Verb Meanings, Object Affordances, and the Incremental Restriction of Reference

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Abstract

There has traditionally been significant interest in the role of verb semantic ristrictions in both psycholinguistic and computational theorizing about language interpretation (e.g., McRae, Spivey-Knowlton, & Tanenhaus, 1998; Resnik, 1996; Trueswell, Tanenhaus, & Garnsey, 1994). The bulk of this research has focused on how such information influences syntactic choices during parsing. The current paper explores in detail the time-course of, and mechanisms for, on-going referential processing. While their eye movements were recorded, subjects acted upon spoken instructions such as "Now I want you to fold the napkin." The verb was either highly constraining (e.g., "fold") or weakly constraining ("pick up"); the array contained either just one object with the appropriate affordances (the target) or two such objects (the target and a competitor). We provide evidence that listeners are capable of rapidly constraining the domain of reference of upcoming constituents to multiple objects with appropriate semantic affordances, which compete for referential consideration. Moreover, in relation to computational theorizing on this topic, the eyemovement patterns suggest that a verb's informativeness (i.e., the "tightness" of the semantic space of possible constituents, Resnik, 1996) affects the speed with which listeners can compute the domain of reference of upcoming constituents.

Introduction

Psychologists have been interested in the process of language comprehension since the earliest days of generative grammar (Fodor & Bever, 1965; Miller & Isard, 1963; Slobin, 1966). Most comprehension studies have focused on the problem of syntactic ambiguity resolution – how listeners or readers decide among competing structural analyses (Caplan, Baker, & Dehaut, 1985; Crain & Steedman, 1985; Ferreira & Clifton, 1986; Frazier & Fodor, 1978; MacDonald, Pearlmutter, & Seidenberg, 1994; Trueswell et al., 1994, among many others). In the last several years, however, there has been a growing interest in on-line *semantic* interpretation – in particular, the extent to which listeners can use combinatory semantic information to determine the reference of words and phrases in a rapid, incremental fashion. Much of this work has been conducted in the so-called visual world paradigm, in which listeners manipulate the contents of a miniature world as their eyes are tracked by a head-mounted visor (Sedivy, Tanenhaus, Chambers, & Carlson, 1999; Tanenhaus, Spivey-Knowlton, & Sedivy, 1995). In this paper we provide evidence, using this paradigm, that the meanings of verbs become available to listeners rapidly enough to constrain the domain of reference for the upcoming direct object.

By virtue of what they mean, words often impose restrictions upon the semantics of other words that appear with them. Many prepositions impose restrictions on the geometric properties of their objects (see especially Landau & Jackendoff, 1993); *through*, for instance, requires that its object have some kind of hole. Verbs are especially picky in this regard: The subject of a verb must be the sort of thing that can perform the denoted action, and the direct object must be the sort of thing that can be sensed, manipulated, or changed in the relevant way. The verb *drink*, for instance, requires a subject capable of drinking, and a direct object capable of being drunk. Hence while *John drank the juice* sounds perfectly natural, both *The table drank the juice* and *John drank the table* register as distinctly odd. Although semantic restrictions have long played a role in linguistic theory (e.g., Chomsky, 1965; Jackendoff, 1972) and in the study of syntactic processing (Boland & Boehm-Jernigan, 1998; McRae et al., 1998; Tabossi, Spivey Knowlton, McRae, & Tanenhaus, 1994; Trueswell et al., 1994) little research has been done until recently to examine their potentially important role in on-line referential processing.

Using the visual world paradigm, Chambers, Eberhard, Carlson, and Filip (1998) have demonstrated rapid access to the meaning of the preposition *inside* and its use to restrict the referential domain of definite noun phrases. Participants in their experiment sat before an array of objects including a duck, a rope, a napkin, a can, and a whistle. When they were instructed to "Put the whistle inside the can," participants launched eye movements to the can even before the onset of the noun. The meaning of *inside* provided enough information for listeners to limit the referential domain of the upcoming noun phrase to the one object with the appropriate physical properties (or *affordances*, in the terms of Gibson, 1977). Crucially, such movements were not found when the preposition was *below* – which does not constrain the affordances of its object – or when the array contained two additional objects with an interior volume (a bowl and a glass).

