

Neural Correlates of Linguistic Demand and Domain-General Demand in an Auditory-Based
Task

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Abstract

Researchers have used language mapping paradigms in functional imaging studies (i.e. fMRI) to identify which regions of the brain support language processing. Previous work has identified brain regions that belong to the multiple demand network as being involved when task difficulty increases in domain-general cognitive tasks. In a recent study conducted by Quillen et al. (2021), researchers manipulated task difficulty in semantic and perceptual decision paradigms to explore what brain regions would be active when task difficulty was increased. They found that linguistic demand modulated a small subset of the multiple demand network and some left frontal region, and domain-general demand modulated an extensive set of the multiple demand network. However, several of these activated regions in the multiple demand network are known to contribute to visuospatial functioning. The present study sought to determine if Quillen et al.'s (2021) results were influenced by the visual modality of his experiment by completing the same experiment in the auditory modality. Eight neurotypical participants performed auditorily-presented easy and hard versions of semantic and perceptual decision tasks in an fMRI scanner. In the present study, linguistic difficulty modulated activation in somewhat bilateral left frontal and temporal regions. Unlike Quillen et al.'s linguistic difficulty contrast, there is very little multiple demand network activation. The current study's domain general demand contrast revealed a strikingly different pattern when compared to that of Quillen et al. (2021) with right frontal regions displaying the most activity. The lack of multiple demand network activation in the present study suggests that the multiple demand network may, in part, be modality dependent. These findings indicate that linguistic and domain-general demand modulate distinct brain networks, a result that remains somewhat true across the visual and auditory domain.

1. Introduction

What parts of the brain are modulated by task difficulty in linguistic and non-linguistic contexts? Our purpose in asking this question is that it influences the interpretation of functional imaging studies of neuroplasticity in post-stroke aphasia patients. Individuals with aphasia, as a result of the disorder, have more difficulty completing language tasks than do neurologically normal control patients. As patients with aphasia recover, they typically find that language tasks become easier. Therefore, comparisons between patients and controls as well as longitudinal analyses as patients recover, are confounded by task difficulty. When observing activation differences between these two groups, it is nearly impossible to determine whether they reflect functional reorganization or effects of task difficulty (Binder et al., 2005; Fridriksson and Morrow, 2005; Thierry et al., 2006; Geranmayeh et al., 2014). Very few studies have been able to successfully manipulate and match task difficulty between patients and controls (Sharp et al., 2004, 2010; Raboyeau et al., 2008; Brownsett et al., 2014; Wilson et al., 2018, 2019).

A recent study by Quillen et al. (2021), however, endeavored to directly compare the brain regions modulated by linguistic demand and domain-general demand. To do so, Quillen and colleagues matched task structure across domains and ensured that the difference in difficulty between easy and difficult conditions was precisely matched across domains in terms of accuracy and reaction time. Quillen et al. scanned 20 neurologically normal individuals with fMRI while they performed an “easy” and “difficult” linguistic task and an “easy” and “difficult” perceptual task. The four active conditions consisted of a pair of words or a pair of symbols strings that were visually presented one above the other in the center of the screen. Participants had to press a button if the words “went together” (that is, were semantically related or if the symbols strings were identical). If the stimuli were not similar, participants were instructed to do nothing. A box would appear around the words or symbols to acknowledge the button press, but

no feedback was given as to the correctness of the response. Participants were told to respond as quickly as possible. In the Semantic Easy condition, words used were high frequency and concrete, and the semantic relationships were relatively transparent (e.g. *mouse* and *cheese*). The words were also presented in green text so that participants knew when they were performing the easy condition. The Semantic Difficult condition was the same as the Semantic Easy condition except these words were low frequency and abstract, and the relationships between the word pairs were opaque. These words were presented in red text to alert participants that they were performing the difficult condition. The perceptual conditions followed the same pattern. Mismatching strings in the Perceptual Easy condition differed in every symbol and in total length of symbols. In the Perceptual Difficult condition, mismatching strings had the same number of symbols and only one symbol differed between the two. Green and red text was also used in the perceptual conditions. Importantly, both tasks were visual in nature. Quillen et al. found that domain-general demand (i.e. regions that were modulated by perceptual difficulty) modulated a set of multiple demand (MD) regions that have been identified in many earlier studies. Linguistic demand modulated only a subset of MD regions and did so to a lesser extent than did perceptual demand. These MD regions included the bilateral inferior frontal junction extending especially in the left hemisphere onto the adjacent precentral gyrus, the bilateral anterior insula, the ventrolateral component of occipito-temporal regions bilaterally, and the right pre-SMA/anterior-mid cingulate. Beyond the MD network, linguistic demand was shown to modulate left frontal language regions and a right frontal region homotopic to Broca's area.

Several of the MD regions modulated by both linguistic and perceptual tasks are widely known to have visuospatial functions. One compelling study (Nobre et al., 1997) used positron emission tomography (PET) to image the neural system underlying visuospatial attention.

Participants performed two attention tasks. One condition emphasized reflexive aspects of spatial orientation (i.e. attentional shifts that could be carried out reflexively), and the other condition demanded controlled shifts of attention. Researchers found nearly equivalent patterns of activation for both the reflexive and non-reflexive shifts of visuospatial attention. However, I will present more specifically on the results from the reflexive task since the visuospatial attention required in the Quillen et al. (2021) study was reflexive. During the reflexive task, researchers found four main cortical areas were activated: right posterior parietal cortex, right anterior cingulate, lateral and medial premotor cortex bilaterally, and the right superior temporal sulcus (Nobre 1997). Some of these areas were activated in the study by Quillen et al., suggesting that these regions may have been activated due to the visual nature of the task.

