Neural Representations of Numerical Processing across Semantic, Phonological, Visual, and Manual Formats

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Outstretched fingers can convey the same information as the symbol “5”, but how does our brain represent these different visual forms so that we understand the number *five*? Four constituents have been implicated as being involved in adult numerical processing: semantic, visual, manual, and phonological. Here, we utilize a novel paradigm that includes all four constituents, allowing us to ask how the brain represents them simultaneously. We collected functional magnetic resonance imaging (fMRI) data from adult participants while they completed our full code paradigm, as well as an additional paradigm that has been used previously to study numerical processing in adults and children (Cantlon & Li, 2013; Emerson & Cantlon, 2015). During our full code paradigm, participants viewed one of two stimulus types indicating a quantity: Arabic numerals (visual) or hands (manual), while completing one of two tasks: deciding if a quantity was greater than another number (semantic) or if the quantity contained a long vowel sound (phonological). Univariate analyses revealed similar activity during both the full code paradigm and the previously-used paradigm within right and left intraparietal sulcus, right IFG/Insula, and anterior cingulate cortex, while only the full code paradigm identified differences between semantic and phonological processing within left IFG/Insula. Such results, as well as opportunities for multivariate analytic techniques to be applied, support the utility of this novel paradigm for future studies investigating numerical processing.

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Preface

I would like to thank all of my friends and family for their support through the research presented in this document. I would also like to thank everyone in the LeNS lab and my advisor, Dr. Marc Coutanche, for their invaluable feedback, guidance, and encouragement throughout this journey.

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1.0 Introduction

Numerical information can be conveyed through many means. Imagine, for example, a parent telling a small child to wait for five minutes while she finishes talking to someone on the phone. This example demonstrates that, in the right context, a hand can represent a numerical value. Such a representation can characterize a proposed manual code in which fingers are used to signify quantities or values (Butterworth, 1999). In addition to this manual code, three other codes for representing numerical information have been studied, together forming the *triple code* model (Dehaene, 1992). One of the constituents within this model concerns the verbal and phonological components of the names of numbers (Dehaene, 1992), while an additional constituent involves the visual code of a number, oftentimes as an Arabic numeral (Abboud, Maidenbaum, Dehaene, & Amedi, 2015), and the final constituent involves the semantic component, representing the quantity of a number (Hubbard, Piazza, Pinel, & Dehaene, 2005), used during estimation and comparison tasks (Dehaene, 1992).

We can consider the neural underpinnings of these constituents as a way to reveal how the same information can be conveyed through different means. The triple code model has been useful for framing our understanding of numerical processing and the neural regions involved in complex tasks. It presents three individual neural codes relating to numerical processing (Myers & Szücs, 2015), conveying the idea that these isolated functions are subserved by distinct neural underpinnings (Skagenholt, Träff, Västfjäll, & Skagerlund, 2018). Often, the intraparietal sulcus (IPS) is implicated in the semantic code (Skagenholt et al., 2018), while the fusiform gyrus is involved in the visual code (Grotheer, Ambrus, & Kovács, 2016), and language areas within the left hemisphere as well as left angular gyrus as processing the verbal code (Dehaene, Piazza, Pinel,

& Cohen, 2003). Previous studies have identified distinct neural regions such as bilateral IPS, inferior frontal gyrus and contiguous insular cortex bilaterally (IFG/Insula), and anterior cingulate cortex (ACC; Emerson & Cantlon, 2015) as important for numerical processing.

While these models provide the conceptual lens through which to view the constituents of numerical processing, rarely have studies intentionally investigated all four constituents using a single paradigm. Instead, studies typically target neural regions supporting numerical processing, more generally, or focused on a limited subset of constituents. One particular paradigm has been used extensively in recent years to measure numerical processing both in adults and in children (Cantlon & Li, 2013; Emerson & Cantlon, 2015). This paradigm (hereafter referred to as the *limited code paradigm*) allows for the identification of regions in the brain which are more active when people compare dot quantities and Arabic numerals, thus providing a glimpse into the neural underpinnings relating to visual and semantic components. However, such a task does not allow for the dissociation of these constituents or a comparison to the verbal and manual codes. Most recently, a first attempt has been made to explore the three constituents of the triple code model using a single paradigm (Skagenholt et al., 2018). In this paradigm, participants were tasked with responding to stimuli such as dot quantities, Arabic numerals, or number words. Participants decided which of two presented stimuli (e.g. "three" versus "seven") was larger. The results support underlying neural correlates of the triple code model, specifically indicating the involvement of right middle temporal gyrus in representing Arabic numerals, left IFG in representing verbal processing, and right IPS in the symbolic number comparison task (Skagenholt et al., 2018). While this study utilizes a novel method to provide support for the triple code model, still, the ability to address all four constituents (manual code in addition to the triple code model) remains elusive.