While highly suggestive, these results are limited in two ways. First, Chambers et al. used only one lexical item (*inside*), and so it is unclear whether semantic restrictions are rapidly available across a range of lexical items. Second, prepositions are generally considered to be closed-class items (Talmy, 1988), which differ from open-class items in a number of important ways, including frequency and semantic richness (Friederici, 1985; Gordon & Caramazza, 1985; Neville, Mills, & Lawson, 1992; Van Petten & Kutas, 1991). Perhaps it is the status of *inside* as closed-class that makes its semantic restrictions so readily available.

Evidence that bears on both of these concerns comes from a recent study by Altmann & Kamide (1999), who used a modified version of the visual world paradigm to explore the online processing of verbs. In their experiment, participants sat before a computer screen displaying several pieces of clip art: for example, a boy, a toy train, a toy car, a birthday cake, and a balloon. Listeners heard the scene described with one of two sentences: "The boy will move the cake," or "The boy will eat the cake." In the first case, multiple objects in the scene satisfied the semantic restrictions of the verb; in the second case, only the cake did so. Altmann and Kamide found that eye movements to the target were launched more rapidly after *eat*-type verbs (where the verb picked out only one object in the array) than after *move*-type verbs (where the verb picked out multiple objects). Looks to the target object were always delayed for *move*-type verbs until after hearing the definite NP *the cake*. These results suggest that semantic restrictions are rapidly available for open-class verbs as well-as for closed-class prepositions, and across a range of lexical items.

Like the Chambers et al. (1998) experiment, the Altmann and Kamide study also has some features that limit what we can conclude about the on-line use of semantic restrictions. First, participants in one of their experiments had to indicate (with a button press) whether the sentence matched the visual scene (in half of all trials, the sentence did *not* match the scene). This metalinguistic judgment might have caused participants to process the incoming sentences in a strategic, non-natural fashion, perhaps encouraging them to focus more closely on verb information than they otherwise might have.[1]

More importantly, the two experiments reported in Altmann and Kamide provide conflicting evidence for the use of semantic restrictions to constrain referential domains. If listeners rapidly exploit the semantic restrictions of verbs to constrain the domain of reference, they should spend less time looking at inedible objects following *eat* than following *move*. Their graph of data from Experiment 1 confirms this prediction. But their graph of data from Experiment 2 reveals the opposite pattern: Participants spent more time fixating non-target objects after *eat* than after *move*. Further complicating interpretation of their results, Altmann and Kamide include in the category "Other" both non-target objects that meet the restrictions of the verb and non-target objects that do not meet those restrictions. It is therefore impossible to judge whether participants excluded incompatible objects from consideration altogether, as would be predicted by a model in which listeners restrict the referential domain rapidly and incrementally.

In reporting their data, Chambers et al. (1998) separate looks to other containers from looks to non-containers. Their data show some signs of early temporary consideration of the cohort of objects with the appropriate affordances (the target plus the other two containers). However, the proportion of early looks to each of these objects was only slightly greater than the proportion of early looks to an unrelated object. The fragmentation of attention among several objects in the multiple containers condition may have made it difficult to distinguish looks to the competitors from (presumably random) looks to unrelated objects. The precise time-course of referential restriction therefore remains uncertain.

In what follows, we report an experiment on the semantic restrictions of verbs using the visual world paradigm, with multiple lexical items and a condition with a single competitor. In this study, participants acted out spoken instructions like "Now I want you to fold the towel." On half of trials, the array contained just one object with the appropriate affordances (the target). On the other half, it contained both a target and one competitor (in this case, a napkin). Participants also acted out instructions like "Now I'd like you to pick up the towel" with precisely the same manipulation of competitor presence. While some verbs (e.g. *fold*) imposed strong semantic restrictions relative to the scene (picking out just one or two objects), other verbs (e.g. *pick up*) imposed only weak restrictions (potentially picking out all four objects).

Two aspects of our experiment should help to illuminate further both the time course and the causes of rapid referential restriction. First, we separate looks to compatible non-target objects from looks to incompatible non-target objects. Second, we include only one competitor in our trials, making it easier to distinguish looks to the competitor from random looks to unrelated (incompatible) objects in the display.

Methods

Participants

Sixteen undergraduates from the University of Pennsylvania participated in this study. They received either course credit or $6.00. All were native speakers of English and had uncorrected vision or wore soft contact lenses.