Another study by Noyce et al. (2017) examined which parts of the lateral frontal cortex (LFC) might be selectively activated depending on the sensory modality of the task. Using fMRI, they had participants complete visual and auditory tasks. They found that the superior precentral sulcus and inferior precentral sulcus were activated for the visual task. Interestingly, these visual regions also showed a significantly higher degree of MD behavior than did the auditory regions. This suggests that these areas contain a heterogeneous neural population, which may include neurons responsible for sensory-independent and for sensory-dependent functions. Another study by Corbetta et al. (1998) had patients complete attention shifting and eye movement tasks while being scanned with fMRI. They found that several regions in the parietal and frontal lobes, specifically those near the intraparietal sulcus and precentral sulcus, were activated bilaterally. In addition, regions in the occipital and temporal lobes like the lateral occipital cortex and superior temporal sulcus were activated. An earlier PET study of visuospatial attention affirmed that parietal and frontal regions primarily control numerous aspects of visuospatial attention

(Corbetta et al.,1993). Based on these findings, it could be speculated that some of the MD regions activated in the study by Quillen et al. were recruited due to the visual nature of the task.

The goal of the present study is to investigate how much of the activation pattern seen in the MD regions was driven by the visual nature of the experimental tasks. In other words, to what extent, if any, were the findings of Quillen et al. influenced by task modality? The current study followed a similar experimental design as that of the study by Quillen et al.; however, it was carried out in the auditory modality. In this way, participants would not recruit any potential neural areas involved in visuospatial processing. Therefore, activation patterns and neural correlates of linguistic demand and domain-general demand would not be influenced by the visual nature of the task.

2. Methods

2.1 Participants

Eight neurologically normal individuals from a population similar to that used in Quillen et al., (2021) were recruited via word of mouth and by posted flyers. Left-handed individuals were not excluded, but those who were found not to be left-lateralized as revealed by contrasts of semantic and perceptual conditions, were excluded.

Prior to running the imaging study, a separate, smaller group took part in behavioral studies for optimizing the experimental design. These participants were recruited similarly; none of them were scanned.

All participants gave written informed consent and were compensated for their time. The study was approved by the Institutional Review Board at Vanderbilt University.

2.2 Experimental design

In the fMRI study, participants were presented with five conditions in a block design: (1) Semantic Easy; (2) Semantic Difficult; (3) Perceptual Easy; (4) Perceptual Difficult; (5) Rest.

Each participant was trained on the task during an untimed presentation of example items from each condition and with specific instructions as described in detail below. Then, participants performed one complete practice run prior to entering the scanner, so that they were familiarized with the four active conditions and could settle on strategies for each condition. Finally, they performed two runs in the scanner while echo-planar images were acquired.

In the four active conditions, each trial consisted of a pair of words or a pair of sound strings that were auditorily presented one before the other through headphones that the participant was wearing. Participants were told to fixate on a crosshair displayed on an otherwise empty, black computer screen. The crosshair changed color in order to alert participants as to what condition they were about to begin. A green crosshair indicated an Easy Condition, a red crosshair indicated a difficult condition, and a white crosshair indicated a rest condition. Participants were instructed to press a button with a finger of their left hand if the words “went together” or if the sound strings “were identical”, and to do nothing otherwise. If they pressed the button, a beep played through their headphones to acknowledge the button press, but no feedback was provided as to the accuracy of the response. Response times and the duration of stimuli were determined based on the results of the pilot study. Participants were instructed to respond as quickly as possible, but they were told that any responses indicated after the stimuli disappeared still counted.

In the Semantic Easy condition, half of the word pairs were semantically related, and half were not. The words were relatively high frequency, concrete, and acquired early, and the semantic relationships between the matching word pairs was chosen to be relatively transparent.

A green crosshair appeared on the screen to let participants know when they were performing the easy condition. They were instructed: “Words presented while a green crosshair is on the screen will be easy. Matches will be obvious: the words will clearly go together. You should be able to respond quickly.” The in-scanner word pairs and practice word pairs for this condition were selected from the easier items of the larger stimulus set described by Wilson et al. (2018).

The Semantic Difficult condition was the same as the Semantic Easy condition except that the words were relatively low frequency, abstract, and acquired later and the semantic relationships between the matching word pairs was chosen to be relatively opaque. In this condition, a red crosshair appeared on the screen so that participants knew when they were performing the difficult condition. They were instructed: “Words presented while a red crosshair is on the screen will be difficult. Matches may be more subtle: the relationship between the words may be less obvious. Respond as quickly as you can, but take the time you need.” The in-scanner word pairs and practice word pairs for this condition were selected from the easier items of the larger stimulus set described by Wilson et al. (2018).

In the Perceptual Easy condition, each sound string consisted of two “da” notes. The differences between matching and mismatching sound strings were readily apparent. Mismatching strings differed in the tone of one of the two “da” notes. A green crosshair appeared on the screen to let participants know when they were performing the easy condition. They were instructed: “Sound strings presented while a green crosshair is on the screen will be easy. If they mismatch, they will be very different. You should be able to respond quickly.”

