This item was submitted to [Loughborough's Research Repository](#) by the author.
Items in Figshare are protected by copyright, with all rights reserved, unless otherwise indicated.

Processing symbolic and non-symbolic proportions: Domain-specific numerical and domain-general processes in intraparietal cortex

PLEASE CITE THE PUBLISHED VERSION

<https://doi.org/10.1016/j.brainres.2019.02.029>

PUBLISHER

Elsevier

VERSION

AM (Accepted Manuscript)

PUBLISHER STATEMENT

This paper was accepted for publication in the journal Brain Research and the definitive published version is available at <https://doi.org/10.1016/j.brainres.2019.02.029>

LICENCE

CC BY-NC-ND 4.0

REPOSITORY RECORD

Mock, J, S Huber, J Bloechle, Julia Bahnmueller, Korbinian Moeller, and E Klein. 2019. "Processing Symbolic and Non-symbolic Proportions: Domain-specific Numerical and Domain-general Processes in Intraparietal Cortex". Loughborough University. <https://hdl.handle.net/2134/12504485.v1>.

1

2 **Processing symbolic and non-symbolic proportions:**

3 **Domain-specific numerical and domain-general processes in intraparietal**

4 **cortex**

5

6 Julia Mock^a, Stefan Huber^a, Johannes Bloechle^{a,b,e}, Julia Bahnmueller^{a,d},

7 Korbinian Moeller^{a,c,d}, & Elise Klein^{a,d}

8 ^a Leibniz-Institut für Wissensmedien, Schleichstraße 6, 72076 Tuebingen, Germany

9 ^b Hertie-Institute for Clinical Brain Research, Division of Neuropsychology, Otfried-Müller-Straße 27, 72076

10 Tuebingen, Germany

11 ^c Department of Psychology, Eberhardt-Karls University Tuebingen, Schleichstraße 4, 72076 Tuebingen, Germany

12 ^d LEAD Graduate School, University of Tuebingen, Geschwister-Scholl-Platz, 72074 Tuebingen, Germany

13 ^e Department of Psychiatry and Psychotherapy, University Hospital Tuebingen, Germany

14

15

16

17 Correspondence:

18 Julia Mock

19 Leibniz-Institut für Wissensmedien

20 Schleichstrasse 6

21 72076 Tuebingen, Germany

22 Email: j.mock@iwm-tuebingen.de

23 Tel.: +49 7071 979-266

24

Abstract

Previous studies on the processing of fractions and proportions focused mainly on the processing of their overall magnitude information in the intraparietal sulcus (IPS). However, the IPS is also associated with domain-general cognitive functions beyond processing overall magnitude, which may nevertheless be involved in operating on magnitude information of proportions. To pursue this issue, the present study aimed at investigating whether there is a shared neural correlate for proportion processing in the intraparietal cortex *beyond* overall magnitude processing and how part-whole relations are processed on the neural level. Across four presentation formats (i.e., fractions, decimals, dot patterns, and pie charts) we observed a shared neural substrate in bilateral inferior parietal cortex, slightly anterior and inferior to IPS areas recently found for overall magnitude proportion processing. Nevertheless, when evaluating the neural correlates of part-whole processing (i.e., contrasting fractions, dot patterns, and pie charts vs. decimals), we found wide-spread activation in fronto-parietal brain areas. These results indicate involvement of domain-general cognitive processes in part-whole processing beyond processing the overall magnitude of proportions. The dissociation between proportions involving part-whole relations and decimals was further substantiated by a representational similarity analysis, which revealed common neural processing for fractions, pie charts, and dot patterns, possibly representing their bipartite part-whole structure. In contrast, decimals seemed to be processed differently on the neural level, possibly reflecting missing processes of actual proportion calculation in decimals.

Word count: 227 words

Keywords: proportions, symbolic, non-symbolic, fMRI, part-whole processing

1. Introduction

Recent research indicated that processing natural numbers and proportions is associated with activation in the intraparietal sulcus (IPS; Piazza, Pinel, Le Bihan, & Dehaene, 2007; Sokolowski, Fias, Mousa, & Ansari, 2017; see Nieder, 2005 for a review). Furthermore, we recently showed that processing overall magnitude of symbolic and non-symbolic proportions draws on similar neural correlates in the IPS (Mock et al., 2018). However, the IPS is not specifically dedicated to number processing. As part of the higher order (also referred to as tertiary) association cortex, the IPS hosts a variety of fine-grained sensory, motor, and cognitive functions including attention orienting, grasping, spatial working memory, saccade planning, mental rotation, and navigation (Culham and Kanwisher, 2001; Humphreys and Lambon Ralph, 2017, 2015; Simon et al., 2002).

However, joint aspects of processing proportions beyond overall magnitude have not yet been systematically investigated at the neural level. By the term *beyond overall magnitude* we refer to domain-specific numerical and domain-general processes involved in proportion processing as compared to the specific processing of overall proportion magnitude as reflected by the distance effect (Mock et al., 2018) and, thus, to processes not necessarily limited to magnitude processing. As such, the aim of the present study was to investigate shared aspects of processing proportions in the IPS reflecting domain-specific numerical as well as domain-general processes. In other words, we suggest that the neural activations evaluated in the present study do not necessarily reflect overall magnitude processing as indicated by the numerical distance effect (Mock et al., 2018). Nevertheless, processing magnitude information might still play an important role in proportion processing when operating on the actual proportion. This might, however, rather involve more top-down regulated proportion processing including domain-specific magnitude-related processes *and* other domain-general cognitive mechanisms.

Processing proportions seems particularly suited for this purpose as their processing is more difficult and requires more steps than just accessing number magnitude information. Furthermore, we evaluated whether different presentation formats (i.e., symbolic and non-symbolic presentation formats) of the same concept (i.e., proportions) share underlying domain-specific numerical as well as domain-general neural processes.

In the following, we will first present recent neuroimaging evidence on the processing of symbolic fractions and non-symbolic proportions. However, because neuroimaging studies in numerical cognition have so far focused mainly on the IPS as the core area for number magnitude processing, we then also introduce the role of the intraparietal cortex for more domain-general cognitive processes that are not necessarily specific to processing proportion magnitude, such as visuo-spatial processing, attention orienting, mental rotation, saccades, or spatial working memory.

1.1 The neural underpinnings of (proportion) number processing

Previous studies showed that a bilateral fronto-parietal network centered around the IPS is associated with number processing (Piazza, Pinel, Le Bihan, & Dehaene, 2007; see Nieder, 2005 for a review). Within this network, the IPS seems to be specifically involved in the processing of numerical magnitude information (Piazza et al., 2007; Pinel et al., 2001) and mental calculation (Arsalidou and Taylor, 2011; Dehaene et al., 1999). Furthermore, it was observed that bilateral inferior parietal lobule (IPL) and precuneus, left superior parietal lobule (SPL) and right superior frontal gyrus (SFG) are involved in processing of both symbolic and non-symbolic numbers (Sokolowski et al., 2017). More specifically, left intraparietal cortex as well as the left angular gyrus and right supramarginal gyrus seem to be involved in the processing of symbolic numbers, exact calculation, and arithmetic fact retrieval (Dehaene et al., 1999; Grabner et al., 2009; Holloway et al., 2010; Simon et al., 2002; Sokolowski et al., 2017; Venkatraman et al., 2005). In contrast, the

right IPS seems to underlie a semantic representation of numbers and an abstract code for absolute and relative magnitude (Cohen Kadosh et al., 2007; Mock et al., 2018; Mussolin et al., 2013). Additionally, a right-lateralized fronto-parietal network including right SPL and IPL, right SFG and right middle occipital gyrus seem to be specifically activated in the processing of non-symbolic numerosities (Holloway et al., 2010; Sokolowski et al., 2017). This suggests that symbolic and non-symbolic numbers are processed using both overlapping and distinct neural substrates (Sokolowski et al., 2017).

Furthermore, recent studies also revealed that brain regions typically associated with natural number processing are also involved in processing proportions (Ischebeck et al., 2010, 2009a, Jacob and Nieder, 2009a, 2009b). For instance, Jacob and Nieder (2009a) observed that the processing of symbolic fraction magnitude within the bilateral IPS seems to be independent of the presentation format and suggested that the same populations of neurons code the same fraction magnitude. Importantly, Jacob and Nieder (2009b) observed similar intraparietal effects for non-symbolic proportions. This is substantiated by a recent study, in which we found that processing symbolic (i.e., fractions and decimals) and non-symbolic proportions (i.e., dot patterns and pie charts) share a neural correlate in occipito-parietal regions including the right IPS (Mock et al., 2018). Interestingly, in our study (Mock et al., 2018), joint IPS activation was observed to be specific for the processing of overall symbolic and non-symbolic proportion magnitude (see also Ischebeck et al., 2009a; DeWolf et al., 2016).

Thus, on the neural level proportion magnitude seems to be represented by its value as a whole (i.e., its relative magnitude; Ischebeck et al., 2009a; Jacob & Nieder, 2009b). Based on this notion, DeWolf and colleagues (2016) investigated whether different symbolic numbers (i.e., fractions, integers, decimals) map onto a joint abstract magnitude code or whether different representations exist for specific number types (integers versus symbolic proportions) or number

1 notations (fractions vs. base-10¹, e.g. $\frac{1}{2}$ vs 0.5). Interestingly, processing fractions, integers, and
 2 decimals activated areas in the IPS. However, fractions yielded a distinct activation pattern from
 3 decimals and integers within the IPS, as revealed by both univariate and multivariate analyses.
 4 Thus, neural processing seemed to be sensitive to number notation (fractions vs. base-10), but not
 5 to number type (integer vs. proportion).

6 Taken together, previous work indicated that similar intraparietal brain regions are involved
 7 in number magnitude processing of integers as well as the magnitude processing of proportions,
 8 irrespective of symbolic or non-symbolic presentation format (for a brief overview on the
 9 processing of symbolic and non-symbolic proportions, see Jacob, Vallentin, & Nieder, 2012).

10 Yet, previous studies on the processing of proportions mainly focused on the processing of
 11 their magnitude in the IPS. However, recent research showed that the intraparietal cortex hosts
 12 other (related), more domain-general functions (e.g., Knops, Thirion, Hubbard, Michel, &
 13 Dehaene, 2009; Simon et al., 2002). This is in line with arguments from an evolutionary point of
 14 view that number processing co-opts brain regions that support these related functions rather than
 15 relying on a specifically dedicated brain region (Dehaene and Cohen, 2007; Knops et al., 2009). In
 16 the following, number unspecific processes subserved by the intraparietal cortex will be briefly
 17 summarized.

18 1.2 Sensory, motor, and cognitive processes of the IPS

19 The parietal cortex is associated with a wide range of sensory, motor, and cognitive functions
 20 (Critchley, 1953). Because of its complex and multimodal responses, the parietal cortex is
 21 considered as part of the “tertiary association cortex” (Culham and Kanwisher, 2001). In particular,
 22

¹ The base-10 place-value structure is based on the position of each digit which determines the numerical value within the respective digit string without proportional aspects (i.e., base-10 place-value structure: e.g., $35.4 = 3 \times 10^1 + 5 \times 10^0 + 4 \times 10^{-1}$; Huber et al., 2014b).

