The neural circuits of number and letter copying: An fNIRS study

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ABSTRACT

In our daily lives, we are constantly exposed to numbers and letters. However, it is still under debate how letters and numbers are processed in the brain, while information on this topic would allow for a more comprehensive understanding of, for example, known influences of language on numerical cognition or neural circuits shared by numerical cognition and language processing. Some findings provide evidence for a double dissociation between numbers and letters, with numbers being represented in the right and letters in the left hemisphere, while the opposing view suggests a shared neural network. Since processing may depend on the task, we address the reported inconsistencies in a very basic symbol copying task by using functional near-infrared spectroscopy (fNIRS). fNIRS data revealed that both number and letter copying rely on the bilateral middle and left inferior frontal gyri. Only numbers elicited additional activation in the bilateral parietal cortex and in the left superior temporal gyrus. However, no cortical activation difference was observed between copying numbers and letters, and there was Bayesian evidence for common activation in the middle frontal gyri and superior parietal lobules. Therefore, we conclude that basic number and letter processing are based on a largely shared cortical network, at least in a simple task such as copying symbols. This suggests that copying can be used as a control condition for more complex tasks in neuroimaging studies without subtracting stimuli-specific activation.

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INTRODUCTION

Advancements in brain imaging techniques have provided growing insights into the localization of various brain functions, such as the basis of mathematical (Arsalidou & Taylor, 2011) and linguistic abilities (Friederici, 2011). However, it is still under debate whether alphanumeric stimuli such as numbers and letters are processed by separate or shared mechanisms (cf. McCloskey & Schubert, 2014).

It has been suggested that the separation of neural mechanisms underlying number and letter recognition manifests from early stages of sensory processing to higher-level processing (Park, Hebrank, Polk & Park, 2012). Polk and colleagues (2002) were among the first to investigate this hypothesis by directly contrasting neural activity during the presentation of numbers and letters. Their functional magnetic resonance imaging (fMRI) study showed that an area near the left fusiform gyrus was activated significantly more in response to letters than to numbers. Park and colleagues (2012) corroborated this fMRI evidence and found an increased activation in the left occipito-temporal cortex in response to letters compared to numbers, in a brain area identified as the visual word form area (VWFA) (Cohen et al., 2000). Moreover, they showed that numbers elicited higher activation in the right ventral pathway and right lateral occipital cortex than letters, and proposed this as evidence for a double dissociation between letter and number recognition (Park et al., 2012). Using intracranial electrophysiological recordings, Shum and colleagues (2013) found a preferential activation in response to numbers in the right inferior temporal gyrus (ITG), which has been previously proposed to be the visual number form area (NFA) (Dehaene & Cohen, 1995; Grotheer, Herrmann & Kovács, 2016). However, due to the fact that the majority of the participants were implanted with electrodes covering their right hemisphere, lateralization could not be explored in this study. Recently, the resting-state functional connectivity analysis of the

NFA and VWFA has revealed that the NFA is more strongly connected to areas which hold quantity representations, such as the right intraparietal sulcus (IPS), while the VWFA is more connected to left hemispheric regions involved in language processing in both sighted and blind individuals (Abboud, Maidenbaum, Dehaene & Amedi, 2015; for a review see Hannagan et al., 2015).

In support of a number-letter dissociation, another fMRI study demonstrated that although the bilateral fronto-parietal network displayed activation in both conditions, letter strings were preferentially processed in the left hemisphere within occipito-temporal regions, while numbers elicited a dominant response in right hemispheric structures such as the right fusiform, inferior and middle temporal gyri, inferior and superior parietal cortices, and supramarginal gyrus (SMG) (Carreiras, Quiñones, Hernández-Cabrera & Duñabeitia, 2015). To investigate the relationship between mathematical thinking and language even further, Amalric and Dehaene (2016) investigated professional mathematicians and non-mathematicians and showed that high-level mathematical thinking relies on a bilateral network comprising prefrontal, parietal, and inferior temporal regions that does not overlap with the left-hemispheric regions involved in language processing.