The Perceptual Difficult condition was the same as the Perceptual Easy condition, except that sound strings consisted of five shorter “da” notes and only one of the five differed in tone in mismatching pairs. In this condition, a red crosshair appeared on the screen so that participants

knew when they were performing the difficult condition. They were instructed: “Sound strings presented while a red crosshair is on the screen will be difficult. If they mismatch, only one of the frequencies will be different. Respond as quickly as you can, but take the time you need.”

It should be noted that the specificity of the instruction provided for each of the four conditions and the practice run prior to scanning was designed to maximize homogeneity of processing strategies across participants. Also, it was important to cue participants to when they were performing the easy or hard conditions. Without explicit cues to easy conditions, for example, participants might seek subtle semantic relationships between words in Semantic Easy mismatching items.

Both reaction time and accuracy data were analyzed using two-way repeated measures ANOVAs as implemented in MATLAB to determine whether mean reaction time and accuracy differed by domain (language vs. perception), difficulty (easy vs. hard), or the interaction between the two.

Neuroimaging

The functional imaging data was preprocessed with tools from AFNI (Cox, 1996). Head motion was corrected, with six translation and rotation parameters saved for use as covariates. Next, the data was detrended with a Legendre polynomial of degree 2, and smoothed with a Gaussian kernel (FWHM = 6 mm). Then, independent component analysis (ICA) was performed using the FSL tool *melodic* (Beckmann & Smith, 2004). Noise components were manually identified with reference to the criteria of Kelly et al. (2010) and removed using *fsl_regfilt*.

First level models were fit for each of the two functional runs using boxcar models of

each active condition convolved with a hemodynamic response function (HRF) based on the difference of two gamma density functions (time to first peak = 5.4 s, FWHM = 5.2 s; time to second peak = 15 s; FWHM = 10 s; coefficient of second gamma density = 0.09) with the program *fmriilm* from the FMRISTAT package (Worsley et al., 2002). The six motion parameters were included as covariates, as were time series from white matter and CSF regions to account for nonspecific global fluctuations, and three cubic spline temporal trends.

The T1-weighted anatomical images were warped to MNI space using unified segmentation in SPM5 (Ashburner & Friston, 2005). Functional images were coregistered with structural images via coplanar T2-weighted structural images using SPM, and warped to MNI space.

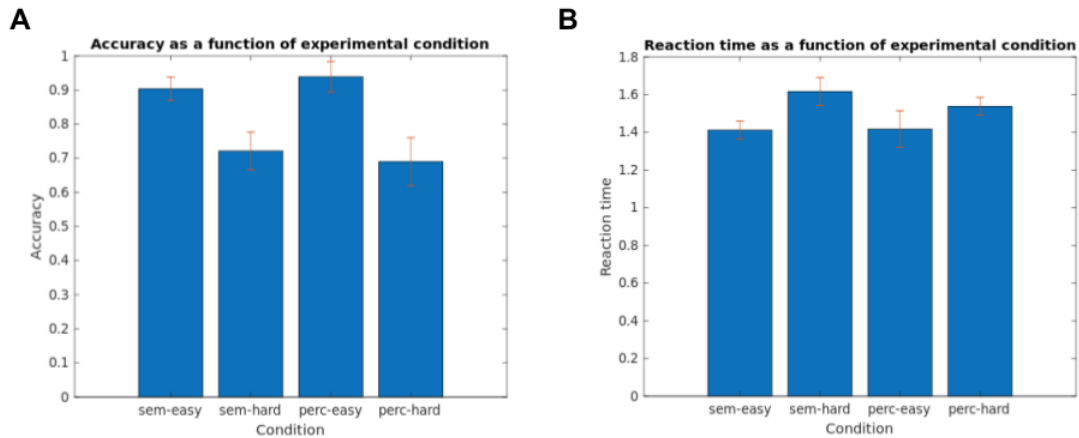
Contrasts were created to compare each of the four conditions to the implicit Rest baseline. Linguistic demand was modeled with the contrast Semantic Difficult – Semantic Easy. Perceptual demand was modeled with the contrast Perceptual Difficult – Perceptual Easy. Language regions were identified with the contrast (Semantic Easy + Semantic Difficult) – (Perceptual Easy + Perceptual Difficult). The interaction of domain by difficulty was modeled by the contrast (Semantic Difficult – Semantic Easy) – (Perceptual Difficult – Perceptual Easy). Second level random effects analyses were performed, but were not corrected for multiple comparisons due to the small number of participants included in the analysis.

3. Results

3.1. Behavioral Data

Figure 1 shows overall accuracy (1a) and reaction time (1b) as a function of domain (semantic vs. perceptual) and difficulty (easy vs. hard). For accuracy, a repeated measures

ANOVA with two within-subjects factors (domain, difficulty) revealed a main effect of difficulty with difficult conditions being less accurate than easy conditions ($F(1,7) = 350.04$, $p < .0001$) but no main effect of domain ($F(1,7) = 0.01$, $p = .92$) and no interaction of difficulty by domain ($F(1,7) = 3.35$, $p = .11$). The observed main effect of difficulty was expected, as tasks that are more difficult to perform are likely to engender more mistakes. However, the lack of domain and interaction effects suggests that whether the task is a language or a perceptual task has little effect on accuracy. Similarly, a repeated measures ANOVA on the reaction time data revealed a main effect of difficulty with slower responses to difficult conditions compared to easy conditions ($F(1,7) = 311.13$, $p < .0001$), but no main effect of domain ($F(1,7) = 3.85$, $p = .09$) and no interaction of domain by difficulty ($F(1,7) = 3.59$, $p = .10$). Again, the observed main effect of difficulty was expected as hard trials are likely to require more time than easy trials; however, whether the task was linguistic or perceptual again did not have a significant effect on reaction time. Importantly, the lack of significant domain by difficulty interactions allows us to compare the neural correlates of linguistic demand and non-linguistic demand without there being potential confounds of accuracy or reaction time.



