = .12$, $SE = .05$, $t = 2.65$, $p = .008$), indicating that overall, participants showed greater competitor preference in the congruent (NN & VV) trials than the incongruent (NV & VN) trials. The effect of constraint was not significant ($\beta = -.01$, $SE = .05$, $t = -.26$, $p = .80$), suggesting that competitor preference was not systematically affected by grammatical

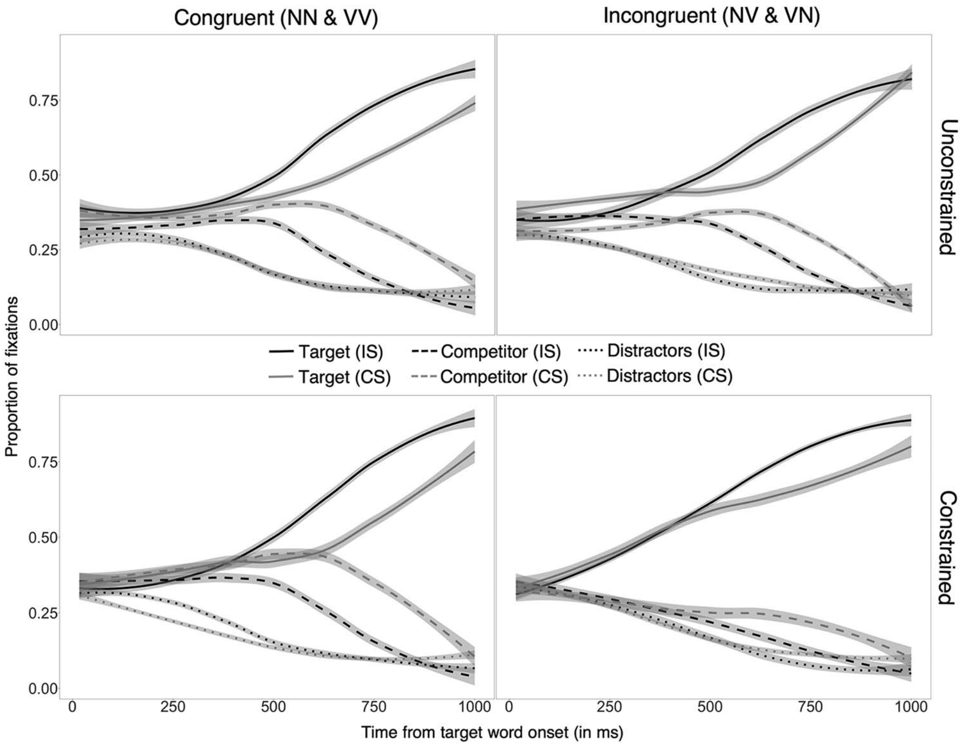

Figure 2. Proportion of fixations to targets (solid lines), competitors (dashed lines) and distractors (dotted lines). Black lines show identity-spliced (IS) stimuli and gray lines show cross-spliced (conditional stimulus; CS) stimuli. Shaded regions represent 95% confidence intervals.

