Investigating The Modality Dependent and Independent Representations of Letters and Numbers.

Dora Gözükara
Maastricht University
dora.gozukara@student.
maastrichtuniversity.nl

ABSTRACT

Multimodal neural representations require a system in which both different aspects of the physical stimuli are represented, and also a multimodal abstraction is. In this study, we compared the representational systems of numbers and letters by using an fMRI experiment. Our findings can be summarized in two points: (1) The left intraparietal sulcus is involved in representing multimodal numbers and letters. (2) There are shared visual and auditory areas in the representations of numbers and letters. The similarities in these systems might help explain the comorbidity between dyslexia and dyscalculia.

Keywords

letters, numbers, neural representations, functional MRI.

INTRODUCTION

The brain is capable of extracting information about the external world via different sensory systems in different modalities. This not only enables it to gather information about various aspects of the world, but also to combine them to create more abstract and multimodal representations as well. For example, the sound of a bird, and the sight of a bird are completely independent sensory experiences; but the brain learns that they originate from the same source, and therefore creates a multimodal representation of the bird which encompasses both the sound and the sight. As a result, we can access to this bird representation both from our visual and auditory senses, and whenever this representation of the bird is accessed from one modality, the information about the bird from different modalities are also readily available. A 2010 fMRI study by Meyer and colleagues demonstrated the link between different modality representations by showing participants silent video clips of events that are strongly associated with sounds, for example a glass shattering, a piano key being pressed, or a dog howling (Meyer et al., 2010). They report in their findings that based on the activation in the auditory cortex as a result of the silent clips, which silent clip the participant was watching could be predicted.

It is therefore interesting to investigate representations in a modality perspective. This perspective can help us asking questions such as, “How are representations from different senses combined?”, “Are multimodal representations independent from the specific sensory representations they are made up of?”, or “Do different multimodal representations have structural similarities independent of the specific sensory representations they are made up of?”.

Numeracy and literacy can be explored in this context. They both are fundamental skills acquired during primary school years. They require the integration of arbitrary visuals (e.g. 3, 5, v, z) and arbitrary sounds (e.g. /three/, /five/, /v/, /z/) to create a multimodal representation of letters and numbers. The comorbidity between dyslexia and dyscalculia already hints at a shared underlying system for the two skills. A 2015 paper by Wilson et. al. examined possible shared cognitive impairments of dyslexia and dyscalculia, and concluded that general deficits in lexical access and phonological processing can be two of several factors contributing to the comorbidity (Wilson et al., 2015). Investigating the modality specific and multimodal representations of both numbers and letters thus can be useful to identify if there is a shared representational structure between the two systems.

Numbers

Eger et al., (2003) compared amodal number representations to amodal letter representations and amodal colour representations. In an MRI scanner, the participants responded every time they saw or heard a target stimulus, one letter, one number and colour. FMRI results showed that bilateral intraparietal sulcus is selectively active for number representations across modalities.

In another study, Holloway et. al. (2013) took advantage of different number symbol systems from different languages, specifically Arabic numerals and Chinese numerical ideographs. The authors compared two bilingual groups, both with the ability to speak and write English and only one group with the ability to speak and write Chinese. Their results demonstrated that the intraparietal sulcus is only active when participants were literate in the number system they were presented with. These results suggest that the semantic meaning of a number is represented in the intraparietal sulcus. This conclusion fits in with the results of Eger et al, indicating that a multimodal region where information from specific modalities are combined is also closely associated with the abstract semantic meaning of the concept, compared to regions where representations are only constructed of specific modalities.

A recent study from 2017 conducted by Vogel et. al.

(2017) examined the semantic nature of neural representations in the intraparietal sulcus accessed from different modalities. Their results show that intraparietal sulcus is the only brain are that is sensitive to the semantic meaning of numbers, both for visual and auditory presentations.

These findings point to a representational network for numbers in which fusiform gyrus and probably auditory cortex contain specific modal representations, visual and auditory respectively, of the number symbols; and the intraparietal sulcus contains an amodal representation of the number concepts. T

Letters

A 2004 study by N. Van Atteveldt et. al. (2004) investigating the letter and speech sound integration revealed a similar structure for the letters as to numbers, regarding the organization of the modality specific and multimodal representations. In their fMRI study, they reported modal representations in superior temporal cortex for auditory letter representations, and occipital temporal cortex for visual letter representations. The activation elicited by the two modalities overlapped in the superior temporal gyrus and sulcus, indicating an integration process. Anterior temporal regions were also found to respond specifically to congruent bimodal letter presentations.