Figure

1. Behavioral data results. Accuracy and reaction time on the semantic and perceptual conditions at easy and difficult task levels are shown. Error bars denote standard deviation.

3.2 Imaging Data

Within-domain effects of difficulty

All images show t-statistics thresholded at $t > 2.551$ with a minimum cluster size of 100 voxels. To examine effects of increasing task difficulty in each domain, hard semantic vs. easy semantic and hard perceptual vs. easy perceptual contrasts were computed (**Figure 2**). The hard semantic vs. easy semantic contrast showed activation in the left greater than right posterior superior temporal sulcus and the pars opercularis, as well as the left pars triangularis and anterior superior temporal gyrus. The hard perceptual vs. easy perceptual contrast showed a strikingly different pattern of activation, with the right pars triangularis, pars opercularis, anterior cingulate, and frontal operculum displaying the most activity.

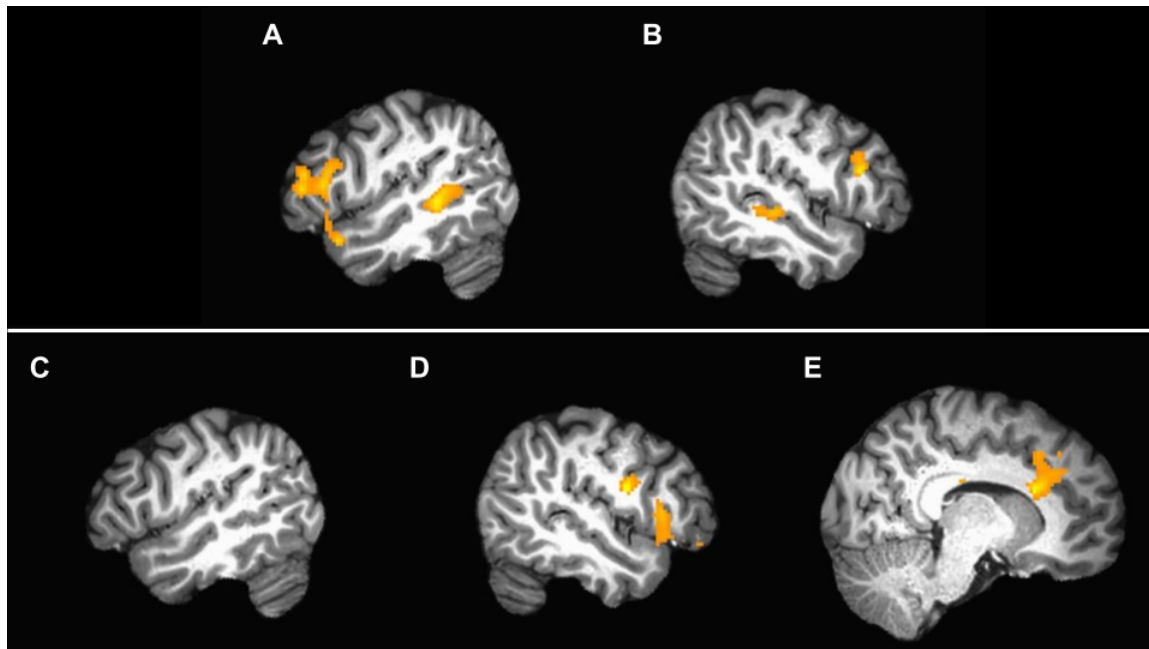


Figure 2: Group activation in hard > easy contrasts within each domain. Panels A-B show activated regions when difficulty was increased in the semantic domain. Panels C-E show activated regions when difficulty was increased in the perceptual domain.

Across-difficulty effects of domain

To evaluate activation specific to the language domain, an “all semantic tasks” vs. “all perceptual tasks” contrast was computed (**Figure 3**). This contrast showed activation in the left greater than right superior temporal sulcus, the left middle temporal gyrus, posterior inferior temporal gyrus, pars triangularis and orbitalis. These findings are in line with language maps generated in Wilson et al. (2018).

To examine differential effects of increasing linguistic tasks difficulty, a (hard semantic vs. easy semantic) vs. (hard perceptual vs. easy perceptual) interaction contrast was computed (**Figure 4**). This contrast showed a highly left-lateralized network consisting of the left pars triangularis and orbitalis, superior temporal sulcus, and temporal pole. There was no significant activation noted in the right hemisphere.

