Strategic Resources Support the Interpretation of Doubly-Quantified Sentences

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Abstract

Quantifiers like "all" and "every" are frequent in daily language. However, when a sentence contains two quantifiers or is "doubly-quantified" (e.g., "Every boy ate a cookie") the meaning can often be ambiguous since there are two potential interpretations: collective (e.g., several boys sharing a single cookie) and distributive (e.g., several boys each eating their own cookie). Psycholinguistic studies have established empirical evidence for conflict between interpretations of a doubly-quantified sentence and have proposed that the interpretation of these sentences is "underspecified". However, little is known about the the neural mechanisms that support the interpretation of doubly-quantified sentences. In an fMRI experiment we demonstrate that conflict between possible interpretations of doubly-quantified sentences is supported by brain regions situated in fronto-parietal cortex. We propose that an "underspecified" account is insufficient to account for our neuroanatomical results and instead argue that strategic decision-making resources may support the interpretation of doubly-quantified sentences.

Keywords: Quantifiers; Semantics; Language Processing; Decision-Making; fMRI

Introduction

Quantifiers like "all" and "every" are extraordinarily frequent in daily language. The meaning of these quantifiers is well known. However, when these words are used in a doubly-quantified sentence the meaning can often be ambiguous. Consider for example, the following doubly-quantified sentences containing the quantifier "all":

(1) a. All the men built a stadium.
    b. All the men ate a cookie.

The quantifier "all" prefers a collective interpretation such as in 1(a) when there is a set of men and they worked together to build a single stadium. However, in 1(b) a conflict arises between the preferred collective interpretation and the unlikely possibility that a set of men collectively eat a single cookie.

The quantifier "every" also has a preferred interpretation, but it is distributive. For example, 2(b) is consistent with the preferred interpretation – a set of men and each man ate a different cookie. However, in 2(a) a conflict arises due to the preferred distributive interpretation and unlikely event of several men each building a unique stadium.

(2) a. Every man built a stadium.
    b. Every man ate a cookie.

Together, the examples in (1) and (2) illustrate that a conflict arises when individuals read doubly-quantified sentences with a preferred interpretation and this interpretation is unlikely. Empirical evidence for quantifier interpretation conflict has been well established within the psycholinguistic literature (Kurtzman & MacDonald, 1993; Filik et al., 2004; Paterson et al., 2008) . In a seminal reading experiment Kurtzman and MacDonald (1993) presented readers with doubly-quantified sentences like "Every boy climbed a tree" followed by a continuation sentence with either a collective interpretation (e.g., "The tree was full of apples") or a distributive interpretation (e.g., "The trees were full of apples") and asked readers to make a plausibility judgement. Participants were more likely to accept, and therefore preferred, the distributive interpretation rather than the collective interpretation. However, the preference for a distributive interpretation was diminished when doubly-quantified sentences were in a passive voice (e.g., The tree was climbed by every kid) or in a more complex noun phrase (e.g., George has every photograph of an admiral). This prompted Kurtzman and MacDonald (1993) to tentatively endorse a parallel parsing model that simultaneously incorporates several principles for resolving quantifier ambiguity and when a principle is not available readers randomly choose between a distributive and collective interpretation. In an eye-tracking experiment, Filik et al. (2004) demonstrated that reading times for doubly-quantified sentences containing "every" were longer for sentences with a less preferred collective continuation compared to a more preferred distributive continuation. This suggests there is a processing cost when readers encounter a less preferred interpretation and is consistent with Kurtzman and MacDonald (1993) parallel processing account (see also Paterson et al. (2008)).

More recently, in an event related potential (ERP) experiment Dwivedi et al. (2010) presented individuals with doubly-quantified sentences and continuation sentences similar to Kurtzman and MacDonald (1993) and these were compared relative to matched unambiguous baselines (Every kid climbed [*a different* / *the same*] tree). This comparison did not yield any significant effects such as the N400 or P600 commonly observed in the presence of semantic violations, but rather within the ambiguous sentences a slow negativity shift was observed. Dwivedi et al. (2010) used this evidence to argue that individuals do not immediately resolve the meaning of ambiguous quantifiers and instead have an underspecified meaning and therefore do not commit to a particular interpretation. Moreover, Dwivedi et al. (2010) characterize their slow negative shift as a Slow Wave and interpret its pattern in the context of Ruchkin et al. (1988) claim that a Slow Wave reflects conceptually difficult processing.

