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Abstract

A core paradox within cognitive science is the emergence of cultural functions, such as writing systems and arithmetic, that develop across time spans far too short for our neural systems to evolve to support them. Previous work has addressed this question with the neural recycling hypothesis, proposing that these newer functions are mapped onto pre-existing interconnected regions of the brain, called neural circuits. We replicated results from a study exploring the specific functions that have been recycled to allow for symbolic subtraction and multiplication. Original findings suggested that numerosity circuitry, typically responsible for comparing the size or quantity of two groups, is employed for subtraction and verbal processing circuitry for multiplication. We reviewed the collected fMRI data to construct a model of the brain with the region responsible for numerosity localized. We confirmed that the region localized by the numerosity task corresponded to the right intraparietal sulcus (IPS). Future research should focus on the corollary of the neural circuitry hypothesis—that later-evolving processes are subject to the restrictions of the circuitry they recycle. In particular, analyzing data obtained from incorrect answers to tasks would help confirm that recycling underlies the correlations we see between the neural activity of certain tasks.

Introduction

Neural Recycling Hypothesis

The neural recycling hypothesis argues that the neural circuitry responsible for evolutionarily older functions are recycled by newer, similar functions in humans. Neural circuits consist of regions of interconnected neurons that collectively perform a function. This hypothesis is important in the constant process of mapping brain regions to certain functions. Additionally, it helps with identifying old and new functions of the brain and is fundamental to studies of the sociocultural human necessities that encourage this evolution. Current studies have revealed that functions that evolved later are expected to reuse several different pre-existing neural circuits spread across the brain instead of having a one-to-one relationship with a specific neural circuit (Anderson, 2010). Neural circuits are thought to be the basis for newer functions such as reading and arithmetic. As such, Haist et al. (2014) found a possibility of an alternate circuit in the brain for comparing fractions, a function which was originally thought to be from the same circuit used to compare whole numbers. This paper itself deals with the neural recycling circuit used to compare whole numbers, simply called “numerosity.”

Evolutionarily Newer Functions

In terms of the neural recycling hypothesis, numerosity is thought to be the base circuit of the later evolving function of subtraction. Likewise, there are other arithmetic functions such as multiplication that may be based on circuits relating to memory. As mentioned previously, we found that in neural reuse, it is expected that later-evolving functions rely on groups of circuits distributed throughout the brain. Thus, as multiplication is built on addition and subtraction principles, we can infer that multiplication is the later-evolving function. Thus, according to this study, brain activity while performing multiplication should not be localized to one specific circuit of the brain. In our exploration, we seek to identify the locations of numerosity and memory circuits in the brain using BOLD signal data from the original study.

Replication

We replicate the part of the study that constructs regions of interest (ROIs) pertaining to numerosity and phonological processing tasks. Replicating studies such as these will help increase confidence that these identified regions in the brain are responsible for evolutionarily older functions and newer functions. More specifically, we can be much more confident that the neural circuit for numerosity is the basis for subtraction and the neural circuit for verbal processing is more or less responsible for multiplication. In order to locate the area of the brain where the circuits lie, we looked at existing BOLD signal data recorded while subjects performed localizer tasks—specifically a numerosity task and a phonological processing task. Then using MATLAB, we averaged voxel activation over time for many subjects and, after thresholding for significance, plotted an approximate area on the brain of the region of interest.