1 a variety of visuospatial tasks has been found to activate the parietal cortex such as hand reaching,
2 grasping, saccades, attention orienting, mental rotation, and spatial working memory as well as
3 guidance of actions yield activation (Culham and Kanwisher, 2001; Simon et al., 2002). These
4 cognitive functions partly share processes across domains, and thus, show overlapping activation
5 in the parietal cortex while smaller sub-regions exhibit domain-specific activations (Humphreys
6 and Lambon Ralph, 2015).

7 In particular, IPS and superior parietal lobule (SPL) are involved in a variety of tasks
8 including top-down attention, numerical calculation, executive semantics, phonological tasks, and
9 tool-praxis decisions (Humphreys and Lambon Ralph, 2015). Furthermore, IPS and SPL are
10 specifically involved in the storage and manipulation of items held in working memory during
11 goal-directed and executively demanding tasks (Humphreys and Lambon Ralph, 2015; Jonides et
12 al., 1998). As these tasks are non-automatic, goal-directed and highly demanding, it was assumed
13 that these brain regions support a general top-down processing system as part of a fronto-parietal
14 executive system across domains (Cabeza, 2008; Corbetta and Shulman, 2002; Humphreys and
15 Lambon Ralph, 2017, 2015).

16 Visual attention processes and reorienting spatial attention are widely considered to show a
17 right hemispheric predominance (Arrington et al., 2000; Corbetta et al., 2000; Thiel et al., 2004).
18 Also neuropsychological studies in patients with parietal lesions in the right hemisphere found
19 deficits in attentional processes (Becker and Karnath, 2007; Heilman et al., 1985; Sturm et al.,
20 2004), while motor attention has been shown to be linked to the left parietal cortex (Rushworth et
21 al., 2003, 2001).

22 Additionally, the IPS is involved in suppression of task-irrelevant distractors (Wojciulik and
23 Kanwisher, 1999) and response-selection processes (Göbel et al., 2004). Thus, in the parietal lobes
24 processes are subserved, which are not specific for magnitude processing itself, but are necessary

1 for or associated with the processing of numbers such as top-down attention, spatial representation,
2 working memory, eye movements, and the guidance of actions (Culham and Kanwisher, 2001;
3 Humphreys and Lambon Ralph, 2015).

4 Thus, previous research indicated that the IPS hosts a domain-general multi-demand system
5 involving a variety of sensory, motor, and cognitive processes ranging from attentional processes
6 to mental navigation as well as from pointing and grasping to number processing (e.g., Humphreys
7 & Lambon Ralph, 2015; Humphreys & Ralph, 2017; Simon et al., 2002). Additionally, there is
8 evidence that these different goal-directed processes interact as they all require a domain-general
9 executive system (e.g., Hubbard, Piazza, Pinel, & Dehaene, 2005; Humphreys & Lambon Ralph,
10 2015). For instance, Knops and colleagues (2009) showed that brain circuits associated with spatial
11 attention contribute to mental arithmetic. These results substantiate the notion that number
12 processing co-opts parietal circuits involved in low-level sensorimotor tasks such as spatial
13 attention and eye movements.

14 Furthermore, shared activation for grasping and pointing was observed in left IPS extending
15 into superior parietal lobule (SPL) and postcentral sulcus (Simon et al., 2002). These motor tasks
16 (i.e., grasping and pointing) also showed joint activation with visuospatial tasks such as saccades
17 and attention orienting in bilateral SPL (Simon et al., 2004, 2002). Interestingly, overlapping
18 activation was also observed with mental calculation, language, and saccades in the left posterior
19 segment of the IPS beneath the angular gyrus (Simon et al., 2002). Thus, number processing and
20 mental calculation does not only co-opt parietal circuits of low-level sensorimotor tasks, but also
21 shares brain areas with other higher cognitive functions such as language. Importantly, these
22 different cognitive processes share common features of executive demands (Humphreys and
23 Lambon Ralph, 2017). As such, the IPS is not a brain region specifically dedicated to numerical
24 cognition. Rather, the ability to process numbers and numerosities seems to involve number-

1 unspecific processes such as top-down processes, spatial attention, working memory, as well as
 2 executive processes which are hosted in an intraparietal executive system across domains with
 3 more domain-specific areas surrounding it (Humphreys and Lambon Ralph, 2017).

5 1.3 The present study

6 Previous research focused either on the magnitude processing of symbolic (DeWolf et al.,
 7 2016; Ischebeck et al., 2009a; Jacob and Nieder, 2009b) or non-symbolic proportions (Jacob and
 8 Nieder, 2009a) or on the question whether symbolic and non-symbolic proportions share an
 9 intraparietal neural correlate for overall magnitude processing, irrespective of presentation format
 10 (Mock et al., 2018). However, it has not yet been investigated whether there is a joint neural
 11 correlate in intraparietal areas associated with above described domain-specific numerical and
 12 domain-general cognitive processes. A closer look at the results of our latest study (Mock et al.,
 13 2018) provides an indication that there may be such shared intraparietal processes not necessarily
 14 specific to overall magnitude processing: the shared neural correlate in the right IPS for overall
 15 magnitude processing of symbolic and non-symbolic proportions as reflected by the numerical
 16 distance effect was rather small ($k = 46$ voxels; Mock et al., 2018). Typically, activated clusters in
 17 IPS are considerably larger for processing natural numbers or proportions, irrespective of
 18 presentation format (e.g., Arsalidou & Taylor, 2011 for a review and meta-analysis). Thus, these
 19 larger clusters might reflect the involvement of further cognitive processes complementing
 20 magnitude processing. In fact, to operate on magnitude information of proportions (e.g., fractions,
 21 decimals, pie charts, and dot patterns), other rather domain-general cognitive processes such as
 22 attention, eye movements during the comparison, working memory, and mental rotation in non-
 23 symbolic formats might be required besides domain-specific numerical processes (e.g.,
 24 magnitude). Furthermore, even though overall magnitude processing of symbolic and non-

1 symbolic proportions elicited joint activation in the right IPS (Mock et al., 2018), it is still unclear
2 whether the underlying neural processes to operate on this relative magnitude information are also
3 shared, or at least similar. Another important question we tackle in the present study is how bipartite
4 part-whole relations (e.g., fractions, pie charts, and dot patterns only) are processed at the neural
5 level. The bipartite structure of these presentation formats requires relating their components (e.g.,
6 denominator and numerator of a fraction) to infer overall magnitude information, which may
7 require additional domain-general cognitive processes to determine part-whole relations.

8 To pursue this issue, the present study took a two-step procedure. In a first step, we aimed at
9 investigating whether there is a joint neural correlate for domain-specific numerical and domain-
10 general processes in proportion processing at the whole-brain level. In a second step, we
11 investigated the processing of part-whole relation in more detail by contrasting conditions requiring
12 processing of part-whole relations (i.e., fractions, dot patterns, and pie charts) to decimals, which
13 do not require part-whole but base-10 processing. Additionally, based on the results of the first
14 step, we also pursued the question whether possibly shared activation patterns also indicate shared
15 underlying neural processes in the parietal cortex. It is important to note that the current work and
16 Mock et al. (2018) report on complementary aspects of the same dataset and that the current results
17 reflect analyses of both domain-specific numerical as well as domain-general processes as
18 compared to the specific processing of overall proportion magnitude in the IPS (as reflected by the
19 numerical distance effect) as evaluated by Mock et al. (2018).

20 We employed four different magnitude comparison tasks with symbolic (e.g., fractions and
21 decimals) and non-symbolic proportions (e.g., dot patterns and pie charts), respectively. As
22 previous studies showed an involvement of bilateral parietal regions and the prefrontal cortex
23 (PFC) during processing of symbolic and non-symbolic proportions, we expected a shared neural
24 correlate for all four presentation formats in this fronto-parietal network including IPS. First, we

identified joint intraparietal activation using a conjunction analysis on the whole-brain level. Second, and most importantly, as DeWolf and colleagues (2016) found that symbolic part-whole relations (e.g., fractions) yielded an activation pattern distinct from that observed for numbers complying with the base-10 structure, we examined the contrast between proportions reflecting bipartite part-whole relations (i.e., fractions, dot patterns, and pie charts) and decimals on a whole-brain level. This way, we were able to evaluate activation specific to part-whole processing without the interference of base-10 processing. Furthermore, in doing so we extended the scope of previous research (DeWolf et al., 2016) by including non-symbolic presentation formats.

To further evaluate proportion processing specifically in the parietal cortex, the resulting clusters of the conjunction analysis were taken as regions of interest (ROIs) for which the respective BOLD signal change was evaluated. Finally, possible differences between processing part-whole relations versus decimals were evaluated by a representational similarity analysis (RSA) differentiating the similarity of the intraparietal BOLD response for the different presentation formats in the bilateral IPL.

2. Results

2.1 Behavioral results

Mean speed of participants in the four conditions for dot patterns, fractions, pie charts, and decimals, respectively, was: $M_{dots} = 0.57$ ($SE = 0.04$) items/sec, $M_{fractions} = 0.57$ ($SE = 0.03$) items/sec, $M_{pies} = 0.85$ ($SE = 0.04$) items/sec, and $M_{decimals} = 1.10$ ($SE = 0.03$) items/sec.

In the next step, a univariate ANOVA with speed as the dependent variable and presentation format (dot patterns, pie charts, fractions, and decimals) as a fixed factor was conducted to compare the effect of presentation format on speed. The main effect was highly significant [presentation format: $F(3, 104) = 48.57$, $p < .001$, $\eta_G^2 = .584$], indicating that participants' speed differed between

presentation formats. Post-hoc comparisons revealed that except for the difference between dot patterns and fractions ($p = 1$) speed differed significantly from each other in all presentation formats (all $p < .001$). Figure 1A gives an overview for speed data.

Moreover, mean accuracy in the four conditions for dot patterns, fractions, pie charts, and decimals, respectively, were: $M_{dots} = 70.7\%$ ($SE = 2.75\%$), $M_{fractions} = 77.7\%$ ($SE = 2.77\%$), $M_{pies} = 91.0\%$ ($SE = 0.9\%$), and $M_{decimals} = 98.0\%$ ($SE = 1.0\%$). Again, the univariate ANOVA revealed significant main effect of presentation format [$F(3, 104) = 36.02$, $p < .001$, $\eta_G^2 = .510$]. Post-hoc comparisons indicated that the difference in accuracy was significant for all presentation formats ($p < .001$) except the difference between pie charts and decimals ($p = .082$) and between dot patterns and fractions ($p = .090$). Accuracy for the different presentation formats is shown in Figure 1B.

> *Insert Figure 1 here* <

2.2 Imaging results

2.2.1 Whole-brain conjunction analysis

The conjunction analysis across the four conditions (e.g., fractions, decimals, dot patterns, pie charts) revealed significant joint activation in visual occipital areas (e.g., lingual gyrus, calcarine gyrus, inferior occipital gyrus), bilateral thalamus and supplementary motor areas. Importantly, joint activation was also found in bilateral inferior parietal cortex, close to its junction with the IPS (see Table 1 and Figure 2).