Together, these psycholinguistic investigations establish empirical evidence for conflict during the interpretation of "every" in doubly-quantified sentences. However, it is not clear from previous investigations whether individuals commit to a particular interpretation or do not resolve the meaning of an ambiguous quantifier. In this paper we use BOLD fMRI to investigate the neural basis for interpreting conflicting or underspecified doubly-quantified sentences.

According to the "underspecified" hypothesis outlined above readers simply interpret quantifiers using their preferred meaning ("all" is collective; "every" is distributive) and if that meaning is in conflict readers choose an arbitrary interpretation as suggested by Kurtzman and MacDonald (1993) or do not choose an interpretation at all (Dwivedi et al., 2010). If readers only rely on the preferred interpretation of a quantifier, we predict that neural mechanisms that support quantifier comprehension will be recruited. Several previous investigations have demonstrated that inferior parietal cortex supports quantifier comprehension. This is because of the role that number knowledge appears to play in the meaning of quantifiers, and number knowledge is supported by inferior parietal cortex. In fMRI studies healthy adults recruited inferior parietal cortex when comprehending sentences like "At least 3 cars are red" (McMillan et al., 2005; Troiani et al., 2009). Converging evidence for the role of inferior parietal cortex in quantifier comprehension comes from neurodegenerative disease patient investigations that have demonstrated that patients with inferior parietal cortex disease have difficulty evaluating a quantifier's meaning (McMillan et al., 2006; Troiani et al., 2009).

While there are no neuroimaging studies to our knowledge on the resolution of quantifier ambiguity, several neuroimaging investigations on semantic ambiguity have suggested that additional mechanisms may be recruited to support semantic ambiguity resolution. For example, fMRI investigations focusing on homonym comprehension have demonstrated that ventrolateral prefrontal cortex and inferior frontal cortex are recruited to support cognitive control demands associated with processing a subordinate meaning (Whitney et al., 2009). Another fMRI study suggested that both frontal and temporal cortex are recruited to support both cognitive control and semantic demands (Rodd et al., 2005). Together, these studies suggest that mechanisms beyond those required to support semantic resources may also be required to support the resolution of ambiguous doubly-quantified sentences.

In the fMRI study reported in this paper we presented readers with sentences like (1) and (2) and probed them to fill in a completion sentence (e.g., "They devoured ____ quickly") with "it" or "them". We manipulated the size of the final noun object paired with the quantifier at the beginning of the sentence in order to modulate conflict between the preferred interpretation and the likelihood of the event − smaller objects are associated with a distributive interpretation and the quantifier "every", while larger objects are associated with a collective interpretation and the quantifier "all". We predict that if ambiguous quantifier interpretation is underspecified we will observe recruitment of regions commonly implicated in quantifier comprehension, including inferior parietal cortex. If, however, individuals do resolve a quantifier's meaning we predict that individuals will recruit neuroanatomic regions beyond those commonly associated with quantifier processing.

Methods

Participants

18 healthy young adults [Mean Age=25.4 years (SD=4.9); Mean Education= 17.0 years (SD=2.4)] from the University of Pennsylvania community participated in the study for monetary payment. All participants were native speakers of English, right-handed, and in good health with no history of neurological difficulty. Informed consent was obtained from all participants according to a protocol approved by the University of Pennsylvania Institutional Review Board.

Experimental Materials

A total of 104 experimental stimulus sentences were generated that contained two quantifiers. Half of the sentences included the quantifier "every *X*" and half included "all of the *X*". The second quantifier in all of the sentences was the existential quantifier "a *Y*". All of the experimental sentences (e.g., "All of the men built a stadium") followed the same simple grammatical structure: a quantifier statement including a noun phrase (e.g., "All of the boys", "Every man"), a verb phrase (e.g., "ate"), an existential quantifier (e.g., "a"), and a final noun (e.g., cookie, stadium).