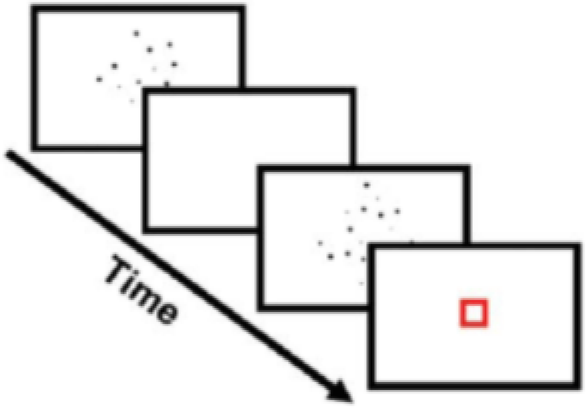
This ROI localized using numerosity data corresponds to the right IPS on the MNI normalized brain, which is a generic model of a brain used to remove individual variation. This is in line with both the expected result and the findings of the original paper. It shows that, independently of any prior knowledge of neural circuitry, the region that we call the IPS is significantly activated in numerosity tasks. Mutreja et al. (2011) demonstrate that the IPS is also correlated with symbolic subtraction tasks, which is in line with the predictions of the neural recycling hypothesis and implies the recycling of numerosity circuits for subtraction in modern society.

Materials and Methods

Materials

We used the original fMRI data from Mutreja et al. uploaded on OpenNeuro. The data was collected from 26 right-handed participants with no sign of neurological disease (from an original pool of 33 volunteers, where seven were excluded due to task error rate or movement within the scanner). Participants were presented with a stimulus for approximately four seconds. For the numerosity task, the stimulus was a pair of dot arrays, and participants identified the array containing more dots (Figure 1). For the phonological processing task, the stimulus was a pair of words, and participants answered whether the words rhymed. Each task was broken up into easy, medium, hard, and control runs based on the stimuli, and 12 trials of each difficulty were run per participant. See Mutreja et al. (2011) for further details on data collection.

Figure 1. In the numerosity comparison task, participants were asked to compare the number of dots in two dot arrays. The ratio of dots between the two arrays was either 12:36 (that is, 12 dots in one array and 36 in the other),



18:36, and 24:36, corresponding to easy, medium, and hard trials respectively. This stimulus engages the numerosity circuit of the brain by asking for a visual comparison of size or quantity. See Mutreja et al. (2011) for further information on the design of this task.

Methods

For the replication, we began by importing the fMRI data for numerosity into MATLAB using the toolboxes designed for working with such data, mainly "gunzip" and "niftiread." We then arranged the data into a 4-dimensional array for each participant, based on *x*, *y*, and *z* coordinates as well as time. By looping through the array over the time ranges designated by the events.json files, we isolated the activation data, voxel-by-voxel, over the relevant time slices. For each participant, we compared the activation during easy and hard tasks, taking the contrasts (difference between the means over time) between difficulties. We then fed the matrix of voxel-by-voxel contrasts into a one sample *t*-test comparing across all participants. The test statistics for each voxel were stored in a matrix, to which we applied a Gaussian blur with sigma = 3. We then applied a z-test to this matrix, recording the z-score of each voxel and using it to create a mask of the voxels whose activation was most significantly different from the rest ($Z < -2.8$, corresponding to $p < .0025$). The left half of the figure shows the portion of this mask containing the voxel with the maximum overall test statistic. The right half of the figure shows the locations of the maximum test statistic per participant within this mask, totaling 26 voxels. Results were plotted on an MNI normalized brain using the open-source project simpleBrainSurface (https://github.com/robertreingit/simpleBrainSurface).

Results

We were interested in how cultural inventions such as reading and completing math problems have led to the evolution of newer brain circuits. According to the neural recycling hypothesis, these newer brain circuits reuse components of older brain circuits. As a result, newer functions would not just use one specific neural circuit but instead be interconnected with a network of different pre-existing neural circuits across different regions of the brain. A core domain we wanted to investigate was the neural recycling circuit used for numerosity as it is the base circuit of the later-evolving function of subtraction, which requires comparison of numbers. Multiplication is even more advanced. Some people, like children, might memorize multiplication tables, whereas adults might use tricks that combine memorized multiplication with addition or subtraction. As such, there should be a network of older neural circuits related to numerosity and memory that the task of multiplication pulls from, rather than localizing to one specific circuit. Word comparison may also use the older neural circuits related to memory. We replicated this specific study because we were interested in analyzing the extent to which older neural circuits correlate with the newer functions of subtraction and multiplication; additionally, it involves identifying the regions in the brain that are stimulated while completing numerosity and memory tasks.