This thesis focuses on two main goals. First, we present a novel paradigm (hereafter referred to as the *full code paradigm*) which incorporates a combination of tasks and stimuli to address all four of the constituents involved in numerical processing (visual, phonological/verbal, semantic, and manual). We explore the important task of dissociating functions and cognitive processes within distinct anatomical locations within this single paradigm.

Second, we compare participants' neural activity while they perform the full code paradigm, as well as the limited code paradigm while undergoing an fMRI scan. Such comparisons allow us to test the viability of the full code paradigm in successfully identifying neural regions involved in numerical processing. Furthermore, we explore possible additional benefits afforded by the full code paradigm (unattainable through the limited code paradigm) and its usefulness for future studies.

2.0 Materials and Methods

Participants were recruited until twenty contributed usable neuroimaging data. Twenty-two right-handed, native English speakers without a learning or attention disorder were recruited from the Pittsburgh community (12 females, mean (*M*) age = 22.5, standard deviation (*SD*) = 3.9). Two participants' data were excluded from further analyses (one for excessive head movement during the scan, one for not following the instructions during the scan). Additionally, the fifth (and final) functional run for the full code paradigm was excluded from two otherwise usable participants (one for excessive head movement, one for a technical disruption during the run). The institutional review board (IRB) at the University of Pittsburgh approved all measures prior to data collection. Participants were compensated for their participation.

2.1 Stimuli, task, and procedure

Prior to beginning the scanning session, participants completed a long vowel practice task in which they identified words containing a long vowel (i.e. selecting *ape* out of a list containing act, ape, bed, and dig). This practice task ensured that participants were familiar (and comfortable) with making judgments relating to long and short vowels. After discussing the safety procedures, participants underwent an anatomical scan, followed by five functional runs of our full code paradigm and four functional runs of the limited code paradigm (beginning with a run of the full code paradigm and then alternating runs between the limited code and full code paradigms), and three functional resting state runs (not analyzed here).

During the limited code paradigm, participants viewed pairs of stimuli consisting of numbers, words, faces, and shapes which have been previously used to study neural activity in children and adults (Cantlon & Li, 2013; Emerson & Cantlon, 2015). The limited code paradigm followed the procedure outlined in previous studies utilizing this paradigm and stimuli, provided by the authors (with minor modifications). Participants judged whether the pair of stimuli were matches or non-matches, by pressing the left button for match and the right button for non-match (consistent within participants throughout the scanning session, and counter-balanced across participants such that half indicated a match by pressing the left button and half indicated a match by pressing the right button). Approximately 50% of the trials were matches, while the others were non-matches.

Pairs of stimuli were presented to the left and right of a central fixation cross on a grey background. The numbers condition consisted of a pairing of dot quantities and Arabic numerals, ranging from 1 to 9, and required participants to judge whether both represented the same quantity or not. The words condition consisted of a pairing of one lowercase and one uppercase word and required participants to judge whether both were the same word or not. The faces condition consisted of a pairing of one face (frontal view) and one face (angled view) and required participants to judge whether both were the same person. The shapes condition consisted of typical shapes (i.e. square, triangle) and shapes resembling tools (i.e. saw, hammer). Participants were randomly assigned to view either the typical shapes or tools stimuli (consistent within participants throughout the scanning session, and counter-balanced across participants such that half viewed the typical shapes and half viewed the tools). The typical shapes consisted of a pairing of two typical shapes and required participants to judge whether both were the same shape or not. The shapes resembling tools consisted of a pairing of two shapes that resembled tools, each slightly rotated, and required participants to judge whether both were the same shape or not. For additional details concerning the stimuli used in the limited code paradigm, please see Emerson and Cantlon (2015).

Figure 1. Four stimulus conditions presented during the limited code paradigm

Stimuli for the limited code paradigm were presented in a blocked-design, across four functional runs. All runs consisted of two blocks per condition and three picture comparison trials from the same condition per block. Blocks were pseudorandomized such that all conditions were presented once before a second presentation of any condition. Within each block, there was at least one match and one non-match trial. Picture comparison trials were presented for two seconds, followed by a two-second inter-trial interval (fixation cross). Each block was followed by eight seconds of fixation.