In half of the sentences the final noun was a small object (e.g., a cookie) to yield either a more compatible interpretation for "every" or a less compatible interpretation for "all". In the remaining half of the sentences the final noun was a large object (e.g., a stadium) to yield a more compatible interpretation for "all" and less compatible for "every". The size of the object was determined in a pretest questionnaire in which we probed participants to rate each object's size on a 1−7. Together, this yielded a 2x2 design with Quantifier (All, Every) and Object Size (Small, Large) as within-participant factors. Each experimental stimulus item was paired with a completion sentence containing a verb phrase followed by a blank and an adverb (e.g., “All the boys ate a cookie” was paired with “They devoured ____ quickly”). Each sentence was designed so that a forced-choice completion with “it” would reflect a collective interpretation (e.g., several boys sharing a single cookie) and a choice of “them” would reflect a distributive interpretation (e.g., several boys, each with their own cookie).

Experimental Procedure

Stimuli were presented using an event-related design comprised of three events. The first event was the presentation of the doubly-quantified sentence for 3000 ms, the second event was a presentation of the completion sentence for 3000 ms and the third event involved the explicit decision between “it” or “them” for 5000 ms. Participants were instructed to complete each sentence with “it” or “them” in order to make the sentences as natural as possible.

Experimental stimuli were presented using E-Prime software (Psychology Software Tools; Pittsburgh, PA) and projected to a screen outside the bore of the magnet. Participants made their responses using a fiber optic responses pad by pressing the left button for “it” and right button for “them”. The experimental session began with a brief practice session outside of the scanner comprised of instructions and 8 experimental trials (2 from each condition). Participants were then given an opportunity to ask questions and receive feedback on performance. The session then include the acquisition of a high resolution volumetric localizer image followed by 4 equal length BOLD fMRI blocks lasting approximately 7 minutes per block. An equal number of each experimental condition were presented in randomized order within each experimental block. Within each experimental block we added an additional 20% of trials to generate “null” events (consisting of a blank screen) in order to dissociate individual trials in the time-series.

MRI Acquisition & Analysis

Scans were acquired on a Siemens 3.0T Trio scanner. Each session began with acquisition of a high-resolution T1-weighted structural volume using an MPRAGE protocol (TR = 1620 ms, TE = 3 ms, flip angle = 15°, 1 mm slice thickness, 192×256 matrix, resolution = 1 mm^3). A total of 584 BOLD fMRI images were acquired in 4 separate runs of equal length. Each image was acquired with fat saturation, 3 mm isotropic voxels, flip angle of 15°, TR = 3 s, TEeff = 30 ms, and a 64×64 matrix.

Image preprocessing and statistical analyses were performed using SPM5 (Wellcome Trust Centre for Functional Neuroimaging, London, UK). We first modeled each individual participants data. Low-frequency drifts were removed with high-pass filtering with a cutoff period of 128 seconds and autocorrelations modeled using a first-order autoregressive model. Images for each participant were realigned to the first image in the series, coregistered with the structural image, and then transformed to MNI152 space using tissue probability maps (Ashburner & Friston, 1997). During spatial normalization functional data were interpolated to isotropic 2 mm voxels. The data were spatially smoothed using a 9 mm FWHM isotropic Gaussian kernel.

For each stimulus category, hemodynamic response was estimated by convolving the onset times of the explicit decision event with a canonical hemodynamic response function. Each event type (doubly-quantified sentence, completion sentence, explicit decision) was entered into a general linear model in order to calculate parameter estimates for each variable for each subject, and linear contrasts for comparisons of interest. These estimates were then entered into second-level random effects analyses to allow us to make inferences across participants. We focus on the explicit decision event in our reported contrasts, though we observed similar activation patterns in contrasts involving the passive reading events. We report the MNI peaks of regions of activation in our analyses which survive a FDR-corrected height threshold of $p<0.05$.

