

1 RUNNING HEAD: Neural correlates of mental calculation in blind

2

3 **Recruitment of occipital cortex by arithmetic processing follows computational bias in early**
4 **blind**

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21 **Keywords:** blindness, mental arithmetic, multiplication, neural correlates, subtraction.

22 **Abstract**

23 Arithmetic reasoning activates the occipital cortex of early blind people (EB). This activation
24 of visual areas may reflect functional flexibility or the intrinsic computational role of specific
25 occipital regions. We contrasted these competing hypotheses by characterizing the brain
26 activity of EB and sighted participants while performing subtraction, multiplication and a
27 control verbal task. In both groups, subtraction selectively activated a bilateral dorsal network
28 commonly activated during spatial processing. Multiplication triggered more activity in
29 temporal regions thought to participate in memory retrieval. No between-group difference
30 was observed for the multiplication task whereas subtraction induced enhanced activity in the
31 right dorsal occipital cortex of the blind individuals only. As this area overlaps and exhibits
32 increased functional connectivity with regions showing selective tuning to auditory spatial
33 processing, our results suggest that the recruitment of occipital regions during high-level
34 cognition in the blind actually relates to the intrinsic computational role of the reorganized
35 regions.

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39 Introduction

40 Studies involving early blind people (EB) provide important insights into the role
41 played by experience and intrinsic biological constraints in shaping the development of the
42 sensory and cognitive tuning of brain regions. In early blind individuals, regions of the
43 occipital cortex that typically process visual information massively enhance their response to
44 non-visual inputs – a phenomenon called cross-modal plasticity (Bavelier and Neville 2002;
45 Sadato et al. 1996). But what are the mechanisms guiding this cross-modal reorganization
46 process?

47 It was suggested that these neuroplastic changes are constrained by the native
48 functional organization of the occipital cortex. For example, hMT+/V5, a region chiefly
49 dedicated to processing visual motion in the sighted reorganizes in the blind to preferentially
50 process auditory (Dormal et al. 2016; Jiang et al. 2016; Poirier et al. 2006) and tactile motion
51 (Ricciardi et al. 2007). Moreover, right dorsal occipital regions typically involved in visuospatial
52 localization in the sighted are active when blind individuals localize sounds (Collignon et al.
53 2011) and altering the function of this region with transcranial magnetic stimulation (TMS)
54 selectively disrupts auditory localization in the blind (Collignon et al. 2007). Similarly, the visual
55 word form area (VWFA), a region specialized to process visual orthographic information in the
56 sighted seems to be selectively recruited in the blind when processing braille words (Büchel
57 et al. 1998; Reich et al. 2011). Those studies suggest that even if the occipital cortex of blind
58 individuals extends their tuning toward non-visual inputs, this reorganization process is not
59 stochastic but is rather constrained by the maintenance of intrinsic computational bias of local
60 regions (Collignon et al. 2009, 2012; Ricciardi et al. 2014; Heimler et al. 2015).

61 Contrasting with this view, it has been suggested that the occipital cortex of EB
62 engages in higher-level cognitive operations that have apparently little to do with occipital
63 functions such as memory (Amedi et al. 2003), language processing (Bedny et al. 2011; Röder
64 et al. 2002) or numerical thinking (Kanjlia et al. 2016). Based on those observations, it has
65 been proposed that the human cortex is functionally flexible early in life (Lane et al. 2015) and
66 can adopt a wide range of distant computation depending on experience (Bedny 2017).