Stimuli

All critical instructions had the form "Now I want you to *verb* the *noun*" (followed in some cases by an additional phrase, such as "into the box"). We chose eight verbs with strong semantic restrictions, and four verbs with weak semantic restrictions (meaning that each weak verb was pre-

[1] Another version of the experiment eliminated the explicit metalinguistic component. But in that experiment, the participants – who did not participate in the prior version – were told that "in this version of the experiment, we aren't asking you to pay any particular attention to the sentences." This allusion to the prior study might have encouraged participants to strategize metalinguistically.

sented twice). As outlined in the Introduction, the experiment had a 2 (Restriction Strength: Strong versus Weak) x 2 (Competitor: Present versus Absent) design. Note that when the verb was Weak, the Competitor acted as such in name only, as the verb lacked the restrictions necessary to pick out a subset of the objects in the array.

Each list contained sixteen target trials; eight with Strong Verbs and eight with Weak Verbs. The design was such that subjects heard each Strong Verb only once, and manipulated each target object only once. The target trials in a list were evenly divided between the four conditions (with four trials per condition); conditions were rotated across lists, resulting in four lists. All trials consisted of two instructions: the critical sentence followed by a second instruction, which asked participants to further manipulate the Target (e.g., "Now I want you to fold the towel. Now cover the box with it.").

Target trials were accompanied by sixteen filler trials that used other verbs and involved the manipulation of other objects. Order of target and filler trials within a list was determined by random assignment, with two constraints: first, that there be no more than two consecutive target trials using the same verb type; and second, that critical trials and filler trials alternated. To control for order of presentation, each list was presented in one of two orders, one the reverse of the other.

Prior to each instruction, participants were told to "Look at the cross" (the central fixation point on the table). Instructions were digitally recorded and played from a laptop computer connected to a pair of external speakers. Post experiment interviews revealed that subjects were unaware of the manipulation or intent of the experiment.

Procedure

Eye movements were monitored with an ISCAN head-mounted eye-tracker. The device had two cameras: One recorded the visual environment from the perspective of the participant's left eye, and the other recorded a close-up image of the left eye. A computer analyzed the eye image in real time, superimposing the horizontal and vertical eye position on the scene image; this composite image was recorded to tape using a frame-accurate digital video recorder. The tracker determined eye position by following the relative positions of the pupil and the corneal surface reflection, thereby canceling out errors in eye position that might result from slippage of the visor. Moreover, because the scene and eye cameras were attached to the visor, tracking accuracy was not affected by movements of the participant's head.

Participants were asked to carry out the instruction as quickly as they could. The entire experiment lasted approximately half an hour.

Results

The digital videotape of each participant's scene and eye-position was analyzed by using the slow motion and freeze frame viewing on a digital VCR. For each trial, the frame number corresponding to the onset of the spoken instruction was noted. Then, the location and onset time of each successive fixation on an object was recorded by inspecting the video frame images until 1 sec after the offset of the instruction. Trials were not included in the analysis if the tracking signal became degraded during the critical portion of the sentence, which was defined as lasting from the onset of the verb until 1 sec after the offset of the instruction. Of the 256 trials, 16 (6.25%) were not included in the analyses.

Figure 1 presents the fixation probabilities over time in 33-ms intervals (the sampling rate of the VCR), for the Target (the upper graph) and the Competitor (the lower graph). The data are plotted relative to the onset of the noun, corresponding to zero milliseconds on the X-axis. The onset of the verb occurred an average of 485 milliseconds prior to the noun, and is marked by a vertical bar above the X-axis. The probabilities do not sum to zero because the plot omits the probabilities of fixating the cross or the other two objects. The probability of fixating either the cross or the other two objects did not differ across conditions.