In order to do so, we tried to replicate the methodology of the original study as closely as possible. Using MATLAB to analyze the fMRI data, we conducted a *t*-test across contrasts between easy and hard tasks to determine which region of the brain was most significantly affected by the difference in difficulty. A cluster analysis was used to be sure that we localized the responsible region rather than an outlier voxel. See Materials and Methods for further logistical discussion.

Our goal was to locate the area of voxels in the brain which are the most sensitive to numerosity comparison using the data from the original paper (Figure 2). In order to construct this ROI, we compared the data we had from the study on easy numerosity localizer tasks to the data on hard numerosity localizer tasks. From our analyses of the most active voxels, we found a set of highly active areas and further processed that using a mask to finalize a specific pattern of activity localized in the right IPS.

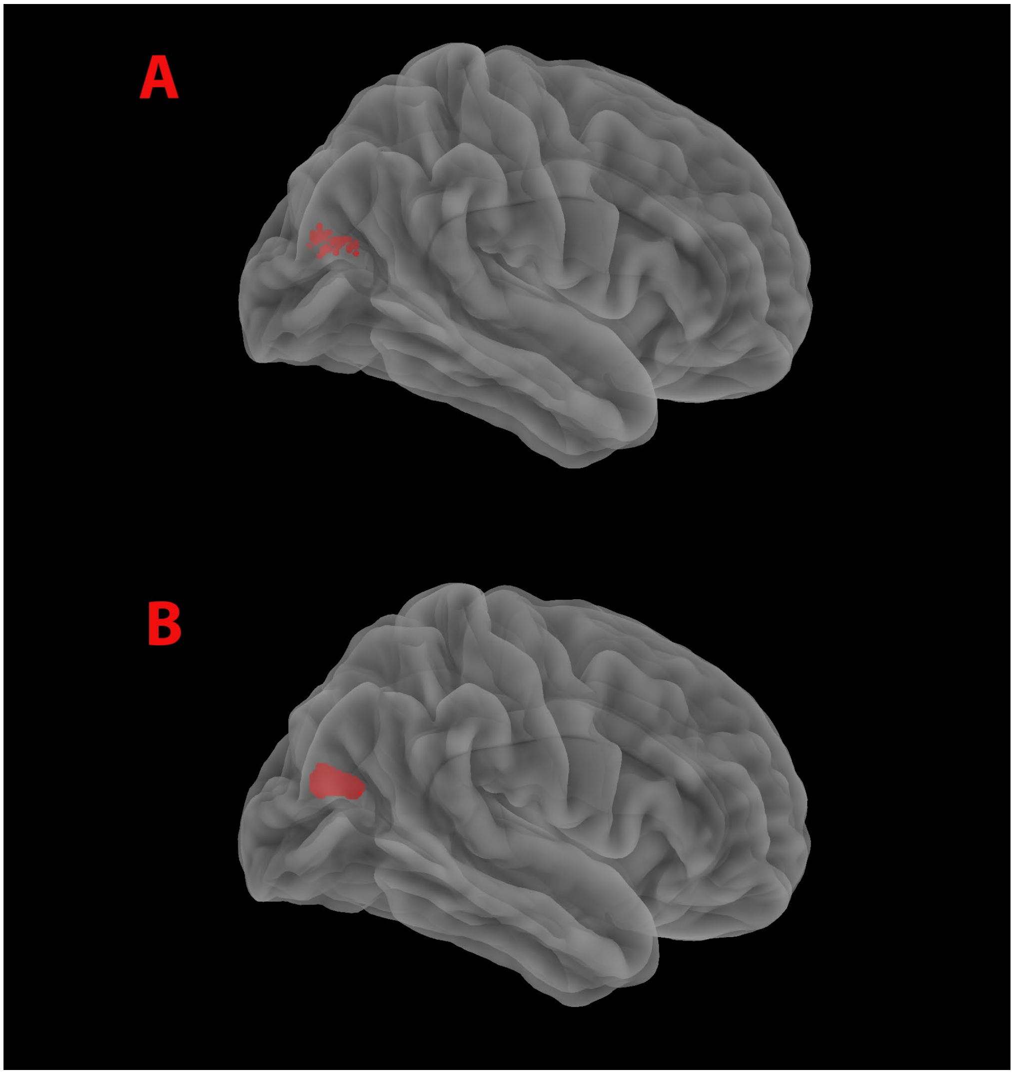


Figure 2. Two MNI normalized brain models with certain clusters of voxels plotted in red. (**A)** A plot of the voxels that showed the most significant difference in activation between easy and hard tasks. One most active voxel was isolated and plotted for each participant. (**B**) The mask of the voxels with the most statistically significant contrasts between easy and hard tasks across all participants.

We also attempted to localize the area of voxels that are related to phonological processing, which are predicted to be in the left tempo-parietal cortex and the inferior frontal cortex areas responsible for verbal processing. Ultimately, we were unable to replicate the methodology of the original paper and could not produce a conclusive ROI for the phonological processing task.

In short, the ROI for the numerosity task was found to be in the right IPS, whereas the ROI for phonological processing was undetermined.

Discussion

The objective of this replication is to test the neural recycling hypothesis, which proposes that newer functions in humans are based on networks of neurons in the brain, or neural circuits, responsible for evolutionary older functions. By analyzing the data from the original study, we reconstructed the ROI for numerosity processing, which is located in the right IPS. However, we were unable to similarly reconstruct the ROI for the phonological processing localizer task. Replications such as these are needed to increase confidence in the conclusions reached by the original study. More specifically, we sought to support