During the full code paradigm, participants viewed stimuli consisting of values from 1 to 9 represented as either Arabic numerals or hands. Participants were first presented with instructions indicating their task for the following three trials: either making a numerical or phonological judgment. For *numerical judgment* trials, participants judged whether the presented quantity was greater than the value presented during the instructions (e.g., *Is the quantity greater than 6?*). This comparison value was either 3, 4, 6, or 7. For *phonological judgment* trials, participants judged whether the presented quantity's name contained a long vowel sound (i.e., *Does the quantity's name contain a long vowel sound?*). For both judgments, participants indicated their response to each trial by pressing the left button for yes and the right button for no (consistent within participants throughout the scanning session, but counter-balanced across participants such that half indicated yes by pressing the left button and half indicated yes by pressing the right button). The yes/no button press assignment for the full code paradigm was consistent with the match/non-match button assignment throughout the scanning session such that yes and match responses were always indicated by pressing the same button while no and non-match were the same button. Approximately 50% of the trials required positive responses (i.e., quantity shown was greater than the value in the instructions; contained a long vowel), while the others required negative responses. Our 2-by-2 factorial design resulted in four different conditions presented to participants: numerical judgment based on numeral stimuli; numerical judgment based on hand stimuli; phonological judgment based on numeral stimuli; phonological judgment based on hand stimuli.

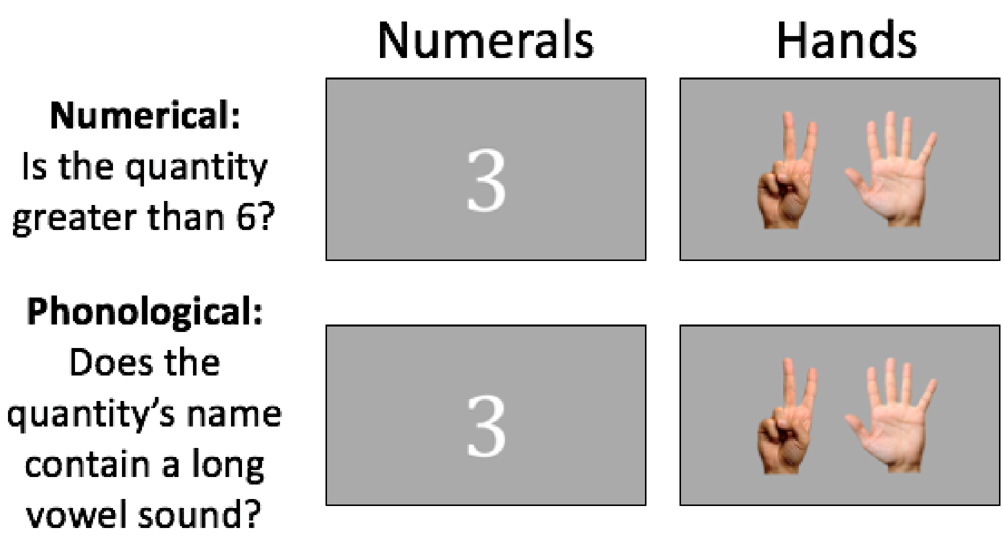

Figure 2. Stimulus conditions presented during the full code paradigm

Stimuli for the full code paradigm were presented in a blocked-design, across five functional runs. All runs consisted of two blocks per condition and three judgment trials from the same condition per block. Blocks were pseudorandomized such that all conditions were presented once before a second presentation of any condition. Within each block, there was at least one trial requiring a positive response and one requiring a negative response. Judgment trials were presented for two seconds, followed by a two-second inter-trial interval (fixation cross). Each block was followed by eight seconds of instructions, informing participants the condition (either numerical or phonological judgment) for the next block of trials.

All experimental stimuli were presented using MATLAB (R2017a) and the Psychophysics Toolbox Version 3 (Brainard, 1997; Kleiner et al., 2007), which synchronized stimulus onset times with fMRI data acquisition.