What is more, number and letter-specific brain areas have been suggested. For example, it has been proposed that the left fusiform gyrus, left insula and parts of the left inferior parietal lobule are all involved in the processing of the alphabet (Joseph, Cerullo, Farley, Steinmatz & Mier, 2006; Pernet, Celsis & Démonet, 2005). However, the degree of recruitment of these brain areas depends on the nature of the task (James & Gauthier, 2006). In addition, there is evidence to argue that the left inferior parietal cortex is involved in increased functional specialization of mental arithmetic as well (Rivera, Reiss, Eckert & Menon, 2005). Similarly, three parietal networks have been proposed to be involved in number processing: the bilateral horizontal IPS, the left angular gyrus, and the bilateral posterior superior parietal lobule (SPL) (Dehaene, Piazza, Pinel & Cohen, 2003). Of these areas, the IPS has been cited as being number-specific, both in tasks where magnitude processing is relevant (Dehaene et al., 2003) and when participants are passively listening to numbers (Klein, Moeller, Nuerk & Willmes, 2010). Moreover, IPS activation was also found to be larger for numerical stimuli compared to letters in an n-back working memory task (Knops et al., 2006). Considering that the left inferior parietal lobule is also involved in letter processing (Joseph et al., 2006), the degree of overlap raises questions about the extent of the double dissociation between numbers and letters.

From the above review, one might conclude that the literature supporting a separate cortical processing network for alphanumeric stimuli is thriving and consistent. However, some studies suggest the opposite, namely that letters and numbers share the same neural network. For example, Zhou et al. (2006) had students recite number and letter sequences. They found that forward and backward recitation of both stimulus types activated perisylvian areas bilaterally, whereas backward recitation additionally engaged the left IPS. The researchers argued that the perisylvian area was consistently activated as it is involved in verbal processing, while the IPS activation found only for backward recitation might be related not to the nature of the stimuli, but to visuo-spatial processing components potentially involved in the task, e.g., mental imagery (Zhou et al., 2006). Interestingly, Arsalidou and Taylor (2011) suggest in their meta-analysis that number tasks not only activate bilateral networks in brain areas such as the inferior and superior parietal lobules, but also the left fusiform gyrus, an area which was previously thought to be letter-specific (Polk et al., 2002). Moreover, McCloskey and Schubert (2014) describe a patient with left hemispheric lesions specifically in the left occipital and temporal lobes who displays deficits in both number and letter identification, suggesting a shared network for alphanumeric identification. In line with this idea, Starrfelt and Behrmann (2011) reviewed data from lesion studies and found neither single nor double dissociation between numbers and letters in a sample of patients suffering from pure alexia. In summary, these studies indicate that number and letter processing are not as distinct as previously suggested.

In this study, we examine number and letter processing in a very basic task, namely copying. This simple task has the advantage that no magnitude or sequence-specific manipulations are involved, which may trigger or mask differences in processing numbers and letters; for instance, working memory is involved in tasks such as reciting sequences of items. Furthermore, no spatial response choice has to be made, which could at least be related to some of the above-described activation patterns, e.g., in the inferior parietal lobule. Therefore, the present study investigates the brain circuits underlying number and letter processing in a stimulus copying task using functional near-infrared spectroscopy (fNIRS). This optical neuroimaging method is optimally suited to assess cortical activation in a copying task, as it is less sensitive to movement-related artefacts than fMRI. We hypothesize that number processing will rely on a bilateral network with a right hemispheric focus, while letters will elicit a left lateralized response. However, it is also possible that in a simple copying task the semantics of numbers and letters are not – or at least not sufficiently – activated to elicit any differences between these stimuli (see Cipolotti & Butterworth, 1995, for a similar proposal, i.e., an asemantic route in transcoding). Frequentist analysis only tests for differences in activation, while absence of evidence for a difference is not the same as evidence of absence for a difference. Therefore, we additionally use Bayesian analysis for evaluating the evidence of common activation, which is indeed evidence for no difference between number and letter processing (cf. Kruschke, 2013). Bayesian analysis enables calculating graded evidence for null hypothesis (i.e., no difference between conditions) and alternative hypothesis (i.e., difference between conditions). Importantly, this allows us to estimate the probability that a null effect is due to a true null difference between conditions, e.g., a joint network for numbers and letters in the copying task.