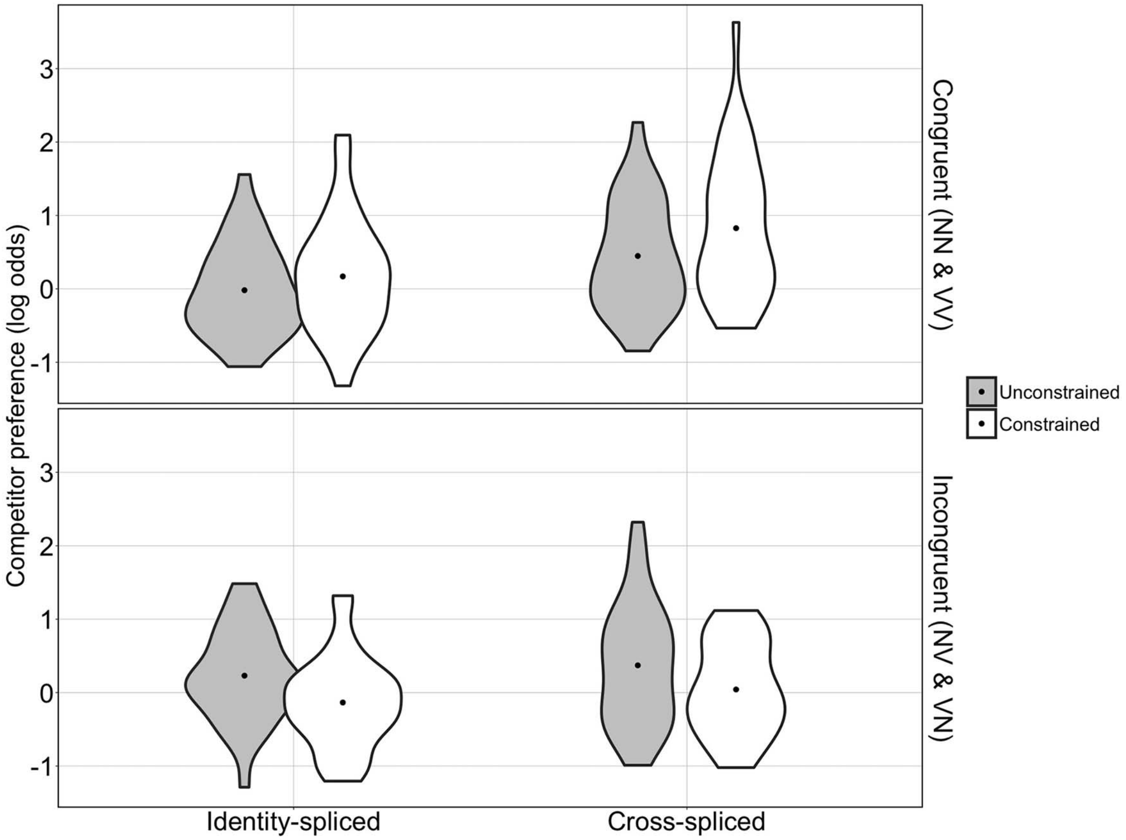

Figure 3. Violin plot showing kernel probability density of competitor preference values (dots = condition means) by splicing, congruence, and constraint for the critical time window.

context when collapsing across conditions. Of most interest to the current study was a significant constraint-by-congruence interaction ($\beta = .15$, $SE = .05$, $t = 3.35$, $p = .001$), indicating that the effect of adding grammatically constraining context differed by congruence condition.

To explore the nature of this interaction, we evaluated the effects of constraint for each congruence condition separately. This revealed that constraint marginally affected congruent trials ($\beta = .14$, $SE = .08$, $t = 1.87$, $p = .06$), with slightly more competitor preference in the constrained than the unconstrained trials. This slight increase may be attributable to the fact that the grammatically constraining context reduced fixations to the grammatically inappropriate distractor items. In contrast, in the incongruent trials, competitor preference was significantly reduced in the constrained trials relative to unconstrained ones ($\beta = -.17$, $SE = .06$, $t = -2.73$, $p = .007$). Thus, constraining context reduced fixations to grammatically unexpected items but not grammatically expected ones.

To assess whether the decision to collapse across congruent (NN & VV) trials and incongruent (NV & VN) trials was warranted, we built a model that included a congruence-by-constraint-by-target type (noun vs. verb) interaction. A significant three-way interaction would suggest that the interaction of interest (constraint-by-congruence) was different for trials with noun versus verb targets. This interaction was not significant ($\beta = -.05$, $SE = .04$, $t = -1.22$, $p = .22$), suggesting that the critical constraint-by-congruence interaction was similar for noun and verb targets.

Prior work (Dahan et al., 2000; Magnuson et al., 2008) has tended to show that activation of grammatically unexpected competitors is reduced to the level of the distractors. The current study tested whether activation of grammatically inconsistent competitors could be revealed when coarticulatory information from the competitor is included in the target, thereby increasing bottom-up support for the competitor. Therefore, to assess whether fixations to the competitors were greater than those to the distractors in conditions with additional bottom-up support for the competitors, we created a model to predict the logit-transformed fixation rates to competitors and distractors with object (competitor vs. distractor) as a fixed effect (coded 1 and −1, respectively), and items and participants as random effects, specifically within the grammatically constrained, incongruent condition. These are the trials of most interest to the current study, as participants hear contextual information that should bias against the (grammatically incongruent) competitor. In the incongruent, identity-spliced condition, fixations to competitors and distractors were comparable ($\beta = .02$, $SE = .04$, $t = .46$, $p = .65$). However, competitors were fixated on significantly more than distractors in the incongruent, cross-spliced conditions ($\beta = .08$, $SE = .03$, $t = 2.90$, $p = .004$), indicating that strong bottom-up support elevated activation for competitors above distractors, even when top-down grammatical constraint made them unlikely.

Discussion

A continuous integration view predicts that when contextual constraints are weak, lexical activation is driven primarily by bottom-up input; when contextual cues are stronger, however, lexical activation is a function of the goodness-of-fit between the acoustic support for a word and the preceding context. Here, we found that fixations to grammatically incompatible competitors were significantly reduced when naturalistic syntactic constraints in English made them improbable, but adding bottom-up support for competitors via cross-splicing increased fixations to those competitors. Thus, these results provide the first evidence for the immediate but graded influence of grammatical context on activation of lexical competitors.