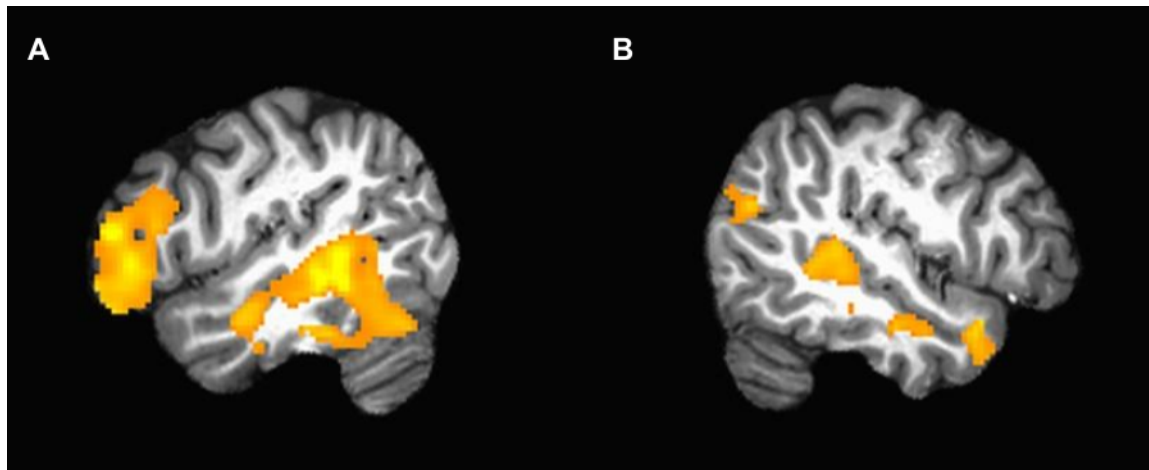


Figure 3: Group activation in “All Semantic Tasks” > “All Perceptual Tasks” contrasts. Panel A displays a left hemisphere view. Panel B displays a right hemisphere view.

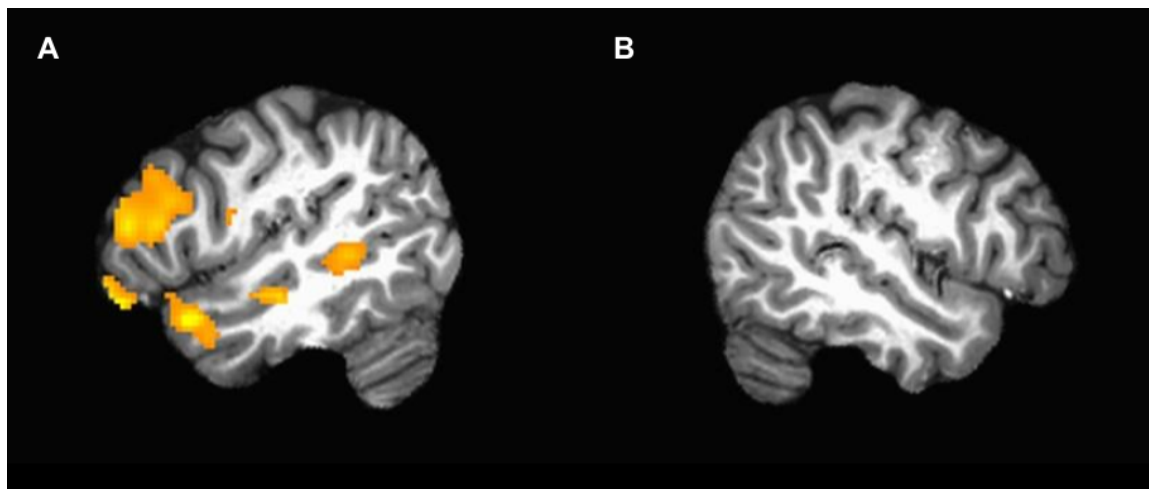


Figure 4: Group activation in (hard semantic vs. easy semantic) vs. (hard perceptual vs. easy perceptual) interaction contrast. Panel A displays a left hemisphere view. Panel B displays a right hemisphere view.

4. Discussion

Findings of the present study

We found that auditory linguistic and perceptual tasks of different difficulties activated distinct networks. Specifically, linguistic demand activated the left greater than right posterior superior temporal sulcus and the pars opercularis, as well as the left pars triangularis and anterior

superior temporal gyrus. Perceptual demand showed a strikingly different pattern of activation, with the right pars triangularis, pars opercularis, anterior cingulate, and frontal operculum displaying the most activity. The difference in regions modulated suggests that auditory linguistic demand and perceptual demand have distinct neural correlates. This is confirmed in the interaction contrast. More precisely, when comparing auditory linguistic demand and perceptual demand directly, auditory linguistic demand showed a highly left-lateralized network consisting of the left pars triangularis and orbitalis, superior temporal sulcus, and temporal pole. There was no significant activation noted in the right hemisphere.

Comparison with Quillen et al. (2021)

The goal of the present study was to investigate how much of the activation patterns seen in the “multiple demand” (MD) network from Quillen et al. was driven by the visual nature of the experimental tasks. To investigate this question, we compared results from the current study, which was completed in the auditory modality, to the results from Quillen et al. (2021), a study completed in the visual modality. First, I will compare the two studies’ maps of linguistic demand. Quillen et al. found the following regions to be modulated by linguistic demand: left inferior frontal gyrus (IFG) and sulcus, inferior frontal junction, precentral gyrus, the anterior insula, and an extensive occipito-temporal regions extending anteriorly along the fusiform gyrus nearly to the temporal pole. Right hemisphere activation was similar although less extensive and included: the ascending ramus of the Sylvian fissure, the inferior frontal junction, the anterior insula, and the right pre-supplementary motor area (SMA)/anterior-mid cingulate. These areas can be seen in Figure 2 of Quillen et al.’s study. These results give evidence for some Multiple Demand (MD) network involvement. The inferior frontal junction, anterior insula, and pre-SMA have all been previously identified as being part of the MD network. In the present study, the

following regions were activated by linguistic demand: the left greater than right posterior superior temporal sulcus and the pars opercularis, as well as the left pars triangularis and the anterior superior temporal gyrus. These areas can be seen in Figure 2 Panels A-B of the current paper. In the present study, the linguistic demand contrast activated mostly bilateral language areas as opposed to the MD network. Thus, we see different patterns of activation for linguistic demand when comparing the present study to that of Quillen et al.