67 However, this later argument resides on the presupposition that higher-cognitive
68 functions have no computational relation with vision. But is it the case? Actually, several
69 studies have suggested that the foundations of numerical thinking were rooted in general
70 visuo-spatial mechanisms (Burr and Ross 2008; Ross and Burr 2010; Simon 1999; Stoianov and
71 Zorzi 2012). Arithmetic has for example been thought to involve shifts of attention along a
72 mental number line: a shift of attention toward the right (or toward larger numbers) for
73 addition and toward the left (smaller numbers) for subtraction (Knops et al. 2009a, 2009b;
74 Masson et al. 2014; McCrink et al. 2007; Pinhas and Fischer 2008). Neuroimaging studies have
75 similarly shown that the underlying neural architecture of number representations closely
76 overlaps the one of visuo-spatial processing (Harvey et al. 2013; Shum et al. 2013; Sathian et
77 al. 1999). For instance, topographic numerosity map (numerotopy) in which neural numerosity
78 preferences progress gradually across the cortical surface (Harvey et al. 2013), analogous to
79 sensory maps, have been found in occipital regions typically supporting visuo-spatial/motion
80 processing (Harvey et al. 2017).

81 The present study was designed to test whether the recruitment of the occipital cortex
82 in early blind individuals by higher-level cognitive functions depends on the intrinsic
83 computational role of specific regions. The study of arithmetic processing represents an

84 interesting test-bed to help disentangling the hypotheses regarding the mechanisms
85 governing cross-modal plasticity (functional recycling versus pluripotency). Indeed, separate
86 arithmetic operations rely on separate brain networks depending on the computational
87 principles they rely on. The resolution of subtraction principally engages a network of dorsal
88 parieto-frontal regions (Chochon et al. 1999; Piazza et al. 2007) presumably due to the
89 “spatial” strategies used to solve such operation (Siegler and Shrager 1984). Like subtraction,
90 multiplication requires the mental manipulation of symbolic numbers, yet it is believed to rely
91 on a distinct temporo-parietal network (Chochon et al. 1999; Zhou et al. 2007) presumably
92 because multiplications are solved by direct fact retrieval (Cooney et al. 1988). This raises the
93 question of whether these different operations produce equivalent neural responses in the
94 occipital cortex of blind individuals, or if, as we presume, subtraction will find a privileged
95 neuronal niche in dorsal occipital regions since these regions keep a privileged role in
96 processing spatial relationship in congenitally blind (Dormal et al. 2012).

97 We characterized the brain activity of 14 congenitally blind and 16 sighted participants
98 while verifying the results of subtractions and multiplications. If functional reorganization is
99 similarly observed in congenitally blind for both arithmetic operations, this would support the
100 idea that occipital regions are functionally flexible during development and can adopt a wide
101 range of computation depending on experience (Bedny 2017). Alternatively, if solving
102 subtraction problems (which in contrast to multiplication relies on spatial strategies)
103 specifically engages regions of the dorsal occipital cortex typically involved in visuo-spatial
104 processing, this will support the idea that the take-over of occipital regions by higher cognitive
105 functions in the blind actually relies on the original computation of the reorganized regions.

106

107 Results

108 Behavioral results

109 Participants' performances were analyzed with a 3 (experimental conditions:
110 subtraction, multiplication, letter) x 2 (groups: SC vs. CB) repeated measures ANOVA
111 performed on the percentage of correct responses. This analysis showed a marginal effect of
112 condition, $F(2, 56) = 3.13, p = .05, \eta_p^2 = .10$. Both groups tended to be less efficient in the
113 subtraction condition ($M \pm SE = 87.07 \pm 2.55$) than in the 2 other conditions ($M \pm SE = 91.38$
114 ± 1.29 for multiplication; $M \pm SE = 91.97 \pm 1.80$ for letters). The group effect was not
115 significant, $F(1, 28) = 0.09, p = .76, \eta_p^2 = .003$, nor was the group x condition interaction, $F(2,$
116 $56) = 0.76, p = .47, \eta_p^2 = .03$ (see Figure 1j).

117 fMRI results

118 **General Arithmetic.** A conjunction analysis performed across groups disclosed
119 arithmetic selectivity in the left Angular Gyrus (AG) for both groups. To investigate the effect
120 of congenital blindness on global arithmetic processing, we compared the cerebral responses
121 of blind vs. sighted participants for both multiplication and subtraction relative to the letter
122 condition ([CB > SC] [subtraction \cap multiplication > letter]). This analysis yielded significant
123 results in the left middle occipital gyrus (see Figure 1 and Table 1). The opposite contrast ([SC
124 > CB] [subtraction \cap multiplication > letter]) did not yield any significant effect.