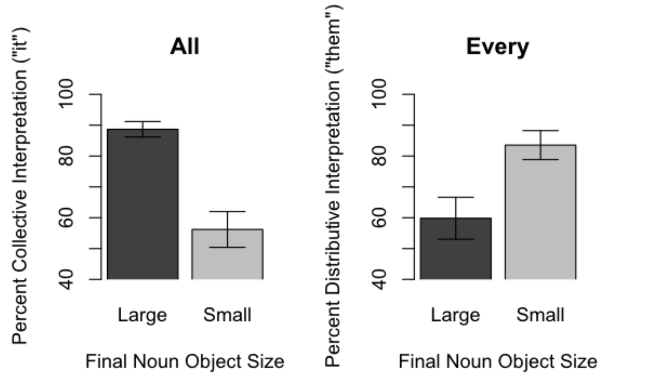

Figure 1: Percent of behavioral responses for the preferred collective interpretation of “all” and the preferred distributive interpretation of “every”.

Results

Behavioral Results

To establish behavioral evidence for conflict between two competing interpretations we analyzed the percent of preferred responses for each quantifier across small (e.g., “cookie”) and large (e.g., “stadium”) object sizes. We report the percent of “it” responses for sentences containing “all” since “all” prefers a collective interpretation and thus a large object. We report the percent of “them” responses for sentences containing “every” since “every” prefers a distributive interpretation and thus a small object. Figure 1 illustrates that participants prefer a collective interpretation of “all” when followed by a large object but have a conflicting interpretation preference when it is followed by a small object. Also, participants prefer a distributive interpretation of “every” when it is followed by a small object and have conflicting interpretations when it is followed by a

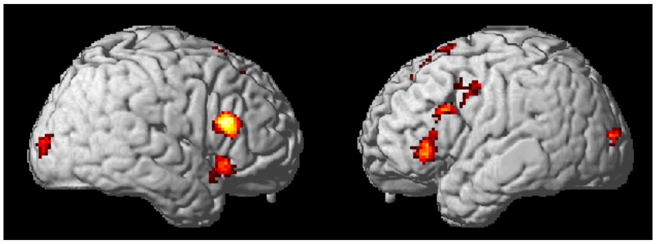

Figure 2: fMRI activation for items with conflicting interpretations (“all” with small objects; “every” with large objects) minus items with more preferred interpretations (“all” with large objects; “every” with small objects). [$p<0.05$ (FDR-corrected)]

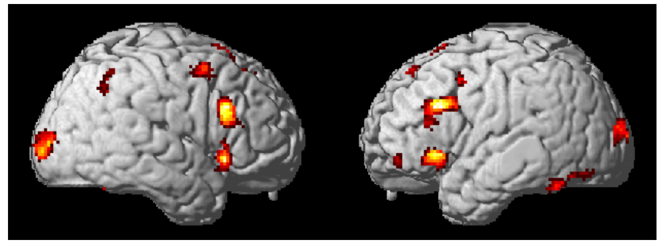

Figure 3: fMRI activation for parametric analysis revealing increased activation associated with increased conflict between object size and preferred interpretation [$p<0.05$ (FDR-corrected)]

large object. Paired samples t-tests confirmed an effect of conflict for both quantifiers: participants prefer larger objects more than smaller objects for “all” [$t(17)=6.54$; $p<0.001$]; and prefer smaller objects over larger objects for “every” [$t(17)=3.99$; $p<0.001$]. We did not observe any significant differences between “all” and “every” (all $p>0.3$). Therefore, we collapsed “all” and “every” for the neuroimaging analyses. These behavioral results establish empirical evidence for conflict when a doubly-quantified sentence has a preferred interpretation and that interpretation conflicts with the object size.

Neuroimaging Results

To investigate the neural basis for resolving quantifier scope ambiguity we compared activation during the interpretation of sentences with conflicting interpretations (“all” with small objects; “every” with large objects) relative to sentences consistent with the preferred interpretation (“all” with large objects; “every” with small objects). By comparing activation across closely-matched doubly-quantified sentences we subtracted out, and therefore controlled for, activation that may be associated with making an explicit decision (e.g., motor responses for a button press) and reading (e.g., visual processing). This subtraction revealed recruitment of several regions situated in frontal cortex including bilateral dorsolateral prefrontal cortex [DLPFC; 42 26 14; -50 28 4], bilateral ventrolateral prefrontal [48 24 -6; -50 28 4], left inferior frontal [-52 18 28], left dorsal inferior [-44 -4 44] and dorsomedial prefrontal [2 34 48] cortex, along with bilateral occipital cortex [22 -92 2; -22 -92 12; see Figure 2 for lateral regions]. The recruitment of these frontal regions, all of which are not language-specific, is not consistent with the “underspecified” hypothesis that predicts up-regulation of resources known to contribute to unambiguous quantifier comprehension.