> *Insert Table 1 here* <

> *Insert Figure 2 here* <

2.2.2 Contrast between part-whole relations and decimals

The contrast between the bipartite part-whole relations (i.e., fractions, dot patterns, and pie charts) and decimals revealed significant activation in bilateral inferior parietal lobule including bilateral IPS, areas in bilateral middle frontal gyrus, bilateral SMA, and bilateral insula (see Table 2 and Figure 3).

> *Insert Table 2 here* <

> *Insert Figure 3 here* <

2.2.3 Signal change within IPL ROIs

Mean percent signal change of the four presentation formats for bilateral IPL clusters found in the conjunction analysis (see 2.2.1) is given in Figure 4. We compared the percent signal change by running a 4×2 ANOVA with factors presentation format (dot patterns, pie charts, fractions and decimals) and hemisphere (left and right). Only the main effect of presentation format was significant, $F(2.67, 61.35) = 18.51, p < .001, \eta_G^2 = .167$. In contrast, the main effect of hemisphere as well as the interaction between presentation format and hemisphere was not significant; hemisphere: $F(1, 23) = 2.98, p = .098, \eta_G^2 = .184$, and presentation format $\times$ hemisphere: $F(2.50, 57.58) = 2.03, p = .130, \eta_G^2 = .006$. Post-hoc comparisons revealed that percent signal changes differed significantly between presentation formats (all $p < .04$) except for percent signal changes for dot patterns and pie charts ($p = .836$).

> *Insert Figure 4 here* <

2.2.4 *Representational similarity*

Descriptively, the resulting RSMs for left and right hemispheres were very similar (see Figure 5). We observed that the activation pattern for dot patterns was very similar to the one for fractions (LH: $\text{sim} = 0.93$; $SD = 0.07$; RH: $\text{sim} = 0.92$; $SD = 0.06$) and pie charts (LH: $\text{sim} = 0.88$; $SD = 0.10$; RH: $\text{sim} = 0.89$; $SD = 0.09$), whereas the activation pattern for decimals differed more from dot patterns (LH: $\text{sim} = 0.77$; $SD = 0.17$; RH: $\text{sim} = 0.74$; $SD = 0.16$). Furthermore, the activation pattern for pie charts was more similar to the activation pattern for decimals (LH: $\text{sim} = 0.86$; $SD = 0.13$; RH: $\text{sim} = 0.83$; $SD = 0.10$). Moreover, the similarity of the activation patterns for pie charts and fractions (LH: $\text{sim} = 0.84$; $SD = 0.12$; RH: $\text{sim} = 0.84$; $SD = 0.08$) was in the same range as the similarity between the one for pie charts and the other presentation formats. However, activation patterns for decimals and fractions differed more strongly (LH: $\text{sim} = 0.74$; $SD = 0.19$; RH: $\text{sim} = 0.70$; $SD = 0.18$).

> *Insert Figure 5 here* <

The resulting dendrograms of the hierarchical cluster analysis for left and right hemisphere are shown in Figure 6. Comparable to the RSM, it indicated that activation patterns for fractions, dots, and pie charts were very similar, whereas activation patterns of decimals differed from the other presentation formats.

> *Insert Figure 6 here* <

3. Discussion

The present study aimed at investigating whether there is a shared neural substrate in the IPL for domain-specific numerical as well as domain-general aspects of processing proportions beyond processing overall magnitude (as reflected by the numerical distance effect, cf. Mock et al., 2018). It is important to note that we already reported complementary aspects specific to overall magnitude processing of this dataset in Mock et al. (2018). Here, we aimed at evaluating the processing of proportions more broadly and part-whole relations in particular. Additionally, we were interested in whether shared neural activation patterns in the parietal cortex may also indicate shared underlying neural processes across different notations. To explore the cognitive demands during proportion processing in bilateral IPL in more detail, we applied an analysis of the BOLD signal change and a complementary RSA based on clusters of joint parietal activation identified in our conjunction analysis. In the following, we will first discuss the joint neural substrate found for processing proportions and part-whole relations in particular before we elaborate on our findings on shared underlying neural processes within the IPL.

3.1 A joint intraparietal neural substrate for processing of proportions

Our observation of joint bilateral IPL activation is in line with a recent meta-analysis by Sokolowski and colleagues (2017) who reported joint activation in bilateral IPL for the processing of symbolic and non-symbolic natural numbers. Importantly, our results extend this previous research because we used symbolic and non-symbolic proportions instead of integers and numerosities only. This substantiates the idea of IPL to be crucially involved in number processing in general.

Yet, the joint neural correlate found in our data may not exclusively reflect number magnitude processing (Sokolowski et al., 2017). On the other hand, we also do not wish to claim that the joint activation found in bilateral IPL exclusively reflects domain-general processes without any aspect

of magnitude processing. Instead, the observed IPL activation may well reflect processing and operating on number magnitude information. However, when investigating intraparietal processing specific to overall magnitude processing within the very same data set in a previous study (Mock et al., 2018, reflected by the numerical distance effect), we observed joint activation for overall magnitude processing of these presentation formats in a small cluster in right IPS only (MNI: 31, -60, 60; $k = 46$ voxels). Thus, the core area for the processing of overall relative magnitude differed from the region we found in the present study (see also Figure 2). Therefore, we suggest that the neural overlap found in the present study might rather reflect shared task demands for all four presentation formats such as visuo-spatial and top-down attention (Humphreys and Lambon Ralph, 2017), estimation, summation, and calculation processes (Castelli et al., 2006; Holloway et al., 2010; Piazza et al., 2006; Venkatraman et al., 2005), working memory during maintenance and manipulation of the to-be-compared items (Humphreys and Lambon Ralph, 2015; Jonides et al., 1998), eye movements (Knops et al., 2009; Simon et al., 2004, 2002), or response-selection (Göbel et al., 2004).

Although symbolic and non-symbolic proportions used in this study were conceptually distinct (part-whole vs. base-10), we nevertheless found a joint neural substrate in the parietal cortex indicating shared processes. Unfortunately, we are not able to further distinguish the processes involved on the basis of our design. However, we speculate that these processes might include domain-general visuo-spatial and top-down attentional processes, and working memory (Culham and Kanwisher, 2001; Göbel et al., 2004; Humphreys and Lambon Ralph, 2017, 2015; Simon et al., 2002) but also more domain-specific estimation, summation, and calculation processes (Castelli et al., 2006; Holloway et al., 2010; Piazza et al., 2006; Venkatraman et al., 2005) necessary to compute the relative magnitude of the given proportions. This is in line with the assumption of Humphreys and Lambon Ralph (2015; 2017) who proposed a domain-general

executive system in the IPS and SPL for shared non-automatic top-down processes during demanding, goal-directed tasks. Overall proportion magnitude, however, may be processed in the right IPS (Mock et al., 2018), which might correspond to a more domain-specific subregion close to this domain-general executive system in a nearby, but different brain area.

As working memory processes are also associated with frontal brain areas, previous studies additionally reported activation in PFC during processing symbolic fractions and non-symbolic proportions (Ischebeck et al., 2009a; Jacob and Nieder, 2009a, 2009b). Hence, we also expected a joint fronto-parietal network being involved in the processing of symbolic and non-symbolic proportions. However, we only observed activation in the dorsolateral PFC for the processing of fractions, dot patterns and pie charts, but not for the processing of decimals (see Appendix for the whole-brain analysis of the four presentation formats against baseline, respectively). As such, the results of our conjunction analysis did not reveal joint prefrontal activation. This suggests that fractions and non-symbolic proportions such as pie charts and dot patterns may be processed differently from decimals, as only the former activated a fronto-parietal network whereas the latter did not (see Appendix; for similar results on differences in processing fractions and decimals, see DeWolf et al., 2016).

3.3 Neural processing of part-whole relations

Fractions, dot patterns, and pie charts reflect bipartite part-whole relations. In particular, the bipartite structure of these presentation formats requires relating their two parts to infer the respective relative magnitude information. That is, the relation between the two proportional components determines overall relative magnitude. In contrast, decimals do not require these relating processes or additional computational steps and simply reflect their magnitudes based on their base-10 structure. To disentangle part-whole from base-10 processing, we evaluated the

1 contrast between part-whole proportions and decimals. Thereby, we were able to investigate part-
2 whole relation processing without interfering symbol-to-referent mapping of base-10 notations.

3 We found large activated clusters in bilateral IPL extending to bilateral occipital gyrus,
4 bilateral SMA, bilateral insula, as well as clusters in bilateral middle and inferior frontal gyrus.
5 Parts of the activation found in bilateral IPL (i.e., right IPS) have been associated with magnitude-
6 specific processing of proportions previously (Mock et al., 2018). However, as these brain regions
7 also seem to host an intraparietal domain-independent system of executive processes, the observed
8 activation might also indicate the involvement of top-down processes, spatial attention, working
9 memory, and other executive processes (e.g., Fias et al., 2013; Humphreys & Lambon Ralph,
10 2017). The activation of bilateral inferior frontal gyri also supports the idea of an involvement of
11 top-down and working memory processes. Activation in these brain areas was associated with
12 visual working memory (e.g., Song and Jiang, 2006), higher cognitive monitoring such as
13 choosing, comparing, or judging and manipulation of information (e.g., Christoff et al., 2000;
14 Ranganath et al., 2003), procedural complexity (e.g., Delazer et al., 2003; Simon et al., 2002), as
15 well as attentional processes (e.g., Ischebeck et al., 2009b). Furthermore, the inferior frontal gyri
16 also seem to underlie strategy choice and planning in mathematical processes (e.g., Arsalidou and
17 Taylor, 2011; Dehaene and Cohen, 1997). Additionally, bilateral insula was associated with the
18 execution of responses (e.g., Huettel et al., 2001) and goal-directed motivated behavior (e.g., Uddin
19 & Menon, 2009). Thus, the broad activation of a fronto-parietal pattern of brain areas may suggest
20 the involvement of domain-general cognitive processes such as working memory, top-down
21 attentional and executive processes, as well as strategy choice that go beyond pure magnitude
22 processing.

23 Interestingly, joint activation of dorsolateral frontal cortex including inferior and middle
24 frontal gyrus, insula, precentral gyrus, and SMA, as well as areas in and around the IPS was

1 interpreted to reflect a so-called multiple demand system (MD, see Duncan, 2010; Fedorenko et
2 al., 2013) or an extrinsic mode network (EMN, see Hugdahl and colleagues, 2015). The MD system
3 is associated with diverse cognitive and executive control demands including perception, response
4 selection, language, memory processes, problem solving, and task novelty independent of the
5 actual task at hand (Duncan, 2013, 2010; Fedorenko et al., 2013). The EMN extends the concept
6 of the MD suggesting a common activation pattern structure and up-regulating during task
7 processing, independent of the specific cognitive task at hand (Hugdahl et al., 2015). For instance,
8 EMN was shown to be activated by distinct cognitive tasks (e.g., spatial working memory, response
9 inhibition, impulse control, executive function, mental rotation, and arithmetic) and responds to
10 focused attention, goal maintenance, strategy selection, working memory and performance
11 monitoring (Fedorenko et al., 2013; Hugdahl et al., 2015). Hence, brain areas associated with MD
12 and the EMN show a broad functional generality.