Now, I will directly compare Quillen et al.'s and the current study's maps of domain-general demand. Quillen et al. saw strong evidence for activation of a large set of MD regions. The specific areas can be seen in Figure 4 of Quillen et al.'s study. In the present study, the domain general demand contrast revealed no significant activation in the left hemisphere. In the right hemisphere, there was activation in the pars triangularis, pars opercularis, anterior cingulate, and frontal operculum. These areas can be seen in Figure 2 Panels C-E of the current paper. This activation pattern is strikingly different from the MD network and from the activation patterns seen in Quillen et al.'s domain-general demand contrast.

The linguistic demand contrast and domain-general demand contrast activation patterns in Quillen et al.'s study appear quite different from the activation patterns seen in the present study. First, there are fewer areas activated in the present study when compared to Quillen et al. This is to be expected since the current study had less statistical power than that of Quillen et al. Quillen and his colleagues had a total of twenty participants whereas I was only able to evaluate eight participants. Second, Quillen et al. saw evidence for MD network involvement in both the linguistic and domain-general demand contrasts. Specifically, he saw the greatest level of MD involvement in the domain-general demand contrast. In the present study, however, there is little to no MD activity in the linguistic demand contrast and in the domain-general demand contrast.

The present study's linguistic demand contrast showed activation in primarily language areas, and the domain-general demand contrast activated regions that look nothing like the MD network.

When comparing areas of activation in the linguistic demand contrast in the study by Quillen et al. and in the present study, the following regions were activated solely in Quillen et al.'s study: left greater than right medial superior frontal gyrus, middle temporal gyrus, extending into the left superior temporal gyrus; the left angular gyrus and hippocampus; the precuneus and posterior and middle cingulate cortex bilaterally. These regions of activation can be seen in Figure 2 in the paper by Quillen et al. Now, I will discuss potential hypotheses as to why these areas were activated in the study by Quillen et al. and not in the present study. An integral skill needed to complete Quillen's visual language task is the ability to read. The left angular gyrus is associated with reading and is posited to be involved in mapping orthographic-to-phonological whole word representations. (Joubert et al., 2003, Black and Behrmann, 1994). In addition, the left angular gyrus has been shown to exhibit greater patterns of activation for reading of very high frequency words when compared to very low frequency words (Joubert et al., 2003, Binder et al., 2003). Moreover, in a study conducted by Horwitz et al. (1998), positron emission tomography demonstrated strong blood flow in the left angular gyrus during a reading task in typical individuals, while in individuals with dyslexia, there was limited blood flow and connectivity in the left angular gyrus during the same task. The middle temporal gyrus and left superior temporal gyrus have been demonstrated to contribute to a phonologically based form of reading (Joubert et al., 2003). The middle temporal gyrus has also been correlated with semantic judgments to visual words in a fMRI study done with a group of 9-15 year olds (Chou et al., 2006).

Another skill necessary in Quillen et al.'s study and not in the current study is visuospatial attention and/or functioning. The precuneus has been found to be involved in visuospatial functions (Mahayana, et al. 2014, Corbetta, 1993) and was implicated in the linguistic demand contrast of Quillen et al.'s study. Finally, the occipital lobe is known to be heavily associated with visual processing and in visuospatial attention (Corbetta, 1993, Corbetta, 1998, Nobre, 1997, Noyce, 2017). There are strong patterns of activation in the occipital lobe in the linguistic demand contrast of Quillen et al.'s study.

In continuation of the comparison of areas of activation in the linguistic demand contrast in the study by Quillen et al. and in the present study, the following regions were activated solely in the present study and not in that of Quillen et al.: the left temporal pole or anterior temporal lobe (ATL), specifically the anterior superior temporal gyrus and posterior superior temporal sulcus. I will now hypothesize as to why this area was modulated by the linguistic demand contrast in the current study and not in that of Quillen et al.'s. In the linguistic demand task of the present study, participants were required to use semantic memory. According to Patterson et al. (2007), the primary function of semantic memory is "to generalize across concepts that have similar semantic significance but not necessarily similar specific attributes" (p. 977). For example, participants would hear a pair of words, "mouse" and "cheese," hold the pair of words in their memory, and then decide whether these words share semantic significance. Semantic memory impairment is one of the symptoms of semantic dementia, a neurodegenerative condition that results in a progressive deterioration of expressive and receptive vocabulary and of knowledge about the properties of everyday objects. Patterson and colleagues discuss numerous imaging studies that demonstrate pronounced, bilateral deterioration of the anterior temporal lobe in symptomatic patients with semantic dementia. In a study done with normal participants, the

same researchers saw the greatest level of activation in the anterior temporal lobe when participants were asked for the most precise classification of a word when compared to a more general classification of a word. For example, when asked whether a photo of a robin depicted an animal, a bird, or a robin, the anterior temporal lobe was most strongly activated when participants were asked to classify the photo at the most specific level (e.g. a robin). Consequently, we might expect to see the greatest levels of activation in the anterior temporal lobe during the difficult linguistic demand task as the stimuli become more specific and belong to narrower categories. Overall, it appears that specific semantic knowledge is strongly associated with the anterior temporal lobe.