To further evaluate the contribution of these mechanisms for resolving quantifier interpretation conflict we conducted a parametric analysis. In this analysis we used object size as a continuous measure of quantifier interpretation conflict. Values for object size were collected in a survey in which individuals were asked to rate how large each object was on a $1-7$ scale. For example, for the quantifier “every” the preferred distributive interpretation becomes more conflicting as the object size (cookie $\rightarrow$ tree $\rightarrow$ stadium) increases. Conversely, for the quantifier “all” the collective interpretation becomes more conflicting as the object size decreases. To account for the polarity of “all” and “every” each of the object sizes for “all” were converted to their reciprocal so that a higher number represents a higher level of conflict. We computed the parametric model by correlating the BOLD signal with object size and observed activation of several frontal regions including left DLPFC [-50 28 28; -32 24 16], right inferior frontal [44 22 28], bilateral ventrolateral prefrontal [42 20 -4; -48 48 -8; -46 20 -4], bilateral dorsal inferior frontal [34 2 48; -36 4 44] and right dorsomedial prefrontal [2 34 52] cortex that are recruited to support increasing conflict. We additionally observed recruitment of right inferior parietal [46 -56 42], left ventral temporal [-38 -50 -22; -44 -74 -14] and bilateral occipital [20 -96 0; -18 -100 10; see Figure 3 for lateral regions] cortex.

General Discussion

Doubly-quantified sentences can often be ambiguous between a collective and distributive interpretation. In particular, a conflict arises when a quantifier’s preferred interpretation is inconsistent with the likelihood of an event happening. For example, a set of boys are unlikely to share a single cookie because of the typically small size of a cookie. We observed in this study that individuals recruit a large-scale fronto-parietal network to support the interpretation of ambiguous doubly-quantified sentences. Moreover, the activation in this network scales in magnitude with increasing conflict between possible interpretations. This is incompatible with the account of the behavioral literature suggesting that conflict results in an arbitrary decision about quantifier interpretation. Moreover, extensive frontal activation indicates that these findings are inconsistent with the hypothesis that readers merely recruit brain regions important for interpreting a quantifier. These findings instead suggest that we engage a decision-making mechanism seen in other studies of ambiguity, such as homonyms (Whitney et al., 2009; Rodd et al., 2005).

Critically, while it is important to evaluate our hypothesized model in a more "naturalistic" setting, we believe that the observed patterns of activation that support the decision-making processes of resolving quantifier ambiguity are distinct from narrow, task-related demands. First, the cortical regions recruited in the current study are neuroanatomically distinct from those reported for sentence comprehension tasks with an explicit decision compared to those that involve passive reading (Hasson et al., 2006). Second, a task-related decision-making account can not account for the selective recruitment of decision-making mechanisms observed in the reported contrasts. Specifically, all task-related resources such as working memory resources, making a button press and orienting attention to a reading task were held constant across all experimental conditions.

Dorsolateral prefrontal cortex (DLPFC)

We observed recruitment of DLPFC when individuals processed sentences containing conflict between a preferred meaning and the likelihood of an event. DLPFC is commonly implicated as a strategic mechanism in both neuroimaging (Smith et al., 2001) and patient (Mangels, 1997) investigations. Specifically, neuroimaging investigations have implicated DLPFC in a variety of domains requiring probabilistic evaluation, including probabilistic category learning (Fera et al., 2005), discriminating between advantageous and disadvantageous choices (Christakou et al., 2009), and evaluating a probabilistic distribution in a decision-making task (Huettel et al., 2005). This is also consistent with the observation of DLPFC activation during the probabilistic calculation of a syntactic structure when confronted with a temporary structural ambiguity (Novais-Santos et al., 2007). Critically, regardless of whether DLPFC activation is a general strategic mechanism or a probability-specific estimator, activation of this region suggests that resources beyond those implicated in unambiguous quantifier processing support the comprehension of ambiguous quantifiers. Future work may help identify the specific role of DLPFC by more precisely localizing this region in order to discriminate between different levels of cognitive and strategic control (Koechlin et al., 2003).