13 Importantly, the brain regions we found for part-whole relation processing are strikingly
14 similar to the ones comprised by the MD and the EMN. This further supports the notion of domain-
15 general processes being involved in the processing of part-whole relations, not only on the whole-
16 brain level but also specifically in parietal brain regions. It is important to note, however, that we
17 do not suggest that part-whole relations are exclusively processed by domain-general networks.
18 Instead, like all human cognition, this processing is accomplished by a combination of domain-
19 specific regions like the parts of the IPS for number magnitude processing (Mock et al., 2018) and
20 domain-general cognitive and neural mechanisms (Duncan, 2013; Fedorenko et al., 2013; Hugdahl
21 et al., 2015). Thus, for the case of processing part-whole relations MD and EMN are complemented
22 by highly specialized brain regions.

23 However, the question remains why we find MD and EMN activation for part-whole relation
24 processing, but not for processing proportions in general including decimals. Hugdahl and

colleagues (2015) argued that the EMN is sensitive to learning and experience, which means that overlearned tasks do not activate the EMN (Hugdahl et al., 2015). As magnitude processing of decimals is very similar to the processing of other multi-digit numbers (when skipping the leading 0) adults are confronted permanently with in everyday life, we suggest that decimals may be overlearned as compared to symbolic or non-symbolic proportions. Hugdahl and colleagues (2015) further suggested that the EMN follows a threshold effect which varies depending on task novelty (Hugdahl et al., 2015). This way, the absence of MD and EMN in our conjunction analysis can be explained by the fact that processing of decimals reduces the experience of novelty, and thus, down-regulates the EMN. In contrast, when task novelty is high, which was apparently the case in the part-whole relation tasks, EMN is up-regulated complementing highly domain-specific brain mechanisms.

3.4 Cognitive demands during proportion processing in bilateral IPL

When analyzing BOLD signal change in the bilateral IPL ROIs identified by the conjunction analysis, we only found a main effect for the four presentation formats. There was no difference between hemispheres and also no interaction although left parietal cortex was recently suggested to be associated rather with the processing of symbolic numbers whereas right parietal cortex with the processing of non-symbolic numerosities (Cappelletti et al., 2010, 2009; Holloway et al., 2010; Sokolowski et al., 2017). However, previous research on this lateralization mainly focused on number magnitude processing, while we investigated proportion processing beyond overall magnitude processing. This might also indicate that the BOLD signal change found in our data rather reflects other cognitive processes necessary for the processing of symbolic and non-symbolic proportions than just overall magnitude processing.

The highest signal change was found for both non-symbolic presentation formats (e.g., dot patterns and pie charts), probably indicating higher demands on visuo-spatial attention as well as maintenance and manipulation of the respective items in working memory. In particular, the processing of proportional dot patterns might require more eye movements between the dots for individuation and summation of non-symbolic items (Holloway et al., 2010) whereas the processing of pie charts might rather involve mental rotation strategies (Alivisatos and Petrides, 1997; Jordan et al., 2001). Regardless of whether summation or mental rotation strategies are used to finally operate on the magnitude of those non-symbolic formats, the task is highly demanding and visuo-spatial attention is highly required. This assumption is further substantiated by additional activation observed in bilateral frontal eye fields (FEF) and posterior superior parietal lobule (PSPL) for both of these non-symbolic presentation formats as these regions are typically associated with eye movements (see Appendix A3 and A4; Knops et al., 2009). Additionally, activation in PFC reflect the involvement of executive control, working memory and attentional processes sending top-down signals to IPL (Humphreys and Lambon Ralph, 2015).

Furthermore, signal change for fractions was higher compared to decimals. This might indicate higher attentional loads as well as working memory demands during additional computational steps to access overall magnitude information of fractions (Mock et al., 2018). Moreover, eye movements between the two fractions or between their numerators and denominators might lead to higher visuo-spatial attention loads. In fact, for the processing of fractions we also observed additional activation in FEF and PSPL which are typically associated with eye movements (Knops et al., 2009) and prefrontal activation reflecting top-down attentional and working memory processes (see Appendix A1; Humphreys & Lambon Ralph, 2015).

In contrast, no additional computations and only low attentional demands are required while processing decimals. Rather, a simple symbol-to-referent mapping might seem plausible for

1 decimals as they directly reflect number magnitudes (Holloway et al., 2010). This idea is
2 corroborated by activation in areas subserving these processes such as left angular gyrus and
3 superior and middle temporal gyrus, which can be observed for decimals using a slightly less
4 conservative correction for the fMRI data ($p < .001$, uncorrected) than reported in the Appendix
5 A2 ($p < .05$, FWE-corrected). In particular, these brain regions are rather associated with bottom-
6 up and automatic processes which further supports the assumption of a direct symbol-to-referent
7 mapping (Humphreys and Lambon Ralph, 2015). Thus, in contrast to the bipartite structure of the
8 other presentation formats decimals do not seem to reflect proportional aspects in the same way.

9 Importantly, activation in parietal brain regions was previously associated with tasks
10 requiring additional attention due to higher levels of difficulty (Culham et al., 1998; Culham and
11 Kanwisher, 2001; Humphreys and Lambon Ralph, 2017; Shuman and Kanwisher, 2004). Thus,
12 parietal activation during numerical tasks might also be driven by task difficulty to some degree.
13 However, in the present study the signal change induced by proportion processing did not exactly
14 resemble the pattern found in the behavioral data. That is, the difficulty pattern found in speed and
15 accuracy differed from the pattern observed for signal change in the bilateral IPL. Speed was lowest
16 for fractions and dot patterns. Yet, comparing pie charts led to faster responses, while participants
17 achieved highest speed when comparing decimals. Additionally, accuracy in our data was highest
18 for decimals and pie charts, whereas accuracy for fractions and dot patterns was similarly low. As
19 increasing response times and error rates might indicate influences of task difficulty, these
20 behavioral results seem to reflect the difficulty in operating on magnitude information between the
21 different presentation formats. However, the signal change analysis revealed a different pattern.
22 Furthermore, previous studies found activations in the intraparietal cortex for either passive
23 listening to number words (Klein et al., 2010) or passive viewing of symbolic numbers versus
24 letters and colors (Eger et al., 2003). This indicates that intraparietal activations can be associated,

at least partially, with number processing independent from difficulty level. Thus, our results cannot be attributed to differences in difficulty exclusively.

3.5 Shared underlying neural processes of symbolic and non-symbolic proportions

Although fractions, dot patterns, pie charts, and decimals reflect conceptually different properties (part-whole vs. base-10), they activated a joint neural correlate as reflected by the conjunction analysis. However, a joint neural substrate does not necessarily implicate one common underlying process. Therefore, we conducted an RSA to gain more fine-grained results because this analysis evaluates similarities in the activation patterns of the four presentation formats.

The RSA revealed that the patterns of neural activations elicited by the part-whole relations (i.e., fractions, dot patterns, and pie charts) were very similar. That is, voxels in bilateral IPL responded very similarly when processing symbolic fractions as well as non-symbolic dot patterns and pie charts.

Thereby, our results indicate a dissociation between the patterns of neural activation elicited by decimals and the other presentation formats which further substantiates our contrast analysis. Furthermore, this is in line with the results of DeWolf and colleagues (2016) who observed that the activation pattern for fractions differed systematically from that of decimals and integers within the parietal cortex. Whereas the latter two number formats were hardly distinguishable, DeWolf and colleagues (2016) were able to clearly differentiate activations for fractions. Thus, the major notations for symbolic proportions (i.e., fractions and decimals) seem to draw on distinct neural processes even when they express the same magnitude (e.g., $\frac{2}{5}$ and 0.4). The present results indicate that fractions share an underlying neural process with proportional dot patterns and pie charts, whereas the neural processing of decimals differs. A plausible explanation for our finding is that the underlying neural processing of fractions, dot patterns and pie charts reflects the bipartite

structure of proportional part-whole relations. In contrast, decimals simply and directly reflect number magnitudes in a base-10 notation (e.g., see Huber et al., 2014b) and do not require the additional processing of proportional aspects. Thus, the structure of proportions (part-whole vs. base-10) seems to determine their underlying neural processing. Depending on the structure task demands might differ which, in turn, seems to change the respective activation patterns. This is in line with Humphreys and Lambon Ralph (2015) who suggested that parietal organization is not split by domain-specific tasks but rather meets the requirements of demanding tasks by adjusting respective neurocomputations. While performing a task, the respective activation pattern within parietal cortex might change due to different task demands (Humphreys and Lambon Ralph, 2015; see also Hugdahl et al., 2015 for a similar threshold effect in the EMN). Relating this to our data, pie charts, dot patterns, and fractions might have elicited similar neurocomputations within the IPL because of their structural similarity (i.e., bipartite part-whole relation), which, in turn, is reflected by the reported RSA pattern. In contrast, neurocomputations required for processing decimals on the neural level might differ as they do not reflect this bipartite part-whole relation.

3.6 Limitations

We are well aware that the current study is only a first step towards a more comprehensive understanding of the underlying processes in proportion processing. Thus, several aspects need to be considered when interpreting the results.

First, the design of the present study does not allow to further differentiate between domain-specific and domain-general mechanisms involved in proportion processing as the task at hand was a magnitude comparison task. However, in our view, activation patterns found for proportion processing in the present study do not reflect magnitude processing exclusively because we observed a core area for overall magnitude processing reflected by the numerical distance effect

exclusively in the right IPS for the same data set (Mock et al., 2018). Thus, although magnitude information might be processed as well in the present study, additional activation found here might reflect the additional involvement of more domain-general processes associated with proportion processing. Although our interpretation has to remain speculative, our findings nevertheless fit well with the literature. Yet, to disentangle this issue, future research is needed in which it would be desirable to specify the suggested domain-general processes.

Second, it needs to be noted that the pattern of our RSA might be influenced by task difficulty. In fact, participants responded more accurate and faster to decimals. In turn, they spent more time viewing the scrambled mask consisting of visual noise than doing the actual proportion magnitude comparison as compared to the other presentation formats. Furthermore, as we used a block design attentional demands might be different between an easy block (e.g., comparing decimals) and a more difficult block (e.g., comparing dot patterns). In turn, this might have led to lower correlations in the RSA. However, usually influences of task difficulty are also reflected in the amplitude of fMRI signal change (Culham et al., 2001; Ress et al., 2000). In line with above argument, signal change was lowest for decimals. Nevertheless, the pattern found for signal change associated with the other presentation formats differed from the pattern found in the RSA as the amplitude in signal change was highest for the two non-symbolic formats. Thus, while we cannot fully exclude influences of task difficulty in the RSA pattern, we suggest that the RSA does at least not exclusively reflect task difficulty.

4. Conclusion

Proportion processing beyond overall magnitude processing elicited activation in frontal, parietal and occipital brain regions including bilateral IPL. However, observed activation in bilateral IPL, an area typically associated with number magnitude processing, did not reflect

processing of overall proportion magnitude in our study. In fact, a shared neural substrate for the processing of abstract relative magnitude was observed in a nearby, but different brain area (i.e., right IPS) in a different analysis on the very same data set (Mock et al., 2018; see also Figure 2). Thus, the activation found in the present study does not necessarily reflect overall magnitude processing. Nevertheless, the shared neural correlate for proportion processing indicates common cognitive processes in a top-down executive parietal system. These processes might include visuo-spatial and top-down attention, estimation and summation processes, working memory, response-selection, and additional part-whole computations in the bilateral IPL for computing actual relative magnitude as well as relating and integrating the to-be-compared proportions.