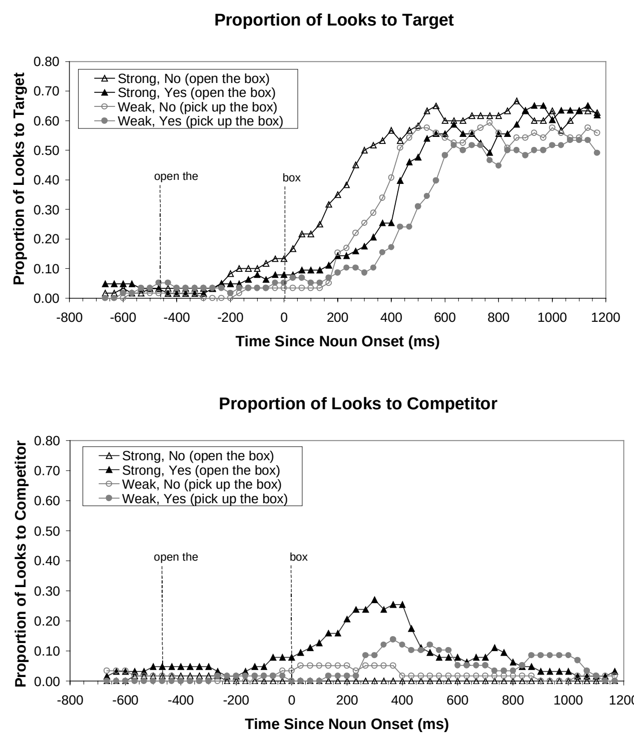

Figure 1: Proportion of trials with fixations to target (top) and competitor (bottom).

In the Strong Verb, Competitor Absent condition, there were early looks to the Target (the open circles in the upper graph) and essentially no looks to the Competitor Replacement (the open circles in the lower graph). Early consideration of the Target begins in this condition prior to the onset of the noun, and rises rapidly during the first 250 msec of the noun. By contrast, in the Strong Verb, Competitor Present condition (e.g., when the array contained both a towel and a napkin), looks to the Target (the filled circles in the upper graph) were reduced, as participants temporarily considered the Competitor (the filled circles in the lower graph). Interestingly, participants evenly distributed their early inspection of the scene between the objects that had the appropriate affordances (e.g., the two foldable objects).

Instructions containing Weak verbs (e.g., "pick up") exhibited a different pattern of fixations. Fixations on the Target (the triangles in the upper graph) were delayed until after the onset of the noun. The greatest delay occurred in the Weak Verb, Competitor Present condition (the filled triangles in the upper graph). This time period was marked by some temporary consideration of the Competitor (the filled triangles in the lower graph). This competition presumably reflects minor confusion arising from perceptual similarity between the Target and Competitor. For instance, a few "accidental" looks to the towel ought to be expected upon hearing "napkin" in the instruction "Now I'd like you to pick up the napkin...". Consistent with this explanation, competition in this condition is small and appears after onset of the noun.

Early Looks to the Target

In order to assess whether early looks to the Target occurred more often in the Strong Verb, Competitor Absent condition than in the other three conditions, we averaged the proportion of time spent fixating the Target during a time slice corresponding to 233 ms after the onset of the verb until 233 ms after the onset of the noun (see Table 1). Because it takes approximately 200-250 ms for the eyes to respond to phonemic input in word recognition studies using this paradigm (e.g., Allopenna, Magnuson, & Tanenhaus, 1998), any significant differences during this portion of the speech are unlikely to be attributable the perception of the noun (e.g., Allopenna et al., 1998). To test differences, subject and item means were entered into separate Analyses of Variance (ANOVAs) with three factors: Verb Type (Strong, Weak); Competitor (Absent, Present) and Presentation List/Item Group (4 lists in the subject analysis and 4 item groups in the item analysis).[2] These analyses revealed a reliable effect of Verb Type ($F1(1,12)=24.70$, $p<0.001$; $F2(1,12)=15.15$, $p<0.005$) with Strong verbs showing more early looks to the Target than Weak verbs. There was also a marginal effect of Competitor Presence ($F1(1,12)=3.27$, $p<0.1$; $F2(1,12)=3.91$, $p<0.1$). There was an interaction between Verb Type and Competitor Presence that was significant in the subject analysis and marginally significant in the item analysis ($F1(1,12)=5.65$, $p<0.05$; $F2(1,12)=4.32$, $p=0.06$). Simple effects tests showed that Strong verbs had an advantage over Weak verbs when the Competitor was Absent ($F1(1,12)=16.28$, $p<0.005$; $F2(1,12)=14.30$, $p<0.005$) but not when it was Present ($F1(1,12)=1.64$; $F2(1,12)=0.89$).[3]

[2] All ANOVAs were conducted on an arcsine transformation of the data, arcsine ((2*p)-1). This was done to adjust for the fact that the proportion p is bounded at 0 and 1. ANOVAs conducted on untransformed data yielded similar statistical patterns.