Whether or not copying numbers and letters is based on a common cortical network has theoretical and practical implications. On a theoretical level, numbers and letters are the symbols that are involved in arithmetic and reading, representing important cultural skills. Because of known influences of language on numerical cognition, the question arises to what extent these symbols are processed in a similar way. The current study informs the debate on separate or shared mechanisms for number and letter processing by a very basic task which does not necessarily require semantic processing and thus targets a basic level of processing. As a practical implication, this study might be relevant for considering a stimulus copying task as a control task for more complex arithmetic or reading tasks. In this case, it is crucial to know whether copying these stimuli includes stimulus specific processing or not.

METHODS

Participants

A total of 34 adults (10 men, age: *M* = 24.5 years, *SD* = 5.27 years) took part in the study. All participants were right-handed, without any neurological or psychiatric problems. Participants gave their written consent and received monetary compensation for their participation. The study was in accordance with the latest version of the Declaration of Helsinki and was approved by the Ethics Committee of the Medical Faculty of the University of Tuebingen.

Experimental Task

Participants engaged in a computerized task that required them to copy number or letter strings consisting of two or three items. The stimuli were presented on a touch screen using Presentation software (Version 16.0, Neurobehavioral Systems, Inc., Berkeley, CA, www.neurobs.com). The strings were displayed written in white against a black background (font: Times New Roman, size: 100-point; cf. Figure 1).

A set of 50 trials each was used for copying number and letter strings, consisting of 25 two- and 25 three-item strings for each condition. For copying number strings, two- and three-digit numbers were included, selected in such a manner that the digits from 1 to 9 were equally distributed at each position (unit, decade, hundred), with parity balanced across stimuli. For generating equivalent stimuli for the letter string condition, the nine most frequently used consonants in the German language (N, S, R, T, D, H, L, C, G) were selected, each of which substituted one digit of the number string condition.

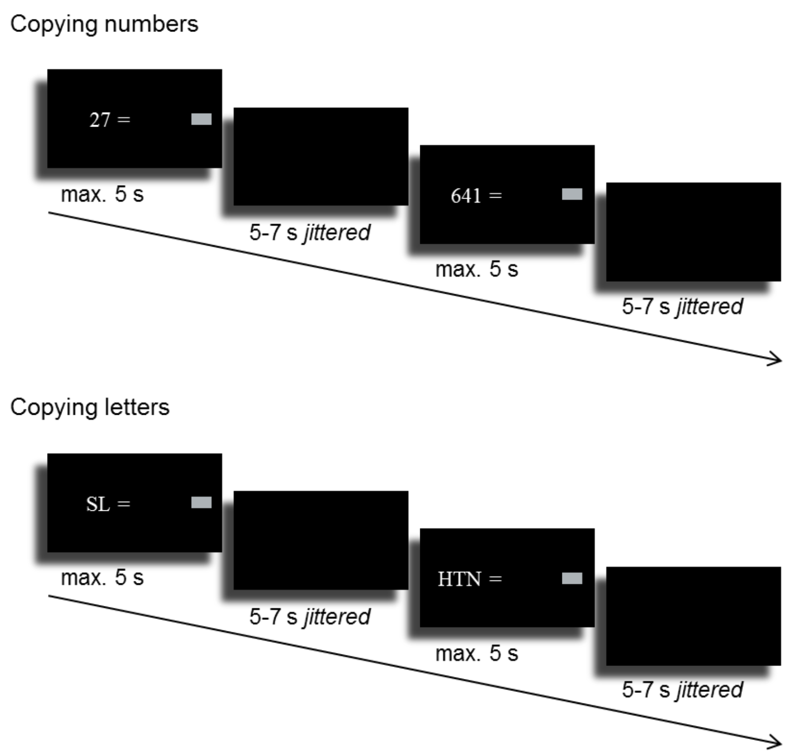

Figure 1: Copying task for numbers and letters (two example trials are shown per condition).

Functional near-infrared spectroscopy

fNIRS was recorded with the ETG-4000 Optical Topography System (Hitachi Medical Corporation, Tokyo, Japan). The probeset was placed bilaterally over fronto-temporo-parietal areas and embedded in the fNIRS cap. Two 22-channel arrays (each with 8 light emitters and 7 photo-detectors) were oriented so that channels 14 over the left hemisphere and 18 over the right hemisphere were placed over P3/P4 of the corresponding hemisphere. The probeset was horizontally oriented towards F3 (left hemisphere) and F4 (right hemisphere) for this row of channels. Optodes were situated at a fixed 30 mm distance from each other. Near-infrared light of two wavelengths was emitted (695 ± 20 nm and 830 ± 20 nm) with a sampling rate of 10 Hz. The estimated changes in oxygenated haemoglobin (O_2Hb) and deoxygenated haemoglobin (HHb) concentration for each channel were obtained by applying a modified Beer-Lambert law. Virtual registration (Rorden & Brett, 2000; Singh et al., 2005; Tsuzuki et al., 2007) was used to map the channels to corresponding cortical areas (cf. Figure 2); the cortical areas were labelled conforming to the automated anatomic labelling (AAL) atlas (Tzourio-Mazoyer et al., 2002).