While DLPFC has been implicated in previous studies of unambiguous quantifier comprehension (McMillan et al., 2005; Troiani et al., 2009), it has only been reported during the comprehension of a different class of quantifiers than those used in the current study. McMillan et al. (2005) only observed DLPFC activation during the comprehension of higher-order quantifiers (e.g, "more than half") compared to first-order quantifiers (e.g., "at least 3"). More recently, Troiani et al. (2009) demonstrated that logical quantifiers such as "all" used in the current study recruit rostral-medial prefrontal cortex. The fact that we did not observe rostral-medial prefrontal cortex activation in the current study is consistent with the claim that readers were not merely recruiting regions important in the interpretation of quantifier meaning, but were instead recruiting additional neuroanatomic resources.

Inferior frontal cortex

When a doubly-quantified sentence yields conflict between a preferred interpretation and the likelihood of an event we observed activation of dorsal and ventrolateral portions of inferior frontal cortex. Dorsal inferior frontal cortex is often implicated as an updating mechanism for working memory which involves substituting information held in working memory when trying to resolve conflict (Wager & Smith, 2003). Our observation of anterior cingulate activation is also consistent with reports of this region contributing to conflict resolution (Botvinick et al., 2001). Ventrolateral prefrontal cortex also has commonly been implicated in the resolution of competing responses (Badre & Wagner, 2007). Specifically, Thompson-Schill et al. (1997) have proposed that ventrolateral prefrontal cortex does not simply maintain competing responses in working memory, but rather it is involved in the strategic selection of relevant semantic information to choose one alternative over another. In our study ventrolateral prefrontal cortex is up-regulated relative to increasing conflict between a collective and distributive interpretation of ambiguous quantifiers. Consistent with Thompson-Schill et al. (1997) we argue that this mechanism contributes to strategically selecting one quantifier interpretation over another.

Inferior parietal cortex

We observed that individuals up-regulated inferior parietal cortex as a function of increasing quantifier meaning conflict. The role of inferior parietal cortex's contribution to resolving quantifier meaning requires further investigation. On the one hand our observation that the magnitude of inferior parietal cortex scales with increased quantifier conflict can be attributed to increased processing demands associated with identifying an underspecified quantifier's meaning. A number of neuroimaging investigations have demonstrated inferior parietal recruitment during the comprehension of unambiguous quantifiers which has been hypothesized to support number knowledge required for quantifier meaning (McMillan et al., 2005; Troiani et al., 2009). Similarly, patients who have cortical atrophy in inferior parietal cortex due to neurodegenerative disease have difficulty with quantifier comprehension (McMillan et al., 2006; Troiani et al., 2009). On the other hand, inferior parietal cortex recruitment may be associated with increased strategic processing demands associated with deciding on the interpretation of an ambiguous quantifier. Inferior parietal cortex has been implicated in integrating different sources of information to make a decision (Naghavi & Nyberg, 2005) and has been reported to support strategic resources when comprehending sentences that do not contain quantifiers but have a preferred interpretation (Novais-Santos et al., 2007). For example, Novais-Santos et al. (2007) observed inferior parietal cortex activation when readers processed sentences with a less compatible compared to more compatible and attributed this to a verbal working memory mechanism that works together with DLPFC to support increased resources during sentence processing.

Conclusion

Together, we propose DLPFC, dorsal and ventrolateral portions of inferior frontal cortex and inferior parietal cortex form a large-scale neural network to support the interpretation of doubly-quantified sentences. All of these components of our proposed network have previously been implicated in strategic processing and their recruitment in this study suggests that strategic mechanisms contribute to the interpretation of ambiguous quantifiers. This observation is in contrast to an "underspecified" account that hypothesizes that the up-regulation of resources which support unambiguous quantifier comprehension are sufficient to support the interpretation of quantified sentences with more than one meaning.

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