125 **Subtraction.** The frontal eye field (FEF) and the PSPL demonstrated enhanced activity
126 for subtraction over multiplication in both groups of participants ([SC \cap CB] [subtraction >
127 multiplication]). Crucially, the right middle/superior occipital gyrus (MOG) demonstrated
128 enhanced activity in CB when compared to SC ([CB > SC] [subtraction > multiplication]). In
129 general, deactivation of this region was found in the sighted while activation was observed in

130 CB (see Figure 1 and Table 1). Interestingly and as shown in Figure 2, part of this region also
131 shows selective tuning to auditory spatial processing in the blind (7). The opposite contrast
132 ([SC > CB] [subtraction > multiplication]) did not yield any significant effect.

133 **Multiplication.** There was common multiplication related activity in SC and CB ([SC \cap
134 CB] [multiplication > subtraction]) in the right Superior Temporal Gyrus (STG) (see Figure 1
135 and Table 1). Neither the contrast ([CB > SC] [multiplication > subtraction]), nor the contrast
136 ([SC > CB] [multiplication > subtraction]) yielded significant effects.

137 **Functional connectivity.** We found increased correlations between the left MOG and
138 a network of dorsal regions in blind relative to sighted participants (main effect of group, seed
139 to whole-cortex analysis $P < 0.05$, FDR corrected; Figure 3 and Table 2). A similar pattern was
140 observed for the right MOG ($P < 0.05$, FDR corrected; Figure 3 and Table 2). Moreover, both
141 seed regions showed enhanced intra-occipital connectivity with ventral occipito-temporal
142 regions as previously shown (Burton et al. 2014; Pelland et al. 2017).

143

144 Discussion

145 We examined how the lack of visual experience impacts on the neuronal basis of
146 specific arithmetical operations by contrasting activity maps elicited by the execution of
147 subtraction or multiplication operations in EB and sighted controls.

148 Reorganization of occipital regions in case of early blindness provides a unique model
149 for understanding how intrinsic physiology and experience together determine cortical
150 function. Previous studies have found that the “visual” cortex of early blind people responds
151 to a variety of auditory (Collignon et al. 2009; Gougoux et al. 2005; Ricciardi et al. 2014;
152 Weeks et al. 2000) and tactile tasks (Büchel et al. 1998, Sadato et al. 1996).

153 Several studies have shown that such cross-modal plasticity follows organizational
154 principles that maintain the functional specialization of the colonized brain regions (Amedi,
155 Hofstetter, Maidenbaum, & Heimler, 2017; Bi, Wang, & Caramazza, 2016; Dormal and
156 Collignon, 2011; Cecchetti et al. 2016; Heimler et al. 2015). However, the observation that
157 the occipital cortex of congenitally blind also activates during higher cognitive functions
158 considered distant from visual function, such as arithmetic processing (Kanjlia et al. 2016), was
159 used to challenge the idea that the maintenance of intrinsic computational bias is a generic
160 principle guiding the mechanism of cross-modal plasticity. In contrast, it was supposed that
161 occipital regions are pluripotent early in development and able to engage in a vast array of
162 distant cognitive functions that are evolutionary and cognitively distant from vision (Bedny
163 2017).

164 Our observation that specific arithmetic operation – subtraction but not multiplication
165 – triggers enhanced activity in selective occipital regions -the right dorsal stream- provides
166 unifying lights between these two apparently discrepant views of occipital (re)organization in
167 congenitally blind people. Our findings suggest that the cross-modal recruitment of occipital
168 regions for higher cognitive operations does not fully depart from its original function but
169 rather emerges from intrinsic computational bias. More precisely, we suggest that the specific
170 recruitment of dorsal occipital regions for subtraction is a by-product of the intrinsic role of
171 this region for spatial processing (Knops et al. 2009a, 2009b; Masson et al. 2014; McCrink et
172 al. 2007; Pinhas and Fischer 2008). Supporting this idea, region showing selective activation
173 for subtraction in our blind population overlapped in part with regions showing preferential
174 tuning to auditory spatial processing in the blind (Collignon et al. 2011; see Figure 3).