2.2 Behavioral analyses

Before analyzing the neuroimaging data, we first analyzed the behavioral responses to ensure that participants were successfully completing the tasks. We compared accuracy as well as response times for each of the four stimulus conditions during the limited code paradigm, and each of the four stimulus/task conditions during the full code paradigm. Response times recorded as faster than 300 ms were removed. Trials with no responses were not included in the response times calculations but were categorized as incorrect in the accuracy calculations. One participant's mean accuracies on the matching judgments during the limited code paradigm were lower than two standard deviations below the mean of the group and a different participant's mean accuracies on the numerical and phonological judgments during the full code paradigm were lower than two standard deviations below the mean of the group. We excluded the neuroimaging data for each of these participants in their respective paradigm (e.g., participant's data with low accuracy during limited code paradigm were excluded from the following analyses for the limited code paradigm, but included in the full code paradigm). Additionally, one participant's mean accuracies on both paradigms were more than two standard deviations below the means of the groups, therefore we excluded the neuroimaging data for this participant from all following analyses. The following analyses report the results from 18 participants in the limited code paradigm and 18 participants in the full code paradigm.

To analyze the behavioral data collected while participants were undergoing both paradigms during the scanning session, we conducted separate linear mixed-effects models (Baayen, Davidson, & Bates, 2008) predicting mean accuracy and mean response times for each of the four conditions in the limited code paradigm, while including a random effect term for participants. We were specifically interested in differences between the numbers condition and each of the other three conditions (words, faces, and shapes). For analyzing the full code paradigm, we again conducted separate linear mixed-effects models predicting mean accuracy and mean response times, however, now we were interested in differences between stimuli (hands and numerals), judgment task (phonological and numerical), as well as the interaction between the two, while including a random effect term for participants.

2.3 fMRI acquisition

Participants were scanned at the University of Pittsburgh's Neuroscience Imaging Center using a Siemens 3-T head only Allegra magnet and standard radio-frequency coil equipped with a mirror device to allow for fMRI stimuli presentation. The scanning session first consisted of a T1-weighted anatomical scan (TR = 1540 ms, TE = 3.04 ms, voxel size = 1.00 x 1.00 x 1.00 mm), followed by T2-weighted functional scans which collected blood oxygenation level-dependent (BOLD) signals using a one-shot EPI pulse (TR = 2000 ms, TE = 25 ms, field of view = 200 mm, voxel size = 3.125 x 3.125 x 3.125 mm, 36 slices). The functional scans for the limited code paradigm were collected in four functional runs of 80 volumes each. The functional scans for the full code paradigm were collected in five functional runs of 84 volumes each. Total scanning time was approximately 55 minutes.

2.4 fMRI preprocessing

Preprocessing was performed using the Analysis of Functional NeuroImages (AFNI) software (Cox, 1996) and consisted of the following: motion correction registration, high-pass filtering, and scaling voxel activation values to have a mean of 100 (maximum limit of 200). Structural and functional images were warped to standardized space (Talairach, 1988) using a nonlinear transformation. Data were smoothed using a 6mm smoothing kernel.

2.5 Regions of interest

To investigate regions involved in numerical processing, we created five 10 mm-radius spheres centered around the peak coordinates reported in Emerson and Cantlon (2015) as corresponding to numerical processing. The spheres were located within right (x = 28.1, y = -56.2, z = 35.8) and left IPS (x = -31.7, y = -56.0, z = 35.0), right (x = 32.0, y = 17.9, z = -2.2) and left IFG/Insula (x = -34.1, y = 15.0, z = -2.8) and ACC (x = -0.7, y = 18.7, z = 35.7). For a visual depiction of the regions of interest (ROI) spheres placed on a standard template brain, see Figure 3.