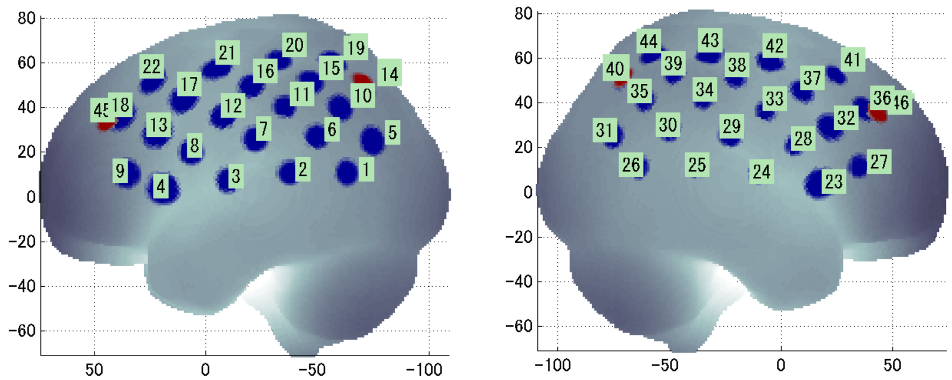

Figure 2: Location of the channels on the brain (by Minako Uga).

Procedure

Participants were seated comfortably approximatively 40 cm in front of the screen in a light-attenuated room. The stimuli were presented with the inter-stimulus interval being jittered between 4 and 7 s. Using a touch pen, participants were instructed to copy the stimuli they were presented with to the space between the equal sign and the grey box (cf. Figure 1). Note that the written response was not visible to the participants. All stimuli were presented until the participants clicked on a grey box presented on the right-hand side of the screen or the time limit of 5 s expired.

As this study was part of a larger project, participants were required to come to the lab twice. They did the number copying task in one session, and the letter copying task in another session, with the order counterbalanced across participants.

Analysis

Behavioural analysis

Response times (RTs) were calculated from stimulus onset until the grey box had been clicked (exclusion of 1.5% of trials due to missing click within the time limit). In addition, trials differing more than three *SD* from the participant's *M* per condition were repeatedly excluded from the analysis (exclusion of 0.2% of trials). A paired *t*-test was conducted to contrast the RTs between copying numbers and letters.

fNIRS

fNIRS data were analysed using MATLAB (The MathWorks Inc., Natick, USA). The continuous signals were band-pass filtered with 0.02-0.25 Hz in order to remove long-term drifts of the baseline and high-frequency cardiac and respiratory activities (Sasai et al., 2011; Tong & Frederick, 2010). Note that no direct physiological data was collected to enable further correction. For each participant, noisy trials were eliminated (8.63 %) and noisy channels were interpolated by surrounding channels (12.99 %). Data from four participants were excluded from the analysis due to an uncorrectable noisy signal. In the next step, motion artefacts and non-evoked systemic effects were reduced based on the correlation-based signal improvement (CBSI) method (Cui et al., 2010). The resulting CBSI time course, which is calculated based on the negative correlation of O_2Hb and HHb concentrations, was used for further analysis as an indicator of cortical activation. The hemodynamic response function was used to apply a general linear model to the event-related fNIRS data, resulting in beta values for each channel, participant, and condition. For each condition, one-sample *t*-tests against zero were performed independently, and paired *t*-tests were calculated to directly compare the experimental conditions. The significance level was .05 and corrected using the Bonferroni-Holm (BH) method (Holm, 1979) for multiple testing. Furthermore, Bayesian analysis was used to test not only for a difference in activation, but also for common activation in both conditions. Thus, for significant activation, Bayesian paired *t*-tests were performed to determine the evidence for a difference in activation (alternative hypothesis) and for common activation (null hypothesis) in copying numbers and letters with the help of JASP (Jeffreys's Amazing Statistics Program, Version 0.8.0.0, JASP Team, 2016). Thereby, Bayes factors between 3 and 10 indicate moderate evidence in favour of one hypothesis and Bayes factors above 10 indicate strong evidence.