However, it is still not entirely clear why the anterior temporal lobe was activated solely in the linguistic difficulty contrast in my auditory-based study and not in Quillen et al.'s visually based study. Visser et al. theorized about why this might be the case in their meta-analysis on semantic processing in the anterior temporal lobe. This team of researchers found that studies using auditory stimuli were more likely to find anterior temporal lobe activation when compared to studies that used other types of stimuli, like visual words and/or pictures. One suggested hypothesis is that the anterior temporal lobe is specialized for deriving overall meaning from auditorily-presented stimuli. Another hypothesis is that the anterior temporal lobe is activated most strongly when this region is worked vigorously. For example, if this area has to process rapidly presented auditory stimuli as compared to visual stimuli that remain on the screen for a longer period of time, the anterior temporal lobe may be activated more strongly during the auditory-based task. A third and final hypothesis is that the anterior temporal lobe has been shown to have strong patterns of activation in tasks requiring auditory-verbal information to be processed. The results from the aforementioned meta-analysis help explain why there was a

pattern of activation in the anterior temporal lobe during the linguistic demand contrast in the current study and not in that done by Quillen et al.

In another study, Mesulam et al. (2015) explored the anatomical regions associated with word and sentence level comprehension. Researchers tested patients with primary progressive aphasia on these two skills and then completed MRI scans on the individuals. They found that those participants with the worst sentence comprehension abilities had the most pronounced patterns of atrophy in the following regions: the left supramarginal gyrus, angular gyri, inferior frontal gyrus, dorsal frontal cortex, and anterior orbitofrontal cortex. Differently, those with the worst word comprehension deficits displayed the most prominent atrophy in the left anterior temporal lobe, including the polar component. In fact, atrophy in the left temporal pole was associated with the most severe word comprehension ability, as measured by standardized tests. Thus, it appears that word and sentence level comprehension have non-overlapping neuroanatomical substrates and that word comprehension is perhaps localized to the anterior temporal lobe. Researchers also posit that intelligible, auditory input would be particularly localized to the anterior temporal lobe as this region is known for its ability to encode word-like properties of auditorily-presented stimuli. As the input proceeds through the synaptic chain, the stimuli would evoke their related associations that collectively define the word's meaning. Thus, a neuronal loss at the level of the anterior temporal lobe would be detrimental to word-level comprehension, which is what researchers found. This line of thinking supports the results of the current study in which the anterior temporal lobe was activated during the linguistic demand contrast which required word-level comprehension in the auditory domain.

In the domain-general demand contrast in the study by Quillen et al., there was evidence for strong MD network involvement. The MD network is thought to include: the inferior frontal

junction, anterior insula, pre-supplementary motor area, anterior-mid cingulate, and intraparietal sulcus (Duncan and Owen, 2000; Fox et al., 2005). As was previously mentioned in the Introduction section of this paper, several of these MD areas activated in this contrast are known to have visuospatial functions. None of the aforementioned areas, albeit part of the anterior-mid cingulate, were activated in the present study's domain-general demand contrast. One explanation could be that because these regions are heavily involved in visuospatial processing, they were modulated only in Quillen et al.'s visually-based study and not my auditory-based study. In the current study's domain-general demand contrast, we saw activation in the right hemisphere, specifically in the pars triangularis, pars opercularis, anterior cingulate, and frontal operculum . This activation pattern is vastly different than that of Quillen et al. The right pars triangularis and pars opercularis are part of the inferior frontal gyrus (IFG). The IFG has been shown to be involved in auditory linguistic processing (Newman & Twieg, 2001, Xiao et al., 2005). This could help account for the fact that we see activation patterns in this region during my auditory-based study and not in Quillen et al.'s visually-based study.

Further Hypotheses

In general, we would expect to see fewer areas activated for both the linguistic and domain-general demand contrasts in the present study because I have eight subjects relative to Quillen et al.'s 20 subjects, and this is, in fact, what we see. I will now hypothesize areas that we might expect to have patterns of activation if the current study had greater statistical power. The primary auditory cortex is one region that we might have expected to become activated in both the linguistic and domain-general demand contrast of the present study; however, this activation was not observed. This lack of activation may be due to the fact that the primary auditory cortex is known to respond to all sound, ranging from birdsong to intelligible speech, when compared to

silence, and both contrasts performed in this study involved comparing sound with other sound, as opposed to sound compared with silence. In their study, *Hierarchical processing in spoken language comprehension (2003)*, Davis and Johnsrude mapped brain regions involved in spoken language comprehension. They distorted English sentences in three acoustically different ways, which resulted in each having a distinct level of intelligibility. Researchers found that the primary auditory cortex did respond to sound when compared to silence but that it did not care whether that sound was intelligible as speech or not. In the present study, participants either heard a pair of words or sound strings compared to one another. That is, in our study, we were subtracting the contrasts from each other ((i.e. hard-easy semantic)-(hard-easy perceptual)) such that all of the auditory cortex activation would subtract out to zero in the final analysis. If we compared any one of our conditions to rest, however, we would see auditory cortex activation. Therefore, we anticipate exactly what the results of the current study showed: no activation in the primary auditory cortex for either contrast.