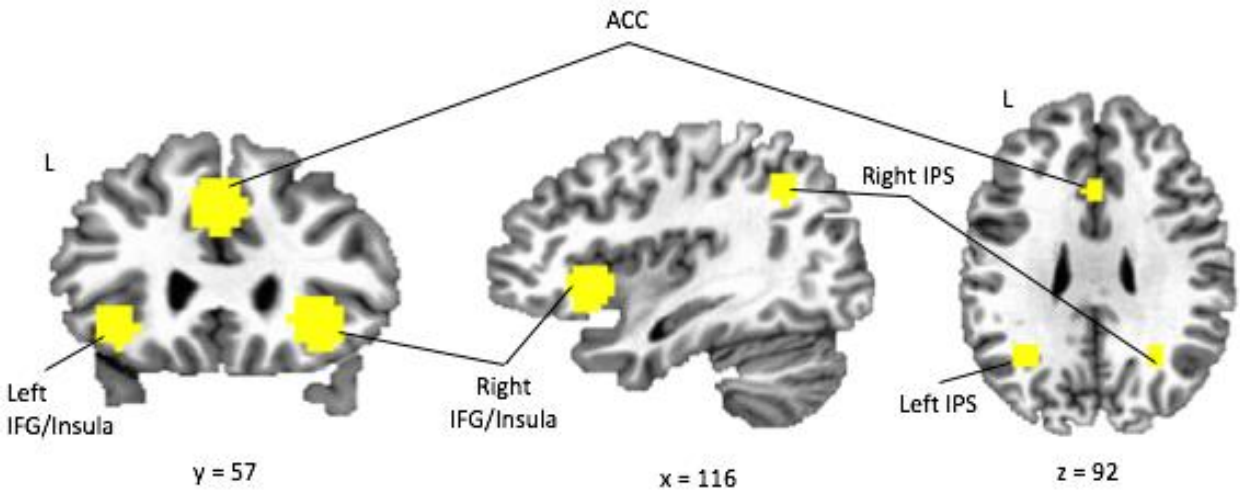

Figure 3. Five spheres within regions involved in numerical processing

2.6 fMRI univariate analyses

We implemented a similar general linear model approach as used in prior studies with the limited code paradigm (Cantlon & Li, 2013; Emerson & Cantlon, 2015). When analyzing data collected during the limited code paradigm, we included regressors of interest for each of the four stimulus conditions, as well as six regressors of no interest for the motion parameters acquired during the preprocessing steps. Additionally, we accounted for differences in task difficulty by including response times for each trial within the model. Trials with no response, or response times faster than 300 ms, were replaced with the participants' mean response time for that trial's condition.

We performed group-level statistics (one-sample t-tests) on the beta coefficients resulting from each participants' regression contrasts within each of the five ROI spheres. To assess the main contrast of interest in the limited code paradigm, we tested the beta coefficients resulting from the numbers vs. all other stimulus conditions (words, faces, and shapes). Additionally, we conducted the same group-level statistics across the whole brain, allowing us to identify functionally-defined clusters of neural activation involved in number processing. Cluster thresholding to correct for multiple comparisons was performed using AFNI's 3dClustSim option (within the 3dttest++ command) which randomizes and permutes datasets resulting in a cluster-size threshold for voxel-wise p-value thresholds as recommended by the group that maintains AFNI (Robert W. Cox, Chen, Glen, Reynolds, & Taylor, 2017) .We used a false discovery rate (FDR) corrected threshold of $p < .05$, along with AFNI's parameters for cluster correction: Nearest Neighbor (NN) level = 2; bi-sided; alpha < .05. The resulting clusters, along with the anatomically-defined spheres, were used in all following analyses.

To compare the limited code paradigm with our full code paradigm, we compared the beta coefficients resulting from the contrast between numerical and phonological judgment tasks (collapsed across presentation of both stimulus types) using the same general linear model approach as described above. Because our full code paradigm also allowed for the additional analysis of comparing stimulus types, we tested the beta coefficients resulting from the contrast between hands and numerals (collapsed across presentation of both task types).

Lastly, to most closely compare the full code paradigm with the results from the limited code paradigm, we tested the beta coefficients resulting from the numerical judgments vs. baseline (i.e. time points consisting of fixation cross and instructions) contrast. Because both the numerical and phonological judgment tasks required participants to access one of the constituents of the number processing network (numerical task: semantic, phonological task: verbal), it is possible that we would not observe effects in a region involved in both of these two components of number processing (if the subtle difference in processing level were not detectable through univariate methods). We, therefore, compared the numerical judgments against a baseline condition so that any effects observed would not have been impacted by other types of processing related to number. We focus on the numerical judgments vs. baseline contrast because it most similarly mirrors the contrast of interest within the limited code paradigm.

3.0 Results

This study examined how and where the constituents involved in numerical processing are represented in the brain through comparisons of univariate activity derived from two distinct paradigms.

3.1 Behavioral performance

During the limited code paradigm, participants displayed evidence of different underlying processes involved when making judgments during the four types of stimulus conditions. Participants performed as well (based on mean accuracy) during the numbers condition (M = 0.97, SD = 0.04) as they did on the faces (M = 0.95, SD = 0.04), words (M = 0.97, SD = 0.04), and shapes (M = 0.96, SD = 0.03) conditions (all ps > .061), however, they were slowest (based on mean response times) to respond to the numbers (M = 1167 ms, SD = 169 ms) when separately compared with each of the other three conditions: faces (M = 1004 ms, SD = 159 ms; ß = -0.42, p < .001), words (M = 1060 ms, SD = 118 ms; ß = -0.28, p < .001), and shapes (M = 916 ms, SD = 135 ms; ß = -0.64, p < .001).