RESULTS

Behavioural results

There was a significant difference in RTs for copying numbers and letters, indicating that copying numbers was performed faster than copying letters (3125 ms vs. 3259 ms; $t(33) = 2.29$, $p = .028$).

fNIRS

While copying numbers, participants showed significant frontal activation bilaterally in the middle frontal gyrus (MFG) and in the left inferior frontal gyrus (IFG), and parietal activation bilaterally in the SPL and in the right SMG (cf. Figure 3, Table 1). Further significant activation was found in the left superior temporal gyrus, bilateral precentral and postcentral gyri.

While copying letters, participants showed significant neural activity bilaterally in the MFG, and left hemispheric activation in the IFG (cf. Figure 3, Table 1). Further significant activation was found in the left precentral gyrus, and bilaterally in the postcentral gyri.

No significant difference in cortical activation was found between copying numbers and letters.[1] Moreover, the Bayesian analysis revealed moderate evidence in favour of the null hypothesis, i.e., common activation in copying numbers and letters, for the bilateral MFG and SPL, and for the right precentral and postcentral gyri (cf. Table 2). However, moderate evidence in favour of the alternative hypothesis, i.e., an activation difference in copying numbers and letters,

[1] Additionally, ANCOVAs were conducted to contrast copying numbers and letters by adding the difference in RT as a covariate. The contrast was not significant for any channel ($p < .05$, BH corrected). Therefore, the non-significant results are not due to the different RTs in copying numbers and letters.

was found for the right SMG, where descriptively higher activation was observed for copying numbers.

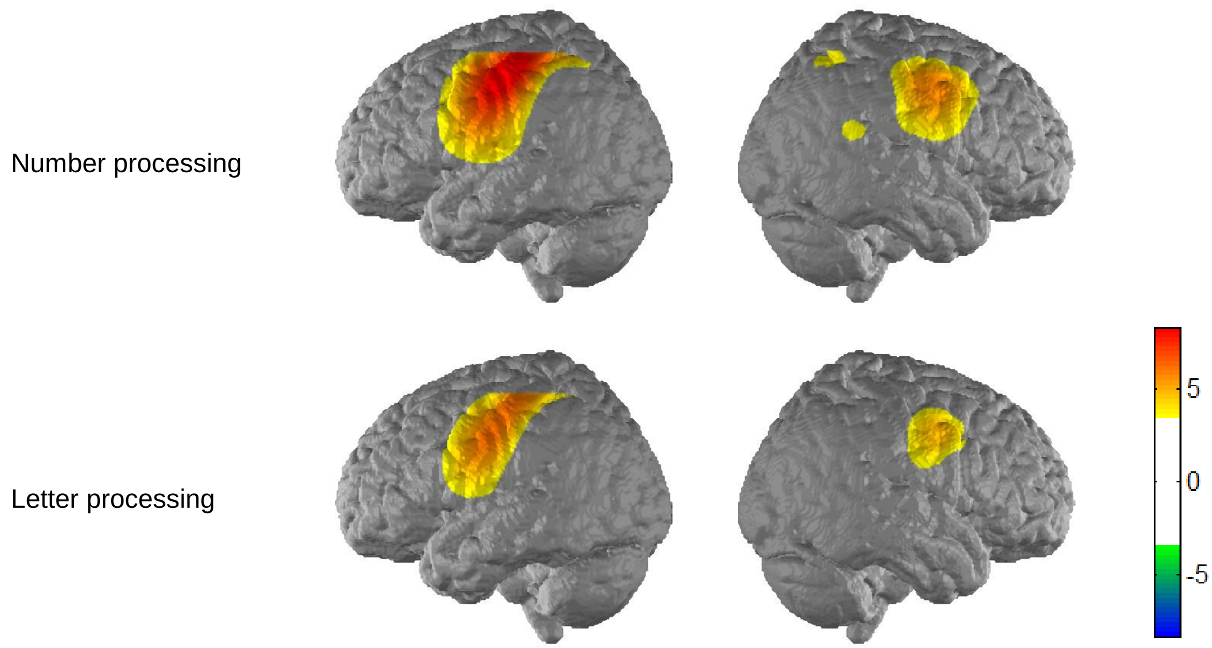

Figure 3: Significant neural activation during copying numbers and letters (t-maps).