In a 2013 study, Rothlein and Rapp measured the BOLD responses elicited by 12 pairs of upper and lower-case letters. They conducted a representational similarity analysis and identified regions in which the visual similarities (like between E and F) of the letters were correlated with the representational similarity of the brain activation related to these stimuli; and regions in which the letter identity (like E and e) was correlated with the representational similarity. They used these correlations as a measure of the degree to which a brain area is sensitive to a specific feature like the visual similarity or a general letter concept. Their findings show that the midfusiform and parahippocampal gyrus are selectively tuned to the abstract letter identity. This region generated similar response patterns to pairs of letters that shared an identity and produced dissimilar response patterns to all other shared aspects such as visual similarity, similarity regarding the motor plans needed to write the letter, or phonetical similarity.

Number And Letter Representations In A Theoretical Framework

The existence of both abstract multimodal and specific modality dependent representations letters and numbers have is in line with the hub and spokes theory of semantic cognition by Patterson et al. According to “the hub and spokes theory of semantic knowledge by Patterson et. al. (2007), concepts are a part of a system of hubs and spokes. The former provides the multimodal representations of the concepts and enable access to the above-mentioned concepts from different modalities. The latter on the other hand would provide the more specific physical aspects of stimuli, and enable the multimodal representations to be linked to their less abstract sensory meanings. Within this system, the modality specific hubs code for the strictly physical properties of the stimuli, for example the shape or the sound of a letter, whereas the multimodal hub code for the more abstract representation of the concept, linking the sound and the vision of the letter to create a letter identity. The summarized literature already hints at two overlapping systems. Visual representations of numbers and letters most likely reside in the occipitotemporal cortex, and auditory representations in the auditory cortex. These representations are not thought to be semantically oriented. For numbers, semantical amodal representations are thought to be found in the intraparietal sulcus, and for letters in the temporal regions. No study so far has been done comparing the representations of letters and numbers elicited from different modalities, thus this conclusion remains speculative so far. The aim of this study is to compare the modal and multimodal representations of both letters and numbers, specifically with visual and aural stimuli.

In this light, we investigated the differences in the numeracy and the literacy representational systems by using fMRI measurements of letter sounds, number sounds, letter symbols, and Arabic number symbols. fMRI responses were acquired using a slow event related design in order to enable single trial analysis.

BEHAVIOURAL PILOT

To fine-tune the task and the stimulus presentation parameters, a behavioural reaction time pilot with 6 participants was conducted.

The Stimuli

The stimuli consisted of the auditory and visual presentations of 3 mono-syllabic letters d, v, and z (/dee/, /vee/, /zet/); and 3 mono-syllabic numerals 3, 5, and 6 (/drie/, /vijf/, and /zes/). There were six distinct visual stimuli: d, v, z, 3, 5, and 6.

Experimental Procedure

The experiment was divided into 6 runs, each containing 4 blocks. Each of the four blocks consisted of letter visual, letter auditory, number visual or, number auditory stimuli, balanced by a Latin square sequence. The participants performed a one-back task, in which they needed to indicate by pressing a button when they see the same stimulus presented twice one after the other. Within each block a total of thirteen stimuli were presented with four repetitions of each number or letter. For each trial, a white fixation cross against a black background was presented. After the fixation cross, the stimulus was presented for 400 milliseconds. A total of 288 presentations were performed, with exactly 24 repetitions of each 12 stimuli (ignoring the target). The experiment was performed using Presentation® software (Version 18.0, Neurobehavioral Systems, Inc., Berkeley, CA, www.neurobs.com)

Analysis

One one-way repeated measures ANOVA between 4 conditions (number visual, number auditory, letter visual, and letter auditory) was performed on mean reaction times of condition blocks. Additionally, reaction times for categories and modalities were created. Specifically, the two conditions sharing the same modality were combined to construct visual and auditory reaction time conditions. The conditions that share the same category were combined to create the letter and number reaction time conditions. Two other one-way repeated measures ANOVA were performed on the two newly constructed mean reaction times of modality and category.