Why might listeners retain sensitivity to the bottom-up input even in the face of strongly constraining context? This approach may promote flexibility in the word recognition system that enables listeners to parse nonliteral language (e.g., "she cut him down with her *words*" is semantically unexpected but quite interpretable). Retaining grammatical flexibility may facilitate the understanding of language change, as English has many words that began as one part of speech and were converted to another (Pinker, 1994). For example, in recent years, the nouns *dialogue*, *bookmark*, and *google* have all entered common usage as verbs.

Although the current study supports the continuous integration view for one form of grammatical context (cues to part of speech), it is possible that other forms of grammatical context may influence lexical activation differently. For example, Riordan and colleagues (2015) found that listeners do not appear to use information about grammatical number to constrain lexical activation. The authors suggest that the differences between the consequences of grammatical number and other previously explored forms of grammatical context (e.g., gender) may be attributable to the fact that number is semantically meaningful whereas gender is arbitrary, or that gender is a property of the item but number is an independent feature. Thus, it may be that some features of grammatical context are more relevant than others for constraining listener expectations.

Future work should test the robustness of these findings on other forms of grammatical context that have been shown to be informative. For example, although prior work on grammatical gender (Dahan et al., 2000) showed that a gendered article reduced activation of grammatically incongruent competitors to the level of the distractors, it may be that increasing bottom-up support for the competitors reveals partial activation of contextually inappropriate competitors. Alternatively, it is possible that listeners simply use grammatical gender and cues to part of speech differently. Grammatical gender may place stronger restrictions on lexical access, given that nouns in French are almost always preceded by their gendered article, but in English, nouns and verbs need not be preceded by "the" and "to," respectively (see Dahan et al., 2000). Thus, the regular co-occurrences present in French may lead to more restrictive consequences of grammatical gender. Both of these scenarios would be consistent with continuous integration, but examining the differences in how listeners process different types of context can elucidate the subtleties of the interplay of bottom-up and top-down influences. Therefore, future work is necessary to determine whether the effects demonstrated here extend to other types of grammatical context.

Consensus is building that listeners simultaneously integrate multiple forms of context with phonological input during spoken word recognition (Dahan & Tanenhaus, 2004; Gaskell & Marslen-Wilson, 2002). However, a mechanism to account for the influence of context has not yet been incorporated into the Neighborhood Activation Model (NAM; Luce & Pisoni, 1998) or the TRACE model (McClelland & Elman, 1986), two influential models of spoken word recognition that seek to describe the processes and consequences of lexical activation and competition. These models have typically focused on how bottom-up input simultaneously activates multiple lexical candidates, and how word recognition is achieved from among these activated representations. Given the accumulating evidence from the current study and other studies demonstrating the effects of context on word recognition, incorporating mechanisms to account for contextual integration is likely to improve the predictive power of these models. Strand and colleagues (2014) suggested that the TRACE model could be modified to incorporate grammatical context effects by including a grammatical class level above the word level in the model architecture. As grammatically constraining information is processed, activation would increase in the corresponding grammatical class nodes, which would then send activation down to words of that grammatical class. Thus, competitors that are not grammatically appropriate would receive less activation than those that are. Although the findings of the current study are consistent with this hypothesis, the study was not intended to be a test of such a model, so further research is necessary to test its viability.

Perceiving spoken language is a cognitively and perceptually demanding task that requires listeners to make use of multiple forms of context along with the phonological input. The current study provides additional evidence about how listeners incorporate grammatical context. The results suggest a similarity in how semantic and grammatical information are used, and demonstrate that listeners make use of contextual constraints very early in word processing while remaining sensitive to bottom-up acoustic input as words unfold.

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(*Appendix follows*)

Appendix

All Target, Competitor, and Distractor Items That Appeared in the Experiment and Lexical Variables for the Targets and Competitors