Table 1: Neural activation for copying numbers and letters.

Area	Channels (left)	*t*	*p*	Channels (right)	*t*	*p*
Number Processing						
IFG	L 8	4.83	<.001			
MFG	L 17	4.30	.001	R 37	5.22	<.001
STG	L 3	3.86	.001			
SPL	L 19	4.24	<.001	R 44	3.73	.001
SMG				R 29	3.30	.003
				R 30	3.25	.003
PreCG	L 21	6.53	<.001	R 28	3.92	<.001
				R 42	4.33	<.001
PostCG	L 7	4.34	<.001	R 33	5.26	<.001
	L 12	7.49	<.001	R 38	3.95	<.001
	L 16	8.29	<.001			
	L 20	7.63	<.001			
Letter Processing						
IFG	L 8	4.48	<.001			
MFG	L 17	3.39	.002	R 37	4.27	<.001
PreCG	L 21	4.39	<.001			
PostCG	L 12	5.99	<.001	R 33	4.38	<.001
	L 16	5.55	<.001			
	L 20	5.40	<.001			

Note: Only significant channels ($p < .05$, BH corrected) are given for the left (L) and right (R) hemisphere as indicated by one-sample *t*-tests (for the position of the channels see Figure 2). Abbreviations: IFG – inferior frontal gyrus, MFG – middle frontal gyrus, STG – superior temporal gyrus, SPL – superior parietal lobule, SMG – supramarginal gyrus, PreCG – precentral gyrus, PostCG – postcentral gyrus.

Table 2: Bayesian analysis for comparing neural activation for copying numbers and letters.

Area	Channels (left)	BF_{10}	BF_{01}	Channels (right)	BF_{10}	BF_{01}
IFG	L 8	0.44	2.25			
MFG	L 17	0.28	3.63	R 37	0.24	4.13
STG	L 3	0.72	1.38			
SPL	L 19	0.21	4.70	R 44	0.20	5.07
SMG				R 29	1.72	0.58
				R 30	5.02	0.20
PreCG	L 21	0.37	2.70	R 28	0.74	1.35
				R 42	0.26	3.90
PostCG	L 7	1.65	0.61	R 33	0.21	4.71
	L 12	0.94	1.07	R 38	0.31	3.19
	L 16	0.53	1.90			
	L 20	1.10	0.91			

Note: Bayes factors in favour of the alternative hypothesis (BF_{10}; difference in activation) and the null hypothesis (BF_{01}; common activation) are given for the left (L) and right (R) hemispheres. Abbreviations: IFG – inferior frontal gyrus, MFG – middle frontal gyrus, STG – superior temporal gyrus, SPL – superior parietal lobule, SMG – supramarginal gyrus, PreCG – precentral gyrus, PostCG – postcentral gyrus.

DISCUSSION

The present fNIRS study investigated the underlying neural circuits for processing number and letter strings in a stimulus-copying task. It has previously been hypothesized that numbers should recruit a bilateral network with dominant activation of the right hemisphere, while letters should elicit left lateralized activation. However, there has also been opposing evidence for a shared network for processing numbers and letters. In our basic copying task, numbers were processed bilaterally in the fronto-temporo-parietal network, while the processing of letters was confined to frontal areas. However, both stimulus types appeared to trigger a preferential activation of left hemispheric networks, which is typical for symbolic compared to non-symbolic processing (e.g., Venkatraman, Ansari, & Chee, 2005). In addition, no significant difference in cortical activation was found when directly comparing between copying numbers and letters, a finding that does not support the idea of specific networks for processing number and letter strings. What is more, a Bayesian analysis generally provided evidence for a lack of differences between copying numbers and letters, with only the exception of the right SMG, where moderate Bayesian evidence for a preference of numbers over letters was obtained. Thus, in general, the results of the present study hint towards a shared network for the processing of alphanumeric stimuli with some possible specificity in the right SMG in this basic task.