Results

Errors occurred in 0.11% of all trials. Because they were very rare they were not further analysed.

The reaction times were averaged per condition for each participant. A one-way repeated measures ANOVA revealed that there was no significant difference F (3, 72) = 1.567, p = 2.0548 between condition reaction times of letter visual (mean=829, variance=664753), letter auditory (mean=667, variance=217335), number visual (mean=600, variance=257821), and number auditory (mean=545, variance=860331). There also were no interaction effects F (15,72) =1.010, p=0.455

Two further one-way repeated measures ANOVA's were conducted: one by stimuli modality (visual or auditory) and one by stimuli category (letter or number). The analyses showed that there is no significant difference for stimuli modality F (1,58) = 0.654, p=0.4.22, between visual (mean=713, variance=464175) and auditory (mean=604, variance=151213). Nevertheless, there was a trend observed for stimuli category F (1,58) = 3.667, p=0.60, between letters (mean=747, variance=437342) and numbers (mean=572, variance=167521).

Given the limited participant number and thus limited power of the pilot, we decided to take the trend of the stimuli category into account for finalizing the stimuli presentation and the task for the fMRI measurements. Therefore we changed the initially intended one back task, to a task-free presentation of the stimuli for the fMRI measurements to eliminate any possible confounds.

FMRI MEASUREMENTS

Participants

9 participants took part in the fMRI measurements. They all were native Dutch speaking, with fluent English.

Experimental Procedure

The same stimuli as the behavioural pilot were used. The procedure used in the fMRI measurements was different than the one used in the behavioural pilot, in which instead of a one back task, the participants were asked to attend to the presented stimuli passively. The number of stimuli presented in each block was reduced to 12 with the omission of the target, but everything else regarding the timings and the structure in which the stimuli were presented was the same.

fMRI Acquisition

Functional and anatomical image acquisitions were performed by using a Siemens Allegra 3 tesla scanner at the Maastricht Brain Imaging Centre. The functional runs measured per subject with a spatial resolution of 2mm isotropic using a standard echo-planar sequence (repetition time (TR) of 1800 milliseconds, acquisition time (TA) of 1300 milliseconds, echo time (TE) of 30 milliseconds). There were 373 volumes and each volume consisted of 60 slices. Anatomical images (voxel size of 1*1*1-millimetre cube) covering the whole brain were acquired after the third run.

fMRI Data Pre-processing

fMRI data were pre-processed and analysed using Brain Voyager QX version 2.8 (Brain Innovation, Maastricht, The Netherlands). A 3D motion correction with trilinear/sinc interpolation, a correction for slice scan time differences with cubic spline interpolation, and a temporal filter with a high pass GLM with Fourier basis set with two cycles were applied to the functional data. Anatomical data were transformed into Talairach space. Functional data were then aligned with the anatomical data and transformed into the same space to create 4D volume time courses.

Univariate fMRI Data Analysis

Univariate analyses were done using a multi subject general linear model (GLM). Predictors per each trial in each stimulus condition were defined with a two-gamma hemodynamic response function applied to them. Several functional contrast maps were constructed to compare areas that are involved in representing spoken and written letters and numbers with the following contrasts: Letter auditory versus baseline, letter visual versus baseline, number auditory versus baseline, number visual versus baseline. Additional maps were constructed by conducting logical operations to the initial contrast maps. The significance threshold used to construct all the maps were p < 0.003 (uncorrected) with no cluster threshold of 100 voxels.

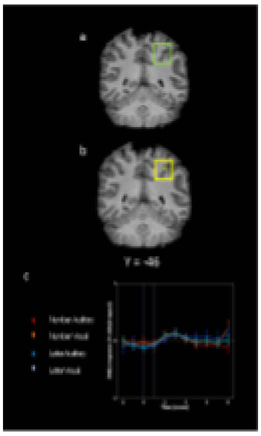

Figure 1) Shared parietal activation for (a) letter visual and letter auditory map, and (b) number visual and number auditory map. In (c), the event related activation for the given given point (x = -28, y = -46, z = 43) in the Talairach space.

RESULTS

Figure 1 specifies the shared location on the (a) multimodal letter and (b) multimodal number maps. The event related activation graph at the shared area is shown in (c). These figures and graph shows that the left intraparietal sulcus is involved equally with numbers and letters both visual and auditory.