Another skill required to complete both the linguistic demand and domain-general demand contrast in the current study is auditory working memory. The design of the present study is such that it requires participants to hold in memory one sound string or word while hearing a second sound string or word. Importantly, Quillen et al.'s visually-based version of this study does not require auditory working memory since the words or symbols strings presented remain in the participants' visual field while they make a decision regarding the pair's similarity or semantic relationship. If the present study had involved a larger sample size, we might have expected to see a pattern of activation in regions supporting auditory working memory during both demand contrasts. A meta-analysis completed in 2019 by Emch and colleagues sought to elucidate the neural correlates of auditory working memory. In general, they found that auditory

working memory corresponds to a network of activation that includes primarily bilateral fronto-parietal areas, the right cerebellum, and several basal ganglia structures. Cortical regions included bilateral inferior frontal gyrus (IFG) and precentral gyrus. Basal ganglia structures were comprised of the cingulate, left insula, and right lenticular nucleus. Researchers found that the greatest bilateral IFG activation occurred when the task “load” was most difficult. In another study done by Kumar et al. (2016), researchers asked participants to complete an auditory working memory task. Overall, they found strong bilateral patterns of activation in the IFG, which is consistent with Emch’s results. In addition, they found the hippocampus to be implicated during the auditory working memory task. The hippocampus is likely recruited due to its part in supporting the phonological loop, which allows for verbal material representation to be kept in an active state. Moreover, researchers found that the hippocampus was activated most strongly when participants performed worst in terms of accuracy and reaction time.

Although the IFG and hippocampus did not show patterns of activation in the current study, it is possible that with a greater sample size, we might see increased bilateral IFG activation when participants complete the “difficult” conditions of the linguistic and domain-general tasks. In addition, because both contrasts in the current study likely involve the phonological loop, I might expect to see superficial hippocampal activation. Furthermore, I would hypothesize seeing greater hippocampal activation as tasks become more difficult.

It is important to note that this section outlines hypotheses regarding areas of activation we might see had there been a larger sample size. Future studies should include a larger sample size in order to verify or adjust the aforementioned hypotheses.

Conclusion and Limitations

The present study offers preliminary evidence that linguistic and perceptual difficulty modulate different brain networks and, to some extent, this remains true across the visual and auditory domain. Caution should be taken when interpreting results of the present study due to the limited sample size. Future research should repeat this experimental design and involve a larger number of participants in order to allow for more conclusive results. Furthermore, although the increased auditory linguistic task difficulty did modulate distinct areas when compared to those modulated by increased perceptual task difficulty, the task itself examined only one specific facet of language: namely, the semantic relationship between words. It is important to note that language as a whole is much more complex than this semantic decision paradigm task and that language is multi-faceted. For example, phonological processing and syntactical knowledge are two other, distinct facets of language. Research has been conducted to examine different language functions such as these. A recent study, for instance, used adaptive rhyming and syllable counting paradigms to map regions involved in phonological processing in individual participants (Yen, DeMarco, & Wilson, 2019). Using such paradigms, future research should explore if the preliminary evidence from the present study could be replicated across other domains in language such as phonological processing. For example, would the distinct neural correlates observed in this study remain the same when studying a different facet of language in auditory-based task and a visually-based task? Ultimately, such research would expand the field's understanding of task difficulty and its implications for fMRI activation in language processing.

The implications of this study include providing a finer-tuned understanding of regions supporting language and difficulty. This is important because language and task difficulty are often conflated when examining fMRI/imaging results in people with aphasia. When certain

regions are modulated during a language task, researchers may assume that the aforementioned areas are activated because the person is completing a language task and that language function is now confined to that area. However, one possibility is that these areas may appear activated because language tasks are inherently difficult for people with aphasia. That is, these regions are, in fact, activated when a task is difficult and not because it is a language-based task. Thus, the finer-tuned understanding of regions supporting language and task difficulty as a result of this study will grant researchers and clinicians the ability to more accurately interpret activation patterns seen in people with aphasia.

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Appendix A. Training Phase Instructions to Participants

Aphasia & Language Imaging Lab

Language Experiment

You will hear pairs of words and pairs of sound strings.

If the words “go together”, press the button.

If the sounds strings are identical, press the button.

Otherwise, do nothing.

The success of our experiment critically depends on you trying as hard as you can to do well at the tasks!

Always try to respond as quickly as possible. But if necessary, you CAN respond AFTER the words/sound strings have been presented, but before the next item is presented.

Green crosshair – indicates an easy condition. Matches will be obvious: the words will clearly go together, and the sound strings will clearly be identical. You should be able to respond quickly.

Red crosshair – indicates a difficulty condition. Matches may be more subtle: the relationship between the words may be less obvious. The sound strings will differ in a more subtle way and will be presented more quickly. Respond as quickly as you can, but take the time you need.

You will do 3 sessions of the experiment. Each lasts for 8 minutes. The first session takes place before you enter the scanner. The other two sessions take place in the scanner.

In the scanner, please try to keep your head still and your eyes on the crosshairs.

Thank you for participating in our study!