Differences in underlying processes were observed during the full code paradigm as well. Participants performed better (based on mean accuracy) during the numerical judgment task (M = 0.96, SD = 0.04) than during the phonological judgment task (M = 0.81, SD = 0.11; ß = -0.67, p < .001). There were no differences between participants' performance for trials involving the hands stimuli (M = 0.87, SD = 0.12) compared to the numerals (M = 0.90, SD = 0.10; ß = 0.12, p = .143).

There was not a statistically significant interaction between the task and stimuli conditions (ß = 0.04, $p = .599$). Participants were slower to respond during the phonological judgment task (*M* = 1411 ms, *SD* = 249 ms) compared to the numerical judgment task (*M* = 1006 ms, *SD* = 199 ms; ß = 0.67, $p < .001$). Participants were also slower to respond to the hands (*M* = 1323 ms, *SD* = 312 ms) than to the numerals (*M* = 1094 ms, *SD* = 248 ms; ß = -0.38, $p < .001$). These differences were further quantified by a statistically significant interaction between the task and stimuli conditions (Phonological task and hands: *M* = 1563 ms, *SD* = 215 ms; Phonological task and numerals: *M* = 1259 ms, *SD* = 181; Numerical task and hands: *M* = 1083 ms, *SD* = 179 ms; Numerical task and numerals: *M* = 929 ms, *SD* = 191 ms; ß = -0.12, $p = .005$).

3.2 fMRI univariate results

We first attempted to replicate the findings from Emerson and Cantlon (2015) of identifying neural regions involved in number processing by contrasting neural activity while participants made a matching judgment while viewing either numbers (and dot quantities), words, shapes (or tools), and faces. Using spheres centered around the coordinates reported as number-selective regions, we found evidence of increased neural activity (reflected in greater beta coefficients) corresponding to number processing (compared to all other conditions) within four of the five spheres placed within the network: Right IPS (*M* = 0.05, *SD* = 0.05, $t(17) = 4.71$, $p < .001$), Left IPS (*M* = 0.06, *SD* = 0.06, $t(17) = 4.44$, $p < .001$), Right IFG/Insula (*M* = 0.07, *SD* = 0.07, $t(17) = 4.40$, $p < .001$), and ACC (*M* = 0.13, *SD* = 0.12, $t(17) = 4.38$, $p < .001$). The sphere placed within Left IFG/Insula did not reach statistical significance (*M* = 0.03, *SD* = 0.11, $t(17) = 1.18$, $p = .255$). In addition to replicating much of these findings within the coordinates reported when utilizing the limited code paradigm, we also localized broader clusters (compared to the spheres) involved in number processing. This whole brain approach allowed us to identify five clusters involved in number processing including right superior frontal gyrus, right superior parietal lobule, left superior parietal lobule, right thalamus, and right insula. Four of the five clusters showed overlap with the spheres previously analyzed, indicating additional evidence of replication between our study and previous studies using the limited code paradigm. We focused only on clusters displaying greater activation for the numbers condition relative to the other three conditions as this was most consistent with results reported in Emerson and Cantlon (2015). Additionally, clusters displaying less activation in this contrast could result from processing of any of the other three varied conditions (the reason for these effects is beyond the scope of this paper). Table 1 presents peak coordinates, cluster size, and information concerning overlap with spheres; Clusters are presented on a standard template brain in Figure 4.

Table 1. Localized regions involved in number processing during limited code paradigm

Peak Region	Cluster size (mm^3)	Peak X	Peak Y	Peak Z	Overlaps with sphere
Right superior frontal gyrus	1555	35.9	56.9	4.1	ACC
Right superior parietal lobule	709	4.7	-71.2	55.3	Right IPS
Left superior parietal lobule	497	-17.2	-71.2	55.3	Left IPS
Right thalamus	471	4.7	-5.6	11.6	-
Right insula	210	54.7	13.1	2.2	Right IFG/Insula