175 It was proposed that specific numerical processing systematically maps onto parietal
176 circuits because this culturally new invention grounds on, or recycle, more ‘basic-primitive’
177 cognitive skills, like space perception or body manipulation, which are evolutionary more
178 ancient (Dehaene and Cohen 2007). We propose that a similar mechanism of functionally
179 specific cortical recycling operates at the ontogenetic level due to experience-dependent
180 neuroplasticity triggered by blindness. Here, subtraction selectively remaps onto dorsal
181 occipital regions due to its reliance on space processing, known to be preserved in these
182 regions in congenitally blind individuals (Dormal et al. 2012). We therefore propose that the
183 recruitment of occipital regions in the blind, even for higher cognitive abilities, finds its
184 “neuronal niche” into a set of circuits that are sufficiently close to the required function and
185 sufficiently plastic as to strengthen or reorient a significant fraction of their neural resources
186 for the non-visual function (Collignon et al. 2009). Interestingly, this raises the possibility that
187 other higher cognitive domains like language, known to also remap in the occipital cortex of
188 the blind (Bedny et al. 2011; Röder et al. 2002), also grounds on the native computational
189 predisposition of these regions (Hasson et al. 2016; van Ackeren et al. 2017).

190 What could be the mechanistic force guiding this functionally specific reorganization?
191 As illustrated by our connectivity analyses (see Figure 3), the right dorsal occipital region
192 showing enhanced preferential involvement for subtraction in EB also shows enhanced
193 connectivity with a right dorsal network typically involved in spatial processing and attention
194 (Corbetta et al. 1995; Yantis et al. 2003). This result supports the idea that a biased inborn
195 connectivity profile between brain regions may guide the functional specialization of brain
196 regions and, by extension, constraints how cross-modal plasticity expresses in the occipital
197 cortex of the blind (Hannagan et al. 2015). In the context of our study, the reinforcement of a

198 privileged connection between dorsal occipital regions and the intraparietal sulcus, probably
199 rooted on common involvement in spatial computation, will extend the preserved function of
200 the parietal cortex (eg. for subtraction) toward dorsal occipital regions in case of early visual
201 deprivation.

202 This additional involvement of dorsal occipital regions for subtraction in EB inevitably
203 raises the question of what is happening to the network typically involved in this function.
204 Even if in our study we did not find any enhanced activity in sighted versus blind participants,
205 previous studies have suggested that the enhanced occipital involvement in EB may be
206 concomitant to a reduction of the computational load of the typical network (Dormal et al.
207 2016).

208 The left AG was the unique region in which both subtraction and multiplication
209 produced superior activity than the letter control task in both sighted and blind individuals
210 (Figure 1). Precisely, this region was less deactivated during calculation than when processing
211 letters in both groups. Deactivation has been consistently reported during arithmetic tasks
212 (Grabner et al. 2007; Mizuhara et al. 2005; Rickard et al. 2000; Wu et al. 2009; Zhou et al.
213 2007) and has been shown to be negatively correlated to mathematical performance: stronger
214 is the deactivation, lower is the arithmetic performance (Wu et al. 2009).

215 More importantly, we demonstrate that specific arithmetic operations activate
216 selective networks: subtraction preferentially activated the FEF and the PSPL regions while
217 the right STG was activated for multiplication in both groups. This dissociation between
218 parieto-frontal regions for subtraction and superior temporal regions for multiplication
219 supports the idea that arithmetic is processed in different formats within distinct cerebral
220 pathways (Dehaene and Cohen 1997). Therefore, visual experience does not have a

221 foundational role in setting-up the functional segregation between subtraction and
222 multiplication. The evidence that the neural representation of numbers is not tied to visual
223 abilities or experience demonstrate that numerical concepts can be acquired through non-
224 visual mechanisms (Dormal et al. 2016; Crollen et al. 2017). A recent study also showed that
225 blind individuals activate parietal regions to solve subtraction (Kanjlia et al. 2016). However,
226 this study did not investigate functional selectivity for specific arithmetical operation. We
227 therefore confirm and extend these results by showing that the dissociation of brain regions
228 supporting specific arithmetic operation is preserved in blind people.