Target	Frequency	PND	Cohort size	Competitor	Frequency	PND	Distractors	
				Type: NN				
bean	2.54	30	69	beach	3.46	21	chain	skate
brick	2.72	12	55	bridge	3.37	6	rib	hang
cake	3.36	24	61	cage	3.01	15	moon	smell
cap	2.98	29	418	cab	3.26	21	pipe	blow
chess	2.58	11	46	chest	3.32	17	bus	give
chin	2.81	21	61	chimp	2.19	5	steak	beg
cone	2.18	31	163	coat	3.33	26	ring	push
ham	2.77	33	201	hand	4.15	13	corn	play
head	4.28	28	207	hedge	1.90	11	fork	rub
heart	4.10	15	172	harp	2.13	8	belt	weld
lake	3.26	31	66	lace	2.28	27	key	walk
roof	3.26	16	90	root	2.73	31	bow	fall
sheep	2.84	27	27	sheet	2.77	31	raft	crawl
ship	3.70	20	60	shin	2.20	26	bed	wag
worm	2.71	10	78	world	4.37	10	bike	pick
yarn	1.91	3	15	yard	3.11	13	match	stir
				NV				
bat	3.02	37	238	bask	1.48	6	peach	shear
boy	4.43	17	17	boil	2.48	17	nurse	squeeze
cheese	3.30	24	27	cheat	2.96	20	seed	pull
dish	2.77	14	1158	dig	3.37	19	plane	climb
eel	1.87	16	100	eat	4.11	12	couch	mow
feet	3.79	22	72	feed	3.34	26	loaf	sail
fish	3.63	12	204	fix	3.65	15	shelf	kneel
grove	2.30	13	29	grow	3.48	8	duck	knit
hip	2.90	27	138	hit	4.15	31	soup	build
knot	2.28	29	154	knock	3.52	25	purse	sing
lid	2.40	24	209	lick	2.75	30	knife	bathe
lunch	3.73	7	76	lunge	1.40	2	nose	serve
page	3.28	16	111	pay	4.11	27	star	wake
rug	2.73	21	97	run	4.25	31	bench	pray
shoe	3.19	33	18	shoot	3.92	16	boat	fetch
stove	2.59	6	27	stow	1.81	7	glass	bounce
				VN				
blare	1.32	8	17	blade	2.82	9	farm	save
burn	3.45	24	91	bird	3.37	29	shell	wipe
carve	2.2	7	589	card	3.64	24	map	speak
cut	4.07	25	145	cup	3.42	15	box	laugh
dine	2.34	31	140	dime	2.79	23	sock	poke
fill	3.35	33	204	film	3.52	6	cart	sift
fold	2.64	25	79	phone	4.14	27	gate	bend
grab	3.56	7	96	graph	1.59	6	scale	jump
graze	1.6	17	65	grave	3.13	16	band	swim
hail	2.79	41	43	hay	2.51	25	nest	merge
hide	3.55	32	124	hive	1.71	15	mouse	snap
hold	4.35	22	108	hole	3.47	37	web	drive
kick	3.57	23	79	king	3.82	16	waist	dial
listen	4.44	5	209	list	3.61	22	dog	wrap
move	4.33	11	38	moose	2.45	20	car	weigh
wish	4.08	14	176	witch	3.15	18	robe	cheer

(*Appendix continues*)

Appendix (*continued*)

Target	Frequency	PND	Cohort size	Competitor	Frequency	PND	Distractors	
				VV				
bake	2.51	31	67	baste	1.28	23	wave	send
catch	3.84	19	418	cast	3.07	21	fence	pluck
choose	3.39	17	7	chew	2.67	30	fan	learn
draw	3.31	2	13	drop	3.82	5	shark	flip
honk	2.09	4	172	hop	2.99	15	clam	sit
lean	2.72	35	81	leave	4.46	21	salt	clap
mend	2.13	17	197	melt	2.57	13	bull	help
reach	3.46	21	438	read	4.09	35	flag	sew
rinse	2.08	7	726	rip	3.01	31	pole	share
rise	3.15	37	84	write	3.81	35	chef	meet
shake	3.31	24	41	shave	2.85	17	grape	cry
shut	4.13	18	34	shove	2.83	6	vase	fly
spill	2.64	9	35	spit	2.99	10	wine	print
stop	4.56	9	73	stomp	2.14	0	ball	yell
wash	3.32	8	75	watch	4.23	6	dock	hurt
wilt	1.97	18	176	win	3.84	30	stool	vote

Note. Frequency values were obtained from the SUBTLEX-US database (Brysbaert & New, 2009) and PND values from the English Lexicon Project (ELP) database (Balota et al., 2007). Number of cohort competitors was calculated by determining the number of words in the ELP lexicon that have the same onset. For words that begin with a consonant, that includes all words that share the initial consonant or consonant cluster and vowel. For example, cohort competitors of "card" include "car," "contrast," and "constitutional," among many others. For vowel-initial words, cohort competitors include all words that begin with that vowel sound. Cohort size is only listed once because the target and competitor necessarily have the same cohort size. PND = Phonological Neighborhood Density; NN = noun target, noun competitor; NV = noun target, verb competitor; VN = verb target, noun competitor; VV = verb target, verb competitor.

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