Figure 2 shows the area in the bilateral auditory cortex that is active at both the number auditory and the letter auditory conditions. The graphs in (a) and (b) show the event related activations for the area in the left and the right hemisphere respectively. Figure 3 shows the area in the occipital cortex which is active for both the number visual and letter visual conditions. The graph in (b) shows the event related averages at the given area.

DISCUSSION

This study is the first to directly aim to compare the representational structures of numbers and letters. We explored the brain regions that were selectively active for specific modalities of numbers and letters, and that were insensitive to the modality differences of the numbers and letters. Our key findings can be summarized in two points: (1) The left intraparietal sulcus is involved in representing multimodal numbers and letters. (2) There are shared visual and auditory systems in the representations of numbers and letters.

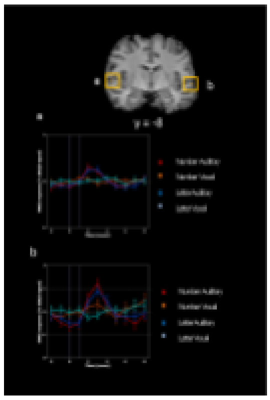

Figure 2) Shared activation in the bilateral auditory cortex at the points (x = -56, y = -8, z = 4) and (x = 57, y = -8, z = -1) in Talairach space. (a) Event related average graph at the point on the right auditory cortex. (b) Event related average graph at the left auditory cortex.

Our results are in accordance with the existing literature, both regarding the previously cited activation areas for

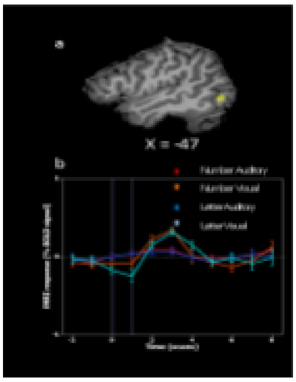

Figure 3) (a) Shared visual area for the both letter and number visual conditions at the point (*x* = -47, *y* = -69, *z* = -5) in the Talairach space. (b) Event related average graph at the given point.

numbers and letters of visual and auditory modality, and regarding the theoretical hub and spokes approach to representations. As expected, we found multiple areas that are associated with the representations of both numbers and letters. What was not expected was that one of these areas to be responsible for the multimodal representations of numbers and letters. Figure 1 shows that the intraparietal sulcus is associated with letter and number representations across modalities. It is known that the intraparietal sulcus is closely associated with the multimodal and abstract number representations, and because of this and its place in the parietal lobe, it was thought to be specialized for spatially oriented cognitions such as magnitude and numerical cognition (Eger, Sterzer, Russ, Giraud, & Kleinschmidt, 2003; Holloway, Battista, Vogel, & Ansari, 2013; Lyons, Ansari, & Beilock, 2015;; Vogel et al., 2017). Its role in letter representations remains to be investigated, but it can be speculated that it has to do with the fact that letters are taught and thought to be on an alphabetical line, as if there was a spatial or at least ordinal relationship between them (Eger et al., 2003; Judge, Knox, & Caravolas, 2013).

In line with the literature, the number and letter representations are associated with similar visual and auditory areas. The bilateral auditory cortex, and left occipital lobe are associated with respectively the auditory and the visual letters and numbers. It should be further investigated in a multivariate manner, if these representations reflect the physical properties (i.e. the similarity of the visual symbols or sounds) of the stimuli, rather than the categorical properties (i.e. letter or number).

CONCLUSION

It can be concluded that the numeracy and literacy representational systems share a lot of brain areas, and this might explain the comorbidity between dyslexia and dyscalculia. These findings also have possible implications for how the education of these two systems are implemented in the societal context. The specificities of the similarities and differences of these two systems may prove to be useful in constructing educational tools. Finally, new purely theoretical and/or philosophical discussions can arise from the comparison of letter and numbers, and its implication for mathematics and language.

ROLE OF THE STUDENT

Dora Gözükara was an undergraduate student working under the supervision of Milene Bonte and Francesco Gentile when the research in this report was performed. The topic was generated by both the student and the supervisors. The design of the experiment, and the processing of the results were done by the student with the guidance of Francesco Gentile. The formulation of the conclusions and the writing were done by the student.

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