[3] For looks to Target only, there were some uninterpretable interactions with the List factor.

Table 1A: Proportion of Looks to the Target

Time Slice 1: (Verb + 233ms) to (Noun+233ms)		
	Competitor Present	
	YES	NO
Strong Verb	0.07	0.17
Weak Verb	0.05	0.04

Time Slice 2: (Noun + 233ms) to (Noun+767ms)		
	Competitor Present	
	YES	NO
Strong Verb	0.39	0.56
Weak Verb	0.29	0.44

Table 1B: Proportion of Looks to the Competitor

Time Slice 1: (Verb + 233ms) to (Noun+233ms)		
	Competitor Present	
	YES	NO
Strong Verb	0.09	0.01
Weak Verb	0.03	0.01

Time Slice 2: (Noun + 233ms) to (Noun+767ms)		
	Competitor Present	
	YES	NO
Strong Verb	0.16	0.00
Weak Verb	0.09	0.03

Early Looks to the Competitor

Similar ANOVAs were conducted on the mean proportion of early looks to the Competitor during this time slice (see Table 1). As can be seen in the table, most looks to the Competitor occurred in the Strong verb condition when the Competitor was Present. The analysis revealed a reliable interaction between Competitor presence and Verb Type ($F1(1,12)=7.97$, $p<0.05$; $F2(1,12)=18.99$, $p<0.005$), a marginal effect of Competitor Presence ($F1(1,12)=3.98$, $p<0.07$; $F2(1,12)=9.79$, $p<.05$) and no effect of Verb Type ($F1(1,12)=3.25$; $F2(1,12)=3.06$). Simple Effects showed an effect of Verb Type when the Competitor was Present ($F1(1,12)=6.50$, $p<0.05$; $F2(1,12)=10.16$, $p<0.01$) but not when it was Absent ($F1(1,12)=2.77$; $F2(1,12)=2.87$).

To assess any preference for looking at the Target over the Competitor during this time slice, two-tailed t-tests on subject and item means were done comparing looks to the Target with looks to the Competitor. To avoid Type I errors, we corrected for the number of tests by dividing the alpha by four. As expected, the only reliable difference arose in the Strong Verb, Competitor Absent condition, where there were significantly more looks to the Target than to the Competitor Replacement (e.g., a Coke can) ($t1(15)= 3.48$, $p=0.003$; $t2(15) = 3.96$, $p=0.001$).

Later Looks to the Target.

We also quantified looks to the Target and Competitor in a second time slice, corresponding to approximately 500 ms after the first time slice (i.e., from 233 ms after the onset of the noun until 767 ms after the onset of the noun; see Table

1). Differences in this region are more likely to be affected by the perception of the target noun phrase. ANOVAs revealed a main effect of Competitor Presence ($F1(1,12)=10.71$, $p<0.01$; $F2(1,12)=11.60$, $p<0.01$), with more looks to the Target when the Competitor was Absent. In addition, there was a marginal effect of Verb type ($F1(1,12)=9.15$, $p<0.05$; $F2(1,12)=3.91$, $p<0.08$) with more looks to the Target when the sentence contained a Strong verb. There was no interaction between these factors ($Fs<1$).

Later Looks to the Competitor

ANOVAs on the mean proportion of time spent looking at the Competitor in this region revealed a main effect of Competitor ($F1(1,12)=11.48$, $p<0.01$; $F2(1,12)= 39.10$, $p<0.001$), no effect of Verb Type ($F1(1,12)=0.38$; $F2(1,12)=1.52$) and a weak interaction between these factors that was significant only in the item analysis ($F1(1,12)=2.72$; $F2(1,12)=6.64$, $p<0.05$).

Discussion

We have presented evidence that the semantic restrictions of verbs become available rapidly enough during comprehension to permit listeners to make predictions about the likely reference of the upcoming direct object. Participants looked more rapidly at the referent of the direct object when the verb had Strong restrictions than when it had Weak ones. For instance, they looked more rapidly at the towel when told to fold it than when told to pick it up. When the scene included a second foldable object, the use of a Strong restrictions verb resulted in early temporary consideration of this second object, which competes with the target object. This pattern replicates the one reported both by Chambers (1998) and by Altmann and Kamide (1999), with several improvements: We used multiple lexical items, a task less likely to induce listener strategies[4], and a single competitor. The last improvement allowed us to show that listeners rapidly eliminated incompatible non-target objects from consideration.