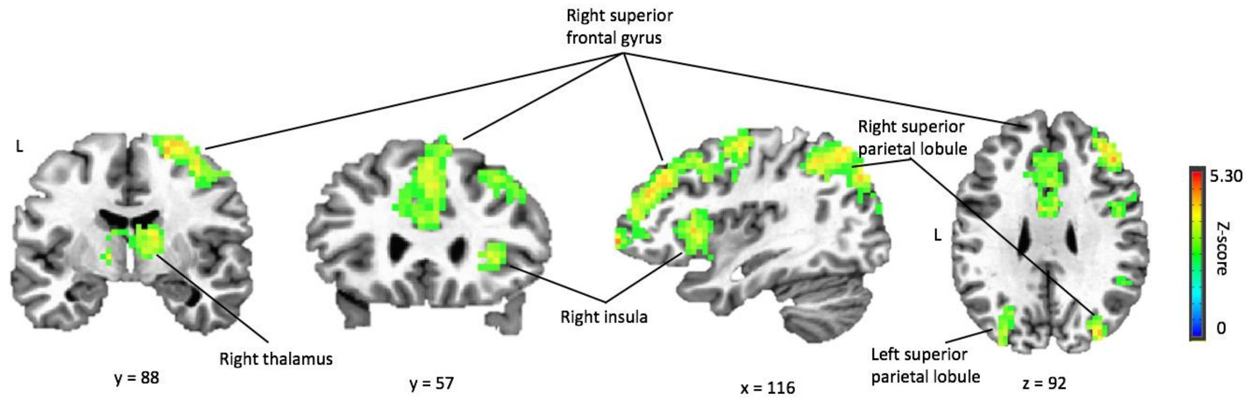

Figure 4. Clusters showing increased activity for numbers compared to all other conditions (words, shapes, faces)

We next asked whether our full code paradigm would also identify these same regions as being involved in number processing. We first analyzed our key contrast of interest (i.e. between phonological and numerical judgment tasks) within each of the five spheres and five clusters by contrasting beta coefficients. Only the right IPS sphere (M = 0.03, SD = 0.05; t(17) = 3.02, p = .008) and the right superior parietal lobule cluster (M = 0.08, SD = 0.08; t(17) = 4.49, p < .001), which overlapped with the right IPS sphere, showed evidence of greater activity during the numerical judgment task compared to the phonological judgment task. The left IFG/Insula sphere showed evidence of less activity during the numerical judgment task compared to the phonological judgment task (M = -0.04, SD = 0.08; t(17) = -2.15, p = .046). No other spheres or clusters reached statistical significance (all ps > .071).

Our full code paradigm consisted not only of participants performing different task judgments, but also different stimulus types. We contrasted the hands and numerals within each of the five spheres and five clusters. The right IPS sphere (M = 0.03, SD = 0.03; t(17) = 3.76, p =

.002), the right superior parietal lobule cluster (*M* = 0.10, *SD* = 0.08; $t(17) = 5.11$, $p < .001$), and left superior parietal lobule (*M* = 0.05, *SD* = 0.08; $t(17) = 2.69$, $p = .015$), which overlapped with the left IPS sphere, showed evidence of greater activity when the hands were presented compared to when the numerals were presented. No other spheres or clusters reached statistical significance (all *p*s > .121).

Our final univariate analysis consisted of comparing the numerical judgment task (including both types of stimuli) with the baseline condition (consisting of time points during presentation of fixation cross and instructions). In the same manner that the limited code paradigm's numbers condition was the only condition to require participants to draw on visual and semantic knowledge of numbers, the numerical judgment task in our full code paradigm required participants to draw on these same constituents. Four of the five *spheres* showed evidence of greater activity when participants were completing the numerical judgment task compared to baseline: right IPS (*M* = 0.09, *SD* = 0.04; $t(17) = 8.25$, $p < .001$), left IPS (*M* = 0.04, *SD* = 0.08; $t(17) = 2.32$, $p = .033$), right IFG/Insula (*M* = 0.04, *SD* = 0.05; $t(17) = 3.13$, $p = .006$), and ACC (*M* = 0.08, *SD* = 0.11; $t(17) = 2.89$, $p = .010$). Four of the five *clusters* showed evidence of greater activity when participants were completing the numerical judgment task compared to baseline: right superior frontal gyrus (*M* = 0.05, *SD* = 0.08; $t(17) = 2.98$, $p = .008$), right superior parietal lobule (*M* = 0.17, *SD* = 0.09; $t(17) = 8.21$, $p < .001$), left superior parietal lobule (*M* = 0.10, *SD* = 0.09; $t(17) = 4.64$, $p < .001$), and right insula (*M* = 0.08, *SD* = 0.07; $t(17) = 5.46$, $p < .001$). Neither the left IFG/Insula sphere nor the right thalamus cluster reached statistical significance (*p*s > .052).