Investigating processing of part-whole relations, we found wide-spread activation in fronto-parietal brain areas. This substantiates the involvement of domain-general cognitive processes in part-whole processing such as working memory, top-down attentional and executive processes, as well as strategy choice that go beyond magnitude processing. Thus, processing part-whole relations seems to be accomplished as an interplay of domain-specific (Mock et al., 2018) *and* domain-general cognitive and neural processes (Duncan, 2013; Fedorenko et al., 2013; Hugdahl et al., 2015) that complement each other.

The dissociation between part-whole relations (i.e., fractions, dot patterns, and pie charts) and decimals was substantiated by an additional RSA. Thus, although processing fractions, decimals, dot patterns, and pie charts elicited joint neural activation, the underlying neural processes seemed to be different depending on the structure of the respective proportion (i.e., part-whole vs. base-10). Thus, underlying structural differences of the notations seem to lead to distinct underlying neural processes.

5. Materials and Methods

5.1 Participants

Participants were 24 right-handed university students who participated voluntarily (13 females, mean age = 23.2 years; $SD = 2.99$ years). Participants gave their written consent according to the protocol of the local Ethics Committee of the Medical Faculty of the University of Tuebingen after being informed about the experimental procedure. All participants reported no previous history of neurological or psychiatric disorders and normal or corrected to normal vision. Participants received monetary compensation.

5.2 Procedure

Four different presentation formats of proportions were used in this study: fractions, decimals, pie charts, and dot patterns. Proportion processing was investigated by means of blocked magnitude comparison tasks (i.e., fractions, decimals, pie charts, and dot patterns). Proportions were presented pseudo-randomly in 24 blocks (six blocks per condition) consisting of one practice trial and four critical trials (120 trials in total: 24 practice and 96 experimental trials).

At the beginning of each block, a cue was presented for 500ms indicating which proportion type had to be compared in the next five trials. The cue was the fraction $1/4$ shown in the respective presentation formats in the center of the screen against a grey background. Afterwards, a black screen was presented for 4,000 ms. Subsequently, trials started with a black fixation cross against a grey background for 500 ms, followed by the presentation of the to-be-compared proportion stimuli for up to 5,000 ms. Participants had to respond within this time frame by pressing one of two MRI compatible response buttons with either their left or right thumb indicating that either the left or the right proportion was larger, respectively. When participants responded faster than the given 5,000 ms, a mask consisting of visual noise (blue, yellow, and grey pixels) was presented for

the remaining time. Then the next trial started. The procedure of the beginning of a block is shown in Figure 7. At the end of each block, a black screen was presented for 6,000 ms.

> Insert Figure 7 here <

5.3 Stimuli

Proportions (i.e., fractions, decimals, pie charts, and dot patterns) were presented in pairs (see Figure 8). The magnitude of the first proportion ranged from 0.13 to 0.86 and the second proportion from 0.22 to 0.89.

Symbolic fraction items were generated first and then converted into the other presentation formats. Numerators of the fractions ranged from 1 to 8 and denominators from 2 to 9. Fractions were constructed such that in half of the items the comparison of numerators and denominators was either congruent or incongruent with the comparison of overall fraction magnitude. For congruent trials, separate comparisons of numerator and denominator magnitudes yielded the same answer as the comparison of the overall magnitudes of fraction pairs (e.g., $1/6 < 3/8$ with $1 < 3$ and $6 < 8$). In contrast, separate comparisons of numerator and denominator magnitudes yielded opposing answers as compared to the overall magnitude of the fractions in incongruent trials (e.g., $4/7 < 2/3$, but $4 > 2$ and $7 > 3$). Thus, participants were not able to solve the task correctly, when relying on the magnitude of numerators or denominators only. We then constructed decimals by dividing numerators by denominators and rounding the result to two digits after the decimal point. Decimals and fractions were presented in blue (font type: Arial; font size: 80; RGB-values: 53, 85, 204) against a grey background (RGB-values: 204, 204, 204). One fraction was located on the left side (x/y-coordinates: 356 / 384 px), whereas the other one was located on the right side (x/y-coordinates: 668 / 384 px) of the screen (screen resolution: 1024×768 px).

Dot patterns were drawn in the center of the left and the right side of the screen on an invisible rectangular area of size 491×363 px. Location of dots varied randomly in these invisible rectangular areas. Dot patterns were colored according to the fractions they denoted using blue (same blue as for fractions) and yellow (RGB-values: 203, 187, 0) against a grey background (same grey as for fractions and decimals). For instance, the dot pattern of $4/7$ was drawn by coloring 4 dots in blue and 3 dots in yellow (and thus, 4 out of 7 dots were colored in blue). Diameter of dots varied randomly from 21 px to 98 px. To ensure that participants cannot rely on the proportion of the sum of visual areas when comparing the dot patterns, the sum of yellow and blue areas of the dots across the two dot patterns, which had to be compared, was equated.

Pie charts were drawn by dividing circles into pie segments according to the magnitude of the respective fraction items using the same colors as for dot patterns. For instance, $4/7$ was drawn by coloring $4/7$ of the pie in blue and $3/7$ in yellow. The background color used was the same grey as for the other presentation formats. The location of the yellow part varied pseudo-randomly. The diameter of pies ranged from 95 px to 289 px. To ensure that participants cannot select the larger proportion by relying only on the visual area of pie segments, we varied the size of the circles such that in half of the items the larger proportion was also larger in accordance to the visual area of the yellow pie segment, whereas in the other half of the items it was smaller.

> Insert Figure 8 here <

5.4 fMRI data acquisition

We acquired MRI data using a 3T Siemens Magnetom TrioTim MRI system (Siemens AG, Erlangen, Germany). A high resolution T1-weighted anatomical scan ($TR = 2300$ s, matrix = 256×256 , 176 slices, voxel size = $1.0 \times 1.0 \times 1.0$ mm³; FOV = 256 mm², TE = 2.92 ms; flip angle =

8°) was run at the end of the experimental session. All functional measurements covered the whole brain using standard echo-planar-imaging (EPI) sequences (TR = 2,400 ms; TE = 30 ms; flip angle = 80°; FOV = 220 mm², 88 × 88 matrix; 42 slices, voxel size = 2.5 × 2.5 × 3.0 mm³, gap = 10%).

FMRI data was acquired in a single run. We included pauses between blocks each lasting for 6,000 ms and presenting a black screen after each block. Total scanning time was about 20 minutes.

5.5 Behavioral data analysis

We analyzed both reaction times and accuracy. Because the distribution of reaction times was strongly skewed to the right, we used the inverse transformation and transformed reaction times into speed with measurement unit 1/sec to approximate normal distribution while conserving statistical power (Ratcliff, 1993). We considered only correctly solved trials in the analysis of speed (84,4% of all trials).

Univariate analyses of variance (ANOVAs) were performed in SPSS (IMB Corp., 2011) to test whether dot patterns, pie charts, fractions, and decimals differed significantly regarding speed and accuracy. Specific comparisons between the four presentation formats were performed using post-hoc Tukey tests ($p < .05$).

5.6 fMRI data analysis

5.6.1 Whole-brain analysis

We analyzed fMRI data using SPM12 (<http://www.fil.ion.ucl.ac.uk/spm>). Images were slice-time corrected, motion corrected, and realigned to each participant's mean image. No participant had to be excluded due to head movements as motion parameters did not exceed 2.5 mm translation in total and a head rotation of 1.5 degree in pitch, roll, and yaw in total. The mean image was co-registered with the whole-brain volume. Then, imaging data was normalized into standard

1 stereotaxic MNI space (Montreal Neurological Institute, McGill University, Montreal, Canada).
2 Images were resampled every 2.5 mm using 4th degree spline interpolation to obtain isovoxel and
3 then smoothed with a 6 mm full-width half-maximum (FWHM) Gaussian kernel to accommodate
4 inter-subject variation in brain anatomy and to increase signal-to-noise ratio in the images. To
5 remove low-frequency noise components the data were high-pass filtered (128s) and corrected for
6 autocorrelation assuming an AR(1) process.

7 The onsets of the four presentation formats (i.e., fractions, decimals, pie charts, dot patterns)
8 were entered as separate conditions in the GLM. Movement parameters estimated at the
9 realignment stage of preprocessing were included as covariates of no interest. Brain activity was
10 convolved over all experimental trials with the canonical haemodynamic response function (HRF)
11 as implemented in SPM12 and its time and dispersion derivatives.

12 We conducted a conjunction analysis in order to evaluate the notion of a joint neural substrate
13 of proportion processing (conjunction null; Nichols, Brett, Andersson, Wager, & Poline, 2005). In
14 a second step, we compared activations for the bipartite part-whole relations (i.e., fractions, dot
15 patterns, and pie charts) to decimals to investigate brain activation based on mere part-whole
16 processing.

17 The SPM Anatomy Toolbox (Eickhoff et al., 2005), available for all published
18 cytoarchitectonic maps (www.fz-juelich.de/ime/spm_anatomy_toolbox), was used for anatomical
19 localization of effects where applicable. In areas not yet implemented, the anatomical automatic
20 labelling tool (AAL) in SPM12 ([http://www.cyceron.fr/web/aal](http://www.cyceron.fr/web/aal_anatomical_automatic_labeling.html)
21 [anatomical_automatic_labeling.html](http://www.cyceron.fr/web/aal_anatomical_automatic_labeling.html)) was used. For the whole brain analysis, activations were
22 thresholded at a whole-brain family-wise error corrected (FWE) p -value of $< .05$ with a cluster size
23 of $k = 10$ voxels.

5.6.2 Signal change and representational similarity analysis

For percent signal change and representational similarity analyses, we focused on the clusters found in bilateral IPL as a result of the conjunction analysis. Furthermore, we conducted the analyses for both hemispheres separately because it was found that symbolic and non-symbolic formats are processed using both overlapping and distinct neural substrates (Sokolowski et al., 2017). Besides overlapping processing in bilateral IPL, bilateral precuneus, left SPL and right SFG, symbolic number processing (Holloway et al., 2010) and mental calculation (Arsalidou and Taylor, 2011; Dehaene et al., 1999) were especially associated with activation in left IPS. In contrast, parts of right parietal cortex were rather found to be involved in (visuospatial) attentional processes (Arrington et al., 2000; Corbetta et al., 2000; Thiel et al., 2004), processing of non-symbolic numerosities (Holloway et al., 2010; Sokolowski et al., 2017), and magnitude processing (Mock et al., 2018; Mussolin et al., 2013; Piazza et al., 2007).