The fNIRS results indicate that the neural activation elicited by copying numbers comprises all the regions involved in copying letters, and some additional brain areas. There is moderate evidence for common frontal and parietal activation of copying numbers and letters in the bilateral MFG and SPL. This evidence of a shared network was challenged by previous fMRI findings from both expert mathematicians (Amalric & Dehaene, 2016) and non-mathematicians (Ansari, 2016) showing that the areas engaged in higher-level mathematical processing are entirely distinct from the areas involved in language. However, our data suggest that such findings are task-specific: In the present study we have used a rather basic visual-motoric task, namely copying number and letter strings, which may be processed entirely differently than mathematical statements or language. In such a simple copying task, the semantics of numbers and letters might not be sufficiently activated so that our data support the proposal of an asemantic route in transcoding suggested by Cipolotti and Butterworth (1995). This further explains the difference to results from working memory tasks including numbers and letters, where number-specific activation was observed (Knops et al., 2006) because of the higher processing demands compared to basic stimuli of the copying task.

Both numbers and letters elicited activation bilaterally in the MFG and left lateralized in the IFG. There was moderate evidence that processing within the bilateral MFG is shared between numbers and letters. Activation in the bilateral MFG contributes to character recognition in general, as was shown for participants reading Chinese characters (Liu et al., 2006). In addition, the right MFG is thought to play a role in reorienting attention from exogenous to endogenous attentional control (Japee et al., 2015), as part of the Ventral Attention Network which mediates bottom-up sensory-driven exogenous attention (Corbetta & Shulman, 2002). The left IFG has also been associated with letter perception and writing (James & Gauthier, 2006), language processing (Acheson & Hagoort, 2013) and phonological and semantic fluency (Katzev et al., 2013). The left lateralization of the IFG in number processing seems surprising, as a meta-analysis of the neural regions involved in number tasks found that the right but not the left IFG is typically activated when single digits are compared to other conditions, such as letters (Arsalidou & Taylor, 2011). In the present study, it could be argued that copying numbers perhaps involves their storage in the phonological loop and engages language production processes, thus eliciting activation of the left

IFG. In contrast, the right IFG was found to be involved in inhibitory control (Hampshire et al., 2010), which was not required in the copying task. Overall, the neural frontal networks activated during the copying of numbers and letters appear to overlap.

Besides common frontal activation, only copying numbers was associated with activation in the bilateral SPL, in line with the view that the parietal cortex and particularly the IPS are the core regions for number magnitude processing (e.g., Dehaene & Cohen, 1995, for a meta-analysis see Arsalidou & Taylor, 2011; Sokolowski, Fias, Ononye & Ansari, 2017). For instance, the bilateral SPL is involved in the visual processing of numbers and is critical for orientation on the mental number line (Dehaene et al., 2003). Moreover, Klein and colleagues (2010) claimed that the magnitude of numbers automatically activates the IPS – even during passive listening to numbers – which suggests number-specific parietal activation. In contrast, letter-specific activation was also observed in the left inferior parietal lobule (Joseph et al., 2006) and in the bilateral SPL (Reilhac, Peyrin, Demonet & Valdois, 2013). Our results point to moderate evidence for a lack of differential SPL activation for numbers and letters, suggesting that in a very basic task such as copying, number magnitude processing might be suppressed in order to perform the task. This is in line with the general idea that the fronto-parietal network actively holds representations of task-relevant information irrespective of the stimulus type and modulates the responses to incoming sensory signals for visual working memory storage (Ester, Sprague & Serences, 2015).

Moderate evidence was found for the activation of the right SMG during copying numbers but not letters, corroborating a dissociation between number and letter processing (Carreiras et al., 2015). A similar finding was obtained for reading numbers compared to letters by stimulating the SMG (Roux, Lubrano, Lauwers-Cances, Giussani, & Démonet, 2008) and for the distance effect in the left SMG for numbers compared to letters (Fulbright et al., 2003). In general, SMG activation is associated with number processing (Klein et al., 2010; for a meta-analysis see Arsalidou & Taylor, 2011), arithmetic processing in adults (Menon et al., 2000) and children (Kaufmann, Wood, Rubinsten & Henik, 2011), and correlates with age (Rivera et al., 2005). Overall, these studies indicate a specific involvement of the right SMG in symbolic number processing (Ansari, 2008), but further research needs to be conducted in order to clarify the function of this area in basic tasks such as copying numbers compared to letters.