4.0 Discussion

In this study, we have presented a novel paradigm, the full code paradigm which can be used to identify neural regions involved in numerical processing. This paradigm was specifically designed to combat pitfalls of currently used paradigms, most notably in that it targets the four proposed constituents of numerical processing: visual, phonological/verbal, semantic, and manual. Additionally, this novel paradigm can be utilized as a more efficient localizer for future studies investigating aspects of numerical processing. By switching the tasks and format of stimuli presented during a single run, our paradigm can be easily adapted for use with children and other populations requiring special considerations when conducting fMRI research. Prior work investigating the verbal and semantic constituents of numerical processing in children with and without mathematical learning disability utilized functional localizers during their fMRI scans (Berteletti, Prado, & Booth, 2014; see also Prado et al., 2011). During two different localizer scans, participants completed a rhyming judgment task (non-numerical words) and a numerosity judgment task (dot quantities). While both localizer tasks proved useful, we suggest our full code paradigm could be an even more efficient method for obtaining similar results, with added benefits in that it is a shorter task and requires responses to numerical components in all conditions.

Although designed based on proposed conceptual advantages, it was necessary to investigate whether the full code paradigm would accomplish what it was intended for. We tested the efficacy of the full code paradigm by comparing it with an oft-implemented paradigm used to study numerical processing in both adults and children (Cantlon & Li, 2013 and Emerson & Cantlon, 2015).

We first replicated findings highlighting right and left IPS, right IFG/Insula, and ACC, as well as identified four functionally-defined clusters that overlap with these regions as being involved in numerical processing (Cantlon & Li, 2013 and Emerson & Cantlon, 2015). We did, however, fail to observe the involvement of left IFG/Insula using the same paradigm as had been expected (discussed further below), and observed unanticipated activation within right thalamus corresponding to numerical processing. While we did not expect the right thalamus region to display greater activity reflecting numerical processing, the triple code model has suggested a possible loop connecting cortical and subcortical components through the thalamus, particularly for rote overlearned calculations of numbers (Dehaene & Cohen, 1997).

The IPS has often been shown to be involved heavily in semantic representations of numerical processing (Skagenholt et al., 2018). Here, we find that right IPS was the only region to show differences in univariate activity when contrasting the processing of numerical judgments with phonological judgments. This suggests that representations within right IPS are robust across different stimuli formats (such as Arabic numerals and hands), while it is possible that other neural regions show greater sensitivity to one format. Additionally, the left IPS did not show a difference in the same numerical vs. phonological judgment contrast, yet it did when comparing numerical judgments with the baseline condition. Therefore, it is possible that the left IPS might be involved in an aspect of the phonological component of a number, whereas the right IPS is more involved in the quantity representations of a number. Additionally, we present evidence that right and left IPS also show a sensitivity to differences in visual representations relating to numerical processing. Greater activity was observed when participants were presented with hands representing numbers, than Arabic numerals.

In this thesis we have provided evidence that our full code paradigm is able to inform us about the underlying representations within neural regions involved in the semantic constituent (as defined through the limited code paradigm) of numerical processing. We also observed that activity within the Left IFG/Insula was greater when participants were processing the verbal aspect of number (compared to the semantic aspect). This finding is in line with previous research implicating this region as being involved in verbal and phonological tasks (Berteletti et al., 2014). Our results build upon these findings by showing that the response is not merely specific to phonology of any word, but that it is representative of words conveying numbers (even when portrayed as Arabic numerals and hands).

To build on the univariate analyses presented and discussed here, an additional feature of the full code paradigm is its ability to be analyzed through a multivariate approach. Using such an approach, planned future work will test the similarity of underlying neural representations of numerical processing across different formats (such as visual stimulus and task). As an example, we plan to compare the neural patterns of activity within regions when participants are completing the numerical judgment trials while viewing the numeral stimuli and the hand stimuli. Patterns of activity (in a given region) that are similar between these two stimuli formats will suggest that a region does not compute stimulus-specific information, but rather the cognitive processes required to complete the task.

While beyond the scope of this initial thesis, these additional planned analyses will inform us about the ability for neural regions to represent information about multiple constituents of numerical processing, even allowing us to investigate possible network connections between regions. Such representations, and even possibly network connectivity, can then be related to behavioral measures of math ability and number knowledge to further our understanding of numerical processing in the brain.

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