the neural recycling hypothesis so that further research or hypotheses can reliably be founded on the basis of this one. For example, assuming that the neural recycling hypothesis is true, one can propose that the limitations of the neural circuit translate to the newer functions. Furthermore, assuming there is a direct relationship between the neural circuit and a comparatively newer function, one can form conjectures about the time it takes for a new function to be acquired and the level of difficulty of this acquisition all based on the features of the neural circuit it is derived from (Dehaene, 2011).

Figure 2 shows the successful replication of results from the original study. Namely, the region most significantly different between hard and easy numerosity tasks lies in the right IPS. This is shown by the mask in Figure 2 (B), which is simply a cluster of voxels meeting a minimum significance threshold with their activation (see Methods). Figure 2 (A) shows the most significantly activated voxel for each participant within that mask. The mask was created by measuring the cluster of voxels that was most significantly and consistently activated by the difference in tasks across all participants, indicating that it represents the center of the numerosity neural circuitry. This is in line with the original paper, which sought to build a mask of the IPS that accounted for individual variation across the participants. By using strictly activation data and statistical analysis to construct this region, we can be sure that there is no coincidence that the mask perfectly models the expected area of the IPS. Instead, we can confirm that this region is central to the execution of numerosity tasks. Figure 2 shows conclusively that the IPS is responsible for numerosity, even independent of any prior knowledge.

Generally speaking, by reconstructing the ROI for the IPS and attempting to reconstruct the ROI for the phonological processing localizer task, we conclude that the IPS coordinates the execution of numerosity tasks. In terms of the neural recycling hypothesis, subtraction and multiplication will reuse the numerosity circuits in the IPS. For future research, we suggest exploring whether the limitations of the numerosity circuit are connected to the limitations of subtraction by using the data for incorrect answers and analyzing the correlation between them. This would support the neural recycling hypothesis by further establishing that there is a direct relationship between the older circuit and the newer function.

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