While it seems clear that semantic restrictions are rapidly available for referential restriction, the precise mechanism of this restriction remains unclear. There are two explanations for the source of this restriction. Listeners might launch eye movements after hearing a strongly constraining verb because they have already assessed the properties of the objects in the display and recognize that only a subset of those objects is compatible with the verb's restrictions. By contrast, listeners might launch eye movements simply because a strongly restricting verb is more likely than a weakly restricting *in any context* to pick out a unique referent (or subset of referents). We will refer to these possibilities as *affordance matching* and *informativeness*, respectively. In fact, the notion of informativeness has been quantified in recent computational theorizing by (Resnik, 1996), who also provides evidence that verb informativeness has very real psycholinguistic consequences.

These two possibilites make different predictions about the likelihood of launching an eye movement just after hearing the verb. If listeners actively match affordances, they should launch eye movements as soon as they determine that one or more objects in the scene satisfy the restrictions of the verb. Thus, they should be equally likely to launch eye movements following a weak verb as following a strong verb, because in both cases, at least one object in the array satisfies the restrictions of the verb; in both cases, interrogation of the array can begin immediately. If, on the other hand, eye movements are triggered by a verb's informativeness, listeners should be more likely to launch eye movements following a strongly constraining verb than following a weakly constraining one, as informative verbs carry enough information to identify their direct objects, whereas weakly informative verbs do not.

To test between these possibilities, we examined the proportion of fixations on any object in two time slices: from 233 ms after the onset of the verb until 233 ms after the onset of the noun, and from 233 ms after the noun to 767 ms after the noun (the same slices used in the analyses presented in the Results section). As Table 2 indicates, listeners were more likely to launch a fixation to any object following a Strong verb than following a Weak verb. In Time Slice 1, the effect of verb type was reliable in the subject analysis, and marginal in the item analysis ($F1(1,12)=9.71$, $p<.01$; $F2(1,12)=4.36$, $p<.06$). In Time Slice 2, the effect of verb type was reliable in both analyses ($F1(1,12)=8.28$, $p<.02$; $F2(1,12)=7.96$, $p<.02$).

Table 2: Proportion of looks to any object

Time Slice 1: (Verb + 233ms) to (Noun+233ms)		
	Competitor Present	
	YES	NO
Strong Verb	0.22	0.22
Weak Verb	0.16	0.12

Time Slice 2: (Noun + 233ms) to (Noun+767ms)		
	Competitor Present	
	YES	NO
Strong Verb	0.60	0.63
Weak Verb	0.46	0.52

While these data are somewhat preliminary, they suggest that a verb's informativeness, independent of context, contributes to the speed with which listeners can compute the domain of reference of upcoming constituents. Because a Strong verb is highly informative about its upcoming direct object, listeners can begin to interrogate the visual scene for

[4] It is of course possible that listeners in our task developed strategies that resulted in them unnaturally focusing on particular classes of information (see Tanenhaus & Spivey-Knowlton, 1996 for a discussion of this issue). However, if strategies were developed to use verb restrictions, we might expect their effects to emerge over the course of the experiment. We tested this possibility in two ways. We inspected the first half of the trials in the experiment, and we inspected the first of paired items in the experiment. In both cases, the pattern of eye movements was similar to the overall pattern, i.e., early looks to the Target in the Strong Verb Competitor Absent condition, and some early looks to the Competitor in the Strong Verb Competitor Present condition.

an object with the appropriate affordances before they have heard the noun phrase.

Whether early eye movements are driven by informativeness or affordance matching, it is clear that verb meanings can be accessed rapidly enough to make predictions about the reference of an upcoming direct object, and to constrain the set of entities to which the direct object might refer. The current findings contribute to a growing body of data that support a view of semantic interpretation as both incremental and predictive. Words not traditionally thought to carry reference – prepositions (Chambers et al., 1998), adjectives (Sedivy et al., 1999), and verbs (Altmann & Kamide, 1999, the present study) – can be exploited by listeners to predict the reference of upcoming nouns. Indeed, the linking of speech to a mental model of the world appears to be an active, continuous process.

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