We found the left STG, an area usually involved in language processing, was activated in response to numbers, but not to letters. The STG has typically been found to encode acoustic-phonetic features of words (Chan et al., 2014) and sentence meaning (Frankland & Greene, 2015). Therefore, activation in the left STG might occur during a very basic task like copying number strings, because number strings are meaningful and elicit semantic processing (Dehaene & Akhavein, 1995), while letter strings – compared to words or sentences – have less semantic meaning. Thus, the degree of overlap between number and letter processing might depend on the task. In a lesion study, Baldo and Dronkers (2007) found that arithmetic and language comprehension rely on partially overlapping brain networks in the left middle and superior temporal gyri, as well as in the left IFG, while only the left inferior parietal lobule was associated with arithmetic, but not with language comprehension.

To conclude, number and letter copying rely on a largely shared brain network. This reflects the close relation between the foundations of numerical cognition and language. The absence of number-specific magnitude activation and letter-specific semantic activation can be used as a rationale to apply such basic stimulus copying tasks as control tasks for evaluating complex cognitive processes in future studies. Thus, in a neuroimaging subtraction paradigm, more complex tasks (e.g., arithmetic or language tasks) can be compared to a number or letter copying control condition without subtracting or masking relevant number- or letter-specific activation. This might be particularly relevant for written production tasks (compared to verification or choice reaction tasks) where individuals have to write down a solution to an arithmetic problem, and enables research on language using handwriting. Furthermore, since arithmetic, reading and writing skills are learned during school education, the next step might be to evaluate the neural network of number and letter processing in children.

Limitations

In the stimulus copying task, participants had to use their right hand to write down the stimuli. Therefore, increased left-hemispheric activation in the current study – and diverging results on left lateralization in previous studies – could be due to motoric aspects of the applied experimental paradigm. In order to generalize from the results of this basic stimulus copying task to the neural correlates of number and letter processing, a motoric control condition could be introduced in future studies. Note that the task in the current study did not only require movements for copying the stimuli but also clicking the grey box. However, as compared to the more complex movements involved in copying, the movement required for clicking seems rather small and occurred in both conditions so that influences on neural activation might be negligible, especially in non-motoric areas.

In the current study, numbers were substituted by frequent letters rather than matched in stimulus components or complexity. This might be a reason for the difference in time to complete copying of numbers and letters. Further research should be undertaken to investigate the effect of stimulus complexity on handwriting speed for digits and letters.

Finally, we would like to note that specific cortical structures involved in the processing of number and letter strings were identified by our fNIRS data, but it might be possible that additional cortical and sub-cortical structures are involved in these processes that were not covered by the current fNIRS arrangement. For instance, as a possible number form area the right ITG was identified in a meta-analysis (Yeo, Wilkey, & Price, 2017; see also Abboud et al., 2015; Dehaene, 2011; Hannagan et al., 2015; Shum et al., 2013). Additionally, it is not clear whether activation of the IPS can be unequivocally measured by fNIRS given the limited penetration depth. Furthermore, future studies focusing on subcortical structures and neural pathways for number and letter processing are needed (cf. Klein et al., 2016).

Conclusions

The present study investigated whether numerical and language processing share common representations by investigating the underlying neural circuits involved in copying numbers and letters by using fNIRS. We found evidence for a bilateral fronto-temporo-parietal network involved in copying numbers, and a left lateralized frontal network involved in copying letters. Despite some differences between neural correlates underlying number and letter copying, the present study shows a largely shared network in processing the basic elements of math and reading, namely number and letter processing, especially with respect to the bilateral MFG. With exception of the right SMG, Bayesian analysis confirmed that these shared networks were not simply due to a lack of evidence for differences; instead, it provided direct evidence for mostly common activation. Only for the right SMG, a difference in activation between numbers and letters was favoured.

Theoretically, this is consistent with a view that numerical cognition and language processing share common representations (which might be based on pre-existing neural circuits, cf. Dehaene & Dehaene-Lambertz, 2016), especially when it comes to simple copying of the constituent symbols. Notable, this does not imply that there exist no differences for more complex representations and computations for numbers and letters. However, as concerns processing of the basic underlying symbols, the brain seems to use common neural circuits in adults. Practically, this study provides suggests that such a stimulus copying task can be applied in neuroimaging research: Because of the absence of differences in number and letter processing in the copying task, this task can be considered as a good control condition in neuroimaging studies.

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