We further investigated the similarity of activation patterns in jointly activated clusters around the bilateral IPS across presentation formats suggesting similar neural representations. For this, we conducted a representational similarity analysis (RSA). The output of the RSA was a matrix (representational similarity matrix) which reflected pairwise correlations between all stimuli. The RSA was based on β estimates of the voxels within jointly activated clusters in IPL. To obtain the representational similarity matrix, we ran Pearson correlations between the four presentation formats for each participant separately, scaled them into [0, 1] by computing the similarity value $\text{sim} = (r+1)/2$, and then averaged similarity values across participants. The higher the value of similarity (sim), the more similar was the neural representation of the different presentation formats with 1 being most similar. Visualized similarity served to characterize the shared representation (Kriegeskorte et al., 2008).

1 In course of the RSA, we further conducted an agglomerative hierarchical cluster analysis
2 based on the mean z -standardized β estimates for the four different notation formats. In the
3 hierarchical cluster analysis, we used the Euclidean distance as distance measure and average
4 linkage clustering as linkage criterion with lower distance being more similar.

Funding

Julia Mock was supported by the German Research Foundation (DFG) providing funding to Ulrike Cress, Hans-Christoph Nuerk and Korbinian Moeller (CR-110/8-1) and to Korbinian Moeller and Elise Klein (MO 2525/2-1). Stefan Huber, Johannes Bloechle and Julia Bahnmueller were supported by the Leibniz-Competition Fund providing funding to Elise Klein. Korbinian Moeller is faculty member and principal investigator, Elise Klein and Julia Bahnmueller are associated members at the LEAD Graduate School [GSC1028] and Research Network funded by the Excellence Initiative of the German federal and state governments. Elise Klein was supported by a Margarete von Wrangell fellowship from the Ministry of Science, Research and the Arts Baden-Württemberg.

Declarations of interest

None.

Authors' contributions

EK and KM conceived the study. KM, EK, and SH participated in its design. JB and JB performed data collection. JM and SH performed processing and statistical analyses. JM drafted the manuscript; all other authors revised it critically. All authors contributed to the interpretation of the data. All authors read and approved the final manuscript.

References

- Alivisatos, B., Petrides, M., 1997. Functional activation of the human brain during mental rotation. *Neuropsychologia* 35, 111–118. [https://doi.org/10.1016/S0028-3932\(96\)00083-8](https://doi.org/10.1016/S0028-3932(96)00083-8)
- Arrington, C.M., Carr, T.H., Mayer, A.R., Rao, S.M., 2000. Neural mechanisms of visual attention: object-based selection of a region in space. *J. Cogn. Neurosci.* 12, 106–117.
- Arsalidou, M., Taylor, M.J., 2011. Is 2+2=4? Meta-analyses of brain areas needed for numbers and calculations. *Neuroimage* 54, 2382–2393. <https://doi.org/10.1016/j.neuroimage.2010.10.009>
- Becker, E., Karnath, H.O., 2007. Incidence of visual extinction after left versus right hemisphere stroke. *Stroke* 38, 3172–3174.
- Cabeza, R., 2008. Role of parietal regions in episodic memory retrieval: The dual attentional processes hypothesis. *Neuropsychologia* 46, 1813–27. <https://doi.org/10.1016/j.neuropsychologia.2008.03.019>
- Cappelletti, M., Lee, H.L., Freeman, E.D., Price, C.J., 2010. The role of the right and left parietal lobes in the conceptual processing of numbers. *J. Cogn. Neurosci.* 22, 331–346. <https://doi.org/10.1162/jocn.2009.21246>
- Cappelletti, M., Muggleton, N., Walsh, V., 2009. Quantity without numbers and numbers without quantity in the parietal cortex. *Neuroimage* 46, 522–529. <https://doi.org/10.1016/j.neuroimage.2009.02.016>
- Castelli, F., Glaser, D.E., Butterworth, B., 2006. Discrete and analogue quantity processing in the parietal lobe: A functional MRI study. *Proc. Natl. Acad. Sci.* 103, 4693–4698. <https://doi.org/10.1073/pnas.0600444103>
- Christoff, K., John, D., Gabriel, E., 2000. The frontopolar cortex and human cognition : Evidence for a rostrocaudal hierarchical organization within the human prefrontal cortex 28, 168–186.
- Cohen Kadosh, R., Cohen Kadosh, K., Schuhmann, T., Kaas, A., Goebel, R., Henik, A., Sack, A.T.,

2007. Virtual Dyscalculia Induced by Parietal-Lobe TMS Impairs Automatic Magnitude Processing. *Curr. Biol.* 17, 689–693. <https://doi.org/10.1016/j.cub.2007.02.056>
- Corbetta, M., Kincade, J.M., Ollinger, J.M., McAvoy, M.P., Shulman, G.L., 2000. Voluntary orienting is dissociated from target detection in human posterior parietal cortex. *Nat. Neurosci.* 3, 292–297.
- Corbetta, M., Shulman, G.L., 2002. Control of goal-directed and stimulus-driven attention in the brain. *Nat. Rev. Neurosci.* 3, 201–215. <https://doi.org/10.1038/nrn755>
- Critchley, M., 1953. The parietal lobes. Williams and Wilkins, Oxford, England.
- Culham, J.C., Brandt, S.A., Cavanagh, P., Kanwisher, N., Dale, A.M., Tootell, R.B., 1998. Cortical fMRI activation produced by attentive tracking of moving targets. *J. Neurophysiol.* 80, 2657–2670.
- Culham, J.C., Cavanagh, P., Kanwisher, N.G., 2001. Attention response functions: Characterizing brain areas using fMRI activation during parametric variations of attentional load. *Neuron* 32, 737–745. [https://doi.org/10.1016/S0896-6273\(01\)00499-8](https://doi.org/10.1016/S0896-6273(01)00499-8)
- Culham, J.C., Kanwisher, N., 2001. Neuroimaging of cognitive functions in human parietal cortex. *Curr. Opin. Neurobiol.* 11, 157–163.
- Dehaene, S., Cohen, L., 2007. Cultural recycling of cortical maps. *Neuron* 56, 384–398. <https://doi.org/10.1016/j.neuron.2007.10.004>
- Dehaene, S., Cohen, L., 1997. Cerebral pathways for calculation: Double dissociation between rote verbal and quantitative knowledge of arithmetic. *Cortex* 33, 219–250. [https://doi.org/10.1016/S0010-9452\(08\)70002-9](https://doi.org/10.1016/S0010-9452(08)70002-9)
- Dehaene, S., Spelke, E.S., Pined, P., Stanescu, R., Tsivkin, S., 1999. Sources of mathematical thinking: behavioral and brain-imaging evidence. *Science* (80-.). 284, 970–974. <https://doi.org/10.1126/science.284.5416.970>

- 1 Delazer, M., Domahs, F., Barthä, L., Brenneis, C., Lochy, A., Trieb, T., Benke, T., 2003. Learning
2 complex arithmetic—an fMRI study. *Cogn. Brain Res.* 18, 76–88.
3 <https://doi.org/https://doi.org/10.1016/j.cogbrainres.2003.09.005>
- 4 DeWolf, M., Chiang, J.N., Bassok, M., Holyoak, K.J., Monti, M.M., 2016. Neural representations of
5 magnitude for natural and rational numbers. *Neuroimage* 141, 304–312.
6 <https://doi.org/10.1016/j.neuroimage.2016.07.052>
- 7 Duncan, J., 2013. The structure of cognition: attentional episodes in mind and brain. *Neuron* 80, 35–
8 50. <https://doi.org/10.1016/j.neuron.2013.09.015>
- 9 Duncan, J., 2010. The multiple-demand (MD) system of the primate brain: mental programs for
10 intelligent behaviour. *Trends Cogn. Sci.* 14, 172–179.
11 <https://doi.org/10.1016/j.tics.2010.01.004>
- 12 Eger, E., Sterzer, P., Russ, M.O., Giraud, A.L., Kleinschmidt, A., 2003. A supramodal number
13 representation in human intraparietal cortex. *Neuron* 37, 719–725.
14 [https://doi.org/10.1016/S0896-6273\(03\)00036-9](https://doi.org/10.1016/S0896-6273(03)00036-9)
- 15 Eickhoff, S.B., Stephan, K.E., Mohlberg, H., Grefkes, C., Fink, G.R., Amunts, K., Zilles, K., 2005.
16 A new SPM toolbox for combining probabilistic cytoarchitectonic maps and functional
17 imaging data. *Neuroimage* 25, 1325–1335.
- 18 Fedorenko, E., Duncan, J., Kanwisher, N., 2013. Broad domain generality in focal regions of frontal
19 and parietal cortex. <https://doi.org/10.1073/pnas.1315235110>
- 20 Fias, W., Menon, V., Szucs, D., 2013. Multiple components of developmental dyscalculia. *Trends*
21 *Neurosci. Educ.* 2, 43–47. <https://doi.org/https://doi.org/10.1016/j.tine.2013.06.006>
- 22 Göbel, S.M., Johansen-Berg, H., Behrens, T., Rushworth, M.F.S., 2004. Response-Selection-Related
23 Parietal Activation during Number Comparison. *J. Cogn. Neurosci.* 16, 1536–1551.
24 <https://doi.org/10.1162/0898929042568442>

- 1 Grabner, R.H., Ansari, D., Koschutnig, K., Reishofer, G., Ebner, F., Neuper, C., 2009. To retrieve or
2 to calculate? Left angular gyrus mediates the retrieval of arithmetic facts during problem
3 solving. *Neuropsychologia* 47, 604–608.
- 4 Heilman, K.M., Watson, R., Valenstein, E., 1985. Neglect and related disorders, in: Heilman, K.M.,
5 Valenstein, E. (Eds.), *Clinical Neuropsychology*. Oxford; New York, pp. 243–293.
- 6 Holloway, I.D., Price, G.R., Ansari, D., 2010. Common and segregated neural pathways for the
7 processing of symbolic and nonsymbolic numerical magnitude: an fMRI study. *Neuroimage*
8 49, 1006–1017.
- 9 Hubbard, E.M., Piazza, M., Pinel, P., Dehaene, S., 2005. Interactions between number and space in
10 parietal cortex. *Nat. Rev. Neurosci.* 6, 435–448. <https://doi.org/10.1038/nrn1684>
- 11 Huber, S., Klein, E., Willmes, K., Nuerk, H.-C., Moeller, K., 2014. Decimal fraction representations
12 are not distinct from natural number representations - evidence from a combined eye-tracking
13 and computational modeling approach. *Front. Hum. Neurosci.* 8, 1–14.
14 <https://doi.org/10.3389/fnhum.2014.00172>
- 15 Huettel, S.A., Güzeldere, G., McCarthy, G., 2001. Dissociating the neural mechanisms of visual
16 attention in change detection using functional MRI. *J. Cogn. Neurosci.* 13, 1006–1018.
17 <https://doi.org/10.1162/089892901753165908>
- 18 Hugdahl, K., Raichle, M.E., Mitra, A., Specht, K., 2015. On the existence of a generalized non-
19 specific task-dependent network. *Front. Hum. Neurosci.* 9, 430.
20 <https://doi.org/10.3389/fnhum.2015.00430>
- 21 Humphreys, G.F., Lambon Ralph, M.A., 2017. Mapping domain-selective and counterpointed
22 domain-general higher cognitive functions in the lateral parietal cortex: Evidence from fMRI
23 comparisons of difficulty-varying semantic versus visuo-spatial tasks, and functional
24 connectivity analyses. *Cereb. Cortex* 27, 4199–4212. <https://doi.org/10.1093/cercor/bhx107>

- 1 Humphreys, G.F., Lambon Ralph, M.A., 2015. Fusion and fission of cognitive functions in the
2 human parietal cortex. *Cereb. Cortex* 25, 3547–3560. <https://doi.org/10.1093/cercor/bhu198>
- 3 IBM Corp., 2011. IBM SPSS Statistics for Windows.
- 4 Ischebeck, A., Koschutnig, K., Reishofer, G., Butterworth, B., Neuper, C., Ebner, F., 2010.
5 Processing fractions and proportions: An fMRI study. *Int. J. Psychophysiol.* 77, 227.
6 <https://doi.org/10.1016/j.ijpsycho.2010.06.325>
- 7 Ischebeck, A., Schocke, M., Delazer, M., 2009a. The processing and representation of fractions
8 within the brain. An fMRI investigation. *Neuroimage* 47, 403–413.
9 <https://doi.org/10.1016/j.neuroimage.2009.03.041>
- 10 Ischebeck, A., Zamarian, L., Schocke, M., Delazer, M., 2009b. Flexible transfer of knowledge in
11 mental arithmetic — An fMRI study. *Neuroimage* 44, 1103–1112.
12 <https://doi.org/https://doi.org/10.1016/j.neuroimage.2008.10.025>
- 13 Jacob, S.N., Nieder, A., 2009a. Tuning to non-symbolic proportions in the human frontoparietal
14 cortex. *Eur. J. Neurosci.* 30, 1432–1442. <https://doi.org/10.1111/j.1460-9568.2009.06932.x>
- 15 Jacob, S.N., Nieder, A., 2009b. Notation-Independent Representation of Fractions in the Human
16 Parietal Cortex. *J. Neurosci.* 29, 4652–4657. [https://doi.org/10.1523/JNEUROSCI.0651-](https://doi.org/10.1523/JNEUROSCI.0651-09.2009)
17 [09.2009](https://doi.org/10.1523/JNEUROSCI.0651-09.2009)
- 18 Jacob, S.N., Vallentin, D., Nieder, A., 2012. Relating magnitudes: The brain’s code for proportions.
19 *Trends Cogn. Sci.* 16, 157–166. <https://doi.org/10.1016/j.tics.2012.02.002>
- 20 Jonides, J., Schumacher, E.H., Smith, E.E., Koeppe, R.A., Awh, E., Reuter-Lorenz, P.A.,
21 Marshuetz, C., Willis, C.R., 1998. The role of parietal cortex in verbal working memory. *J.*
22 *Neurosci.* 18, 5026–5034.
- 23 Jordan, K., Heinze, H.J., Lutz, K., Kanowski, M., Jäncke, L., 2001. Cortical activations during the
24 mental rotation of different visual objects. *Neuroimage* 13, 143–152.

- 1 <https://doi.org/10.1006/nimg.2000.0677>
- 2 Klein, E., Moeller, K., Nuerk, H.-C., Willmes, K., 2010. On the neuro-cognitive foundations of
3 basic auditory number processing: An fMRI study. *Behav. Brain Funct.* 6, 1–13.
4 <https://doi.org/10.1186/1744-9081-6-42>
- 5 Knops, A., Thirion, B., Hubbard, E.M., Michel, V., Dehaene, S., 2009. Recruitment of an Area
6 Involved in Eye Movements During Mental Arithmetic. *Science* (80-.). 324, 1583–1585.
- 7 Kriegeskorte, N., Mur, M., Bandettini, P., 2008. Representational similarity analysis – connecting
8 the branches of systems neuroscience. *Front. Syst. Neurosci.* 2, 1–28.
9 <https://doi.org/10.3389/neuro.06.004.2008>
- 10 Mock, J., Huber, S., Bloechle, J., Dietrich, J.F., Bahnmueller, J., Rennig, J., Klein, E., Moeller, K.,
11 2018. Magnitude processing of symbolic and non - symbolic proportions : an fMRI study.
12 *Behav. Brain Funct.* 1–19. <https://doi.org/10.1186/s12993-018-0141-z>
- 13 Mussolin, C., Noel, M.P., Pesenti, M., Grandin, C., De Volder, A., 2013. Neural correlates of the
14 numerical distance effect in children. *Front. Psychol.* 4, 1–9.
- 15 Nichols, T., Brett, M., Andersson, J., Wager, T., Poline, J.B., 2005. Valid conjunction inference with
16 the minimum statistic. *Neuroimage* 25, 653–660.
17 <https://doi.org/10.1016/j.neuroimage.2004.12.005>
- 18 Nieder, A., 2005. Counting on neurons: The neurobiology of numerical competence. *Nat. Rev.*
19 *Neurosci.* 6, 177–190. <https://doi.org/10.1038/nrn1626>
- 20 Piazza, M., Mechelli, A., Price, C.J., Butterworth, B., 2006. Exact and approximate judgements of
21 visual and auditory numerosity: An fMRI study. *Brain Res.* 1106, 177–188.
22 <https://doi.org/10.1016/j.brainres.2006.05.104>
- 23 Piazza, M., Pinel, P., Le Bihan, D., Dehaene, S., 2007. A Magnitude Code Common to Numerosities

- 1 and Number Symbols in Human Intraparietal Cortex. *Neuron* 53, 293–305.
- 2 <https://doi.org/10.1016/j.neuron.2006.11.022>
- 3 Pinel, P., Dehaene, S., Rivière, D., Le Bihan, D., 2001. Modulation of parietal activation by
- 4 semantic distance in a number comparison task. *Neuroimage* 14, 1013–1026.
- 5 <https://doi.org/10.1006/nimg.2001.0913>
- 6 Ranganath, C., Johnson, M.K., D’Esposito, M., 2003. Prefrontal activity associated with working
- 7 memory and episodic long-term memory. *Neuropsychologia* 41, 378–389.
- 8 [https://doi.org/10.1016/S0028-3932\(02\)00169-0](https://doi.org/10.1016/S0028-3932(02)00169-0)
- 9 Ratcliff, R., 1993. Methods for dealing with reaction time outliers. *Psychol. Bull.* 114, 510–532.
- 10 <https://doi.org/10.1037/0033-2909.114.3.510>
- 11 Ress, D., Backus, B.T., Heeger, D.J., 2000. Activity in primary visual cortex predicts performance
- 12 in a visual detection task. *Nat. Neurosci.* 3, 940–945. <https://doi.org/10.1038/78856>
- 13 Rushworth, M.F.S., Johansen-Berg, H., Göbel, S.M., Devlin, J.T., 2003. The left parietal and
- 14 premotor cortices: motor attention and selection. *Neuroimage* 20, S89–S100.
- 15 <https://doi.org/https://doi.org/10.1016/j.neuroimage.2003.09.011>
- 16 Rushworth, M.F.S., Krams, M., Passingham, R.E., 2001. The attentional role of the left parietal
- 17 cortex the district lateralization and localization of motor attention in the human brain. *J. Cogn.*
- 18 *Neurosci.* 13, 698–710.
- 19 Shuman, M., Kanwisher, N., 2004. Numerical magnitude in the human parietal lobe: Tests of
- 20 representational generality and domain specificity. *Neuron* 44, 557–569.
- 21 Simon, O., Kherif, F., Flandin, G., Poline, J.B., Rivière, D., Mangin, J.-F., Le Bihan, D., Dehaene,
- 22 S., 2004. Automatized clustering and functional geometry of human parietofrontal networks for
- 23 language, space, and number. *Neuroimage* 23, 1192–1202.
- 24 <https://doi.org/10.1016/j.neuroimage.2004.09.023>

- Simon, O., Mangin, J.-F., Cohen, L., Le Bihan, D., Dehaene, S., 2002. Topographical Layout of Hand , Eye , Calculation , and Language-Related Areas in the Human Parietal Lobe. *Neuron* 33, 475–487.
- Sokolowski, H.M., Fias, W., Mousa, A., Ansari, D., 2017. Common and distinct brain regions in both parietal and frontal cortex support symbolic and nonsymbolic number processing in humans: A functional neuroimaging meta-analysis. *Neuroimage* 146, 376–394.
- Song, J., Jiang, Y., 2006. Visual working memory for simple and complex features : An fMRI study 30, 963–972. <https://doi.org/10.1016/j.neuroimage.2005.10.006>
- Sturm, W., Longoni, F., Weis, S., Specht, K., Herzog, H., Vohn, R., Thimm, M., Willmes, K., 2004. Functional reorganisation in patients with right hemisphere stroke after training of alertness: A longitudinal PET and fMRI study in eight cases. *Neuropsychologia* 42, 434–450. <https://doi.org/10.1016/j.neuropsychologia.2003.09.001>
- Thiel, C.M., Zilles, K., Fink, G.R., 2004. Cerebral correlates of alerting, orienting and reorienting of visuospatial attention: An event-related fMRI study. *Neuroimage* 21, 318–328. <https://doi.org/10.1016/j.neuroimage.2003.08.044>
- Uddin, L.Q., Menon, V., 2009. The anterior insula in autism: Under-connected and under-examined. *Neurosci. Biobehav. Rev.* 33, 1198–1203. <https://doi.org/https://doi.org/10.1016/j.neubiorev.2009.06.002>
- Venkatraman, V., Ansari, D., Chee, M.W.L., 2005. Neural correlates of symbolic and non-symbolic arithmetic. *Neuropsychologia* 43, 744–753.
- Wojciulik, E., Kanwisher, N., 1999. The Generality of Parietal Involvement in Visual Attention. *Neuron* 23, 1–18.

Figure legend

Figure 1: A Speed and B accuracy in the four conditions (dot patterns, fractions, pie charts, and decimals).

Figure 2. Significant joint activation for proportion processing across the four conditions (e.g., fractions, decimals, dot patterns, pie charts) is given in red. The blue clusters indicate significant activation specific to overall magnitude processing as reflected by the numerical distance effect across the four presentation formats in a nearby, but different brain region (Mock et al., 2018). Activations were thresholded at a whole-brain FWE-corrected p -value of $< .05$.

Figure 3. Contrast between part-whole proportions (i.e., fractions, dot patterns, and pie charts) and decimals (part-whole – decimals). Significant activation depicts part-whole relation processing without base-10 related processing. Activations were thresholded at a whole-brain FWE-corrected p -value of $< .05$.

Figure 4. Percent signal change of the four presentation formats of the clusters in the inferior parietal cortex for left and right hemisphere. Error bars indicate ± 1 standard error of the mean.

Figure 5. Min-max normalized Representational Similarity Matrix for the four different notation formats with 1 being most similar.

Figure 6. Dendrograms for left and right hemisphere of the agglomerative hierarchical cluster analysis on the mean z-standardized β estimates for the four different notation formations. Distance indicates the Euclidean distance with lower distance being more similar.

Figure 7. Experimental procedure at the beginning of each block (i.e., one out of five trials).

Figure 8. Example stimuli (4/7 vs. 2/3) for the four different presentation formats. A depicts decimals, B fractions, C dot patterns, and D pie charts.

Figures

Figure 1

Figure 2

Figure 3 **Figure 4**

1 **Figure 5**

2

3

4

5 **Figure 6**

6

7

8

9

1

2 **Figure 7**

3

4

5

6

7 **Figure 8**

8

Table

Table 1. Joint activations across the four conditions (i.e., fractions, decimals, dot patterns, pie charts) as revealed by the conjunction analysis. Activations were thresholded at a whole-brain FWE p -value of $< .05$ with a cluster size of $k = 10$ voxels.

Contrast	Brain region	MNI (x, y, z)			k	t
Conjunction	LH inferior parietal lobule	-45	-32	43	40	6.08
	RH inferior parietal lobule	51	-25	48	28	5.74
	LH thalamus	-22	-27	-3	39	11.73
	RH thalamus	23	-27	-3	42	10.21
	RH supplementary area	1	6	53	56	7.86
	RH lingual gyrus	16	-97	-8	3637	25.15
	LH lingual gyrus*	-10	-90	15		17.67
	RH calcarine gyrus*	13	-90	3		17.24
	LH calcarine gyrus*	-5	-90	-5		18.17
	LH middle occipital gyrus*	-22	100	3		20.37
	RH middle occipital gyrus*	16	102	8		19.57
	LH inferior occipital gyrus*	-22	-95	10		22.95
	RH inferior occipital gyrus*	31	-85	10		16.11

Abbreviations: k = cluster size; LH = left hemisphere; MNI: Montreal Neurological Institute; RH = right hemisphere; FWE-corrected p -value $< .05$, cluster size $k = 10$ voxels; t = t -value. * Minor maximum.

Table 2. Activations for part-whole processing as revealed by the contrast part-whole (i.e., fractions, pie charts, and dot patterns) vs. decimals. Activations were thresholded at a whole-brain FWE p -value of $< .05$ with a cluster size of $k = 10$ voxels.

Contrast	Brain region	MNI (x, y, z)			<i>k</i>	<i>t</i>
Part-whole vs. decimals	RH Inferior parietal lobule (hIP2)	46	-40	50	1825	10.99
	RH Inferior parietal lobule (IPL)*	51	-37	53		10.59
	RH Superior occipital gyrus*	28	-65	40		9.53
	RH Superior parietal lobule*	26	-67	40		9.34
	LH Inferior parietal lobule (hIP3)	-35	-50	48	1164	8.48
	LH Inferior parietal lobule (IPL)*	-47	-37	48		8.36
	LH Middle occipital gyrus*	-25	-65	38		8.34
	LH Inferior parietal lobule (hIP1)*	-32	-47	43		8.30
	RH Middle frontal gyrus	43	36	20	633	10.70
	RH Inferior frontal gyrus*	48	13	30		8.96
	RH Supplementary motor area	6	26	45	267	8.96
	LH Supplementary motor area*	-7	21	45		8.11
	RH Insula	33	28	-3	169	10.46
	RH Middle frontal gyrus	31	11	60	166	7.35
	LH Precentral gyrus (Area 44)	-42	3	33	153	6.71
	LH Insula	-32	21	-3	121	8.49
	LH Inferior frontal gyrus (Area 45)	-47	28	30	88	6.55
	LH Middle orbital gyrus	-42	46	-3	68	6.45
	RH Middle orbital gyrus	38	53	-3	46	6.34

1 Abbreviations: *k* = cluster size; LH = left hemisphere; MNI: Montreal Neurological Institute; RH =
2 right hemisphere; FWE-corrected *p*-value < .05, cluster size *k* = 10 voxels; *t* = t-value. * Minor
3 maximum.

Appendix

Table A1. Activations found for magnitude comparisons with fractions. Activations were thresholded at a whole-brain FWE p -value of $< .05$ with a cluster size of $k = 10$ voxels.

Contrast	Brain region	MNI (x, y, z)			k	t
Fractions	LH Inferior parietal lobule	-47	-37	48	1101	12.07
vs.	LH Intraparietal sulcus (hIP3) *	-32	-50	48		11.23
Baseline	LH Superior parietal lobule *	-25	-62	45		10.62
	RH Intraparietal sulcus (hIP2)	46	-40	48	1052	10.82
	RH Intraparietal sulcus (hIP3) *	36	-50	48		10.48
	RH Intraparietal sulcus (hIP1) *	28	-55	48		9.15
	LH Precentral Gyrus (Area 44)	-45	6	30	679	11.04
	LH Inferior frontal gyrus (Area 45) *	-45	31	23		7.42
	RH Inferior frontal gyrus (Area 44)	46	6	25	311	10.39
	RH Middle frontal gyrus (Area 45)	48	36	23	225	9.94
	RH Superior frontal gyrus	28	1	53	149	8.30
	LH Middle frontal gyrus	-25	1	55	90	7.65
	LH Inferior frontal gyrus	-47	43	10	53	5.90
	RH Insula	33	26	0	170	10.64
	LH Insula	-30	23	3	127	9.56
	LH Thalamus	-22	-27	-3	60	13.12
	RH Thalamus	23	-27	-3	51	10.55
	RH supplementary area	6	18	48	431	10.72

RH Lingual gyrus	16	-97	-8	4891	25.15
RH Calcarine gyrus*	23	-100	-3		24.89
LH Inferior occipital gyrus*	-22	-95	-10		22.95
LH Inferior occipital gyrus*	-12	-100	-8		22.21
LH Middle occipital gyrus*	-15	-92	-8		21.44
LH Middle occipital gyrus*	-22	-100	3		20.37
RH Cuneus*	16	-102	8		19.57
LH Calcarine gyrus*	-5	-90	-5		18.17
LH Lingual gyrus*	-10	-90	-15		17.67
RH Calcarine gyrus*	13	-90	3		17.24
LH Cerebelum (VII)	-32	-67	-50	26	7.23

Abbreviations: k = cluster size; LH = left hemisphere; MNI: Montreal Neurological Institute; RH = right hemisphere; t = t-value. * Minor maximum.

Table A2. Activations found for magnitude comparison with decimals. Activations were thresholded at a whole-brain FWE p -value of $< .05$ with a cluster size of $k = 10$ voxels.

Contrast	Brain region	MNI (x, y, z)			k	t
Decimals	LH Inferior parietal lobule	-45	-32	43	66	6.08
vs.	LH Postcentral Gyrus*	-50	-27	55		5.73
Baseline	RH Postcentral Gyrus	51	-25	48	40	5.74
	LH Thalamus	-22	-17	-3	58	11.73
	RH supplementary motor area	1	6	53	169	7.86

RH Calcarine gyrus	16	-97	-5	3797	30.74
LH Middle occipital gyrus [*]	-15	-92	-8		28.40
LH Inferior Occipital gyrus [*]	-12	-100	-8		27.65
LH Calcarine gyrus [*]	-17	-100	-5		26.87
RH Cuneus [*]	16	-102	8		22.10

Abbreviations: k = cluster size; LH = left hemisphere; MNI: Montreal Neurological Institute;

RH = right hemisphere; t = t -value. ^{*} Minor maximum.

Table A3. Activations found for magnitude comparison with dot patterns. Activations were thresholded at a whole-brain FWE p -value of $< .05$ with a cluster size of $k = 10$ voxels.

Contrast	Brain region	MNI (x, y, z)			k	t
Dot patterns	RH Calcarine gyrus	16	-97	-5	9332	28.43
vs.	RH Intraparietal sulcus (hIP2) ^{**}	46	-35	48	716	12.84
Baseline	RH Intraparietal sulcus (hIP3) ^{**}	36	-50	50		12.59
	LH Inferior parietal lobule ^{**}	-47	-37	48	480	13.24
	LH Intraparietal sulcus (hIP3) ^{**}	-32	-50	48		11.53
	LH Middle occipital gyrus [*]	-15	-92	-8		26.54
	RH Lingual gyrus [*]	18	-90	-8		26.16
	RH Superior occipital gyrus [*]	23	-97	5		25.69
	LH Inferior occipital gyrus [*]	-12	-100	-8		25.26
	LH Calcarine gyrus [*]	-17	-100	-5		24.73
	RH Cuneus [*]	16	-100	10		21.79

RH Precentral gyrus	43	6	28	772	11.25
RH Middle frontal gyrus*	43	36	18		10.82
RH Inferior frontal gyrus (Area 45) *	48	13	30		10.44
LH Precentral gyrus	-42	1	33	359	9.36
RH Superior frontal gyrus	28	1	53	326	9.33
LH Superior frontal gyrus	-25	-2	53	152	8.45
LH Inferior frontal gyrus	-37	28	20	143	6.91
LH Middle frontal gyrus	-45	53	0	110	6.18
RH Middle frontal gyrus	38	58	8	100	5.31
RH Insula	33	26	0	251	11.03
RH Putamen *	23	16	0		5.23
LH Insula	-30	23	3	187	9.81
LH Putamen	-22	6	3	58	5.60
RH Thalamus	23	-27	-3	54	10.22
LH Thalamus	-22	-27	-3	47	11.83
RH supplementary area	6	18	48	543	11.59
LH Cerebellum (VIII)	-30	-67	-50	73	8.79
RH Cerebellar Vermis (9)	1	-55	-35	27	7.44

Abbreviations: k = cluster size; LH = left hemisphere; MNI: Montreal Neurological Institute;

RH = right hemisphere; t = t -value. * Minor maximum; ** Secondary peak.

Table A4. Activations found for magnitude comparison with pie charts. Activations were thresholded at a whole-brain FWE p -value of $< .05$ with a cluster size of $k = 10$ voxels.

Contrast	Brain region	MNI (x, y, z)			<i>k</i>	<i>t</i>
Pie charts	RH Postcentral gyrus	48	-25	45	989	10.10
vs.	RH Superior parietal lobule (hIP3)*	33	-45	48		8.07
Baseline	RH Inferior parietal lobule (hIP2)*	41	-40	50		7.85
	RH Inferior parietal lobule (hIP3)*	31	-55	53		7.35
	LH Postcentral gyrus	-42	-35	43	665	9.40
	LH Superior parietal lobule (hIP3)*	-37	-45	58		7.77
	LH Inferior parietal lobule (hIP3)*	-32	-45	48		7.06
	RH Middle frontal gyrus	31	-2	55	103	6.90
	RH Superior frontal gyrus*	28	-5	63		6.31
	RH Inferior frontal gyrus	46	6	25	95	6.85
	LH Precentral gyrus	-50	3	30	66	6.42
	LH Thalamus	-22	-27	-3	74	13.64
	RH Thalamus	23	-27	-3	59	10.54
	LH Putamen	-22	8	3	54	6.01
	RH supplementary area	1	6	53	258	8.76
	RH Calcarine gyrus	16	-97	-5	5439	28.29
	LH Calcarine gyrus*	-12	-92	-8		26.54
	LH Inferior occipital gyrus*	-12	-100	-8		25.75
	RH Superior occipital gyrus*	23	-97	5		24.94
	LH Calcarine gyrus*	-17	-100	-5		24.81

- 1 Abbreviations: *k* = cluster size; LH = left hemisphere; MNI: Montreal Neurological Institute; RH =
- 2 right hemisphere; *t* = t-value. * Minor maximum.