229 Does this overlap of the brain circuits involved in arithmetic processing in early blind
230 and sighted individuals means that the way these regions implement numerical processing is
231 immune to visual input and experience? One possibility is that those selective neural networks
232 supporting specific numerical operations rely on computational procedures, like memory
233 retrieval for multiplication and spatial processing for subtraction (Campbell and Xue, 2001).
234 These procedures may be abstracted from sensory input and experience and may therefore
235 be built on amodal representational format (Damarla et al. 2016; Eger et al. 2003; Nieder
236 2012, 2016). However, the fact that similar regions activate in blind and sighted individuals
237 during the same specific task (i.e., parietal network during subtraction) does not guarantee
238 that the specific format of the cognitive operation is similar across both groups. Indeed, if the
239 lack of vision does not preclude the optimal development of various numerical skills (Dormal
240 et al. 2016; Castronovo 2014; Crollen and Collignon 2016), some qualitative properties of
241 numerical representations seems however to critically depend on early visual experience. For
242 example, early blindness changes the nature of the reference frame in which the spatial
243 processing of numbers occurs: while sighted and late blind participants associate numbers to

244 an external frame of reference, congenitally blind individuals principally rely on an association
245 between numbers and an egocentric coordinate system (Crollen et al. 2013). Blindness also
246 alters the typical development of finger-counting, a procedure often used by sighted
247 individuals while learning basic addition and subtraction operations (Crollen et al. 2011, 2014).
248 Given that early blindness affects the use of an external visuo-spatial frame of reference and
249 the implementation of finger-counting, it is possible that the common regions involved in
250 numerical processing in both groups rely on distinct representational format in early blind and
251 sighted individuals. It will therefore be important for future studies to assess whether the
252 representations of the numerical information embedded in those brain circuits are truly
253 independent of visual experience or if visual experience influences the format of these
254 representations despite overlapping activation.

255

256 **Materials and Methods**

257 **Participants**

258 Sixteen sighted controls (SC) [6 females, age range 22-64 y, (mean \pm SD, 44 \pm 14 y)]
259 and 14 congenitally blind (CB) participants [3 females, age range 23-61 y, (mean \pm SD, 44 \pm
260 13 y)] took part in the study (see supplemental table 1 for a detailed description of the CB
261 participants). The SC did not statistically differ from the CB group for age ($t(28) = -0.02, p >$
262 $.9$) and sex ratio ($\chi^2 = 1.54, p = .21$). The participants in the blind group were totally blind
263 since birth or had, at the utmost, only rudimentary sensitivity for brightness differences and
264 never experienced patterned vision (never saw colors, shapes, or motion). In all cases,
265 blindness was attributed to peripheral deficits with no additional neurological problems.
266 Procedures were approved by the Research Ethics Boards of the University of Montreal.

267 Experiments were undertaken with the understanding and written consent of each participant.
268 Sighted participants were blindfolded when performing the task.

269

270 **Task and general experimental design**

271 Participants were scanned in 1 fMRI session using a block design procedure. During
272 scanning, participants had to: 1) verify the result of subtractions; 2) verify the result of
273 multiplications; and 3) perform vowel/consonant judgment verification on letters. Additions
274 were not presented as they are thought to not only involve spatial displacements on the
275 mental number line but are also assumed to rely on rote verbal memory (Dehaene & Cohen,
276 1997). In the subtraction verification task, triplets of auditory numbers were presented and
277 participants had to judge whether the third number corresponded to the difference of the
278 first two numbers. The first operand was either 11 or 13; the second operand ranged from 3
279 to 8. The third number was either the correct result of the subtraction or the correct result \pm
280 1. In the multiplication verification task, triplets of auditory numbers were presented and
281 participants had to judge whether the third number corresponded to the product of the first
282 2 numbers. The first operand was either 3 or 4. The second operand ranged from 3 to 8. The
283 third number presented corresponded either to the correct result or to the correct result \pm
284 the first operand (e.g., three, five, twelve). In order to examine the neural activity of arithmetic
285 in general (common activity for subtraction and multiplication), participants had also to
286 perform a control letter task. This task was matched to the numerical tasks in terms of stimuli
287 presentation (3 consecutive – non-numerical – symbolic stimuli) and response requirements.
288 Triplets of letters were thus auditory presented and participants had to judge whether the
289 third letter pertained to the same category (vowel vs. consonant) as the first 2 letters (the first

290 2 letters were always of the same category). The letters used were the vowels A, E, I, O, U
291 and the consonants B, D, M, N, P, R, S. Participants responded with their right index finger
292 using the top (for correct triplet) or the bottom (for incorrect triplet) key of a response box.

293 The fMRI session consisted of 30 successive blocks (24 s duration each) alternating the
294 three tasks in a fixed order and separated by rest periods ranging from 7 to 9 s (median 8 s).
295 Each block consisted of 6 successive auditory triplets of 4000 ms. In the scanner, auditory
296 stimuli were delivered by means of circumaural fMRI-compatible headphones (Mr Confon,
297 Magdeburg, Germany).

298 Before the fMRI acquisition, all participants underwent a training session in a mock
299 scanner with recorded scanner noise played in the bore of the stimulator to familiarize them
300 with the fMRI environment and to ensure that the participants understood the task.

301

302 **fMRI data acquisition and analyses**

303 Functional MRI-series were acquired using a 3-T TRIO TIM system (Siemens, Erlangen,
304 Germany), equipped with a 12-channel head coil. Multislice T2*-weighted fMRI images were
305 obtained with a gradient echo-planar sequence using axial slice orientation (TR = 2200 ms,
306 TE = 30 ms, FA = 90°, 35 transverse slices, 3.2 mm slice thickness, 0.8 mm inter-slice gap,
307 FoV = 192×192 mm², matrix size = 64×64×35, voxel size = 3×3×3.2 mm³). Slices were
308 sequentially acquired along the z-axis in feet-to-head direction. The 4 initial scans were
309 discarded to allow for steady state magnetization. Participants' head was immobilized with
310 the use of foam pads that applied pressure onto the headphones. A structural T1-weighted
311 3D MP-RAGE sequence (voxel size= 1x1x1.2 mm³; matrix size= 240x256; TR= 2300 ms, TE=
312 2.91 ms, TI= 900 ms, FoV= 256; 160 slices) was also acquired for all participants.

313 Functional volumes were pre-processed and analyzed using SPM8
314 (<http://www.fil.ion.ucl.ac.uk/spm/software/spm8/>; Wellcome Department of Imaging
315 Neuroscience, London), implemented in MATLAB (MathWorks). Pre-processing included slice
316 timing correction of the functional time series (Sladky et al. 2011), realignment of functional
317 time series, co-registration of functional and anatomical data, a spatial normalization to an
318 echo planar imaging template conforming to the Montreal Neurological institute space, and
319 a spatial smoothing (Gaussian kernel, 8mm full-width at half-maximum, FWHM).

320 Following pre-processing steps, the analysis of fMRI data, based on a mixed effects
321 model, was conducted in two serial steps accounting respectively for fixed and random
322 effects. For each subject, changes in brain regional responses were estimated through a
323 general linear model including the responses to the 3 experimental conditions (subtractions,
324 multiplications, letters). These regressors consisted of a boxcar function convolved with a
325 canonical double-gamma hemodynamic response function. Movement parameters derived
326 from realignment of the functional volumes (translations in x, y and z directions and rotations
327 around x, y and z axes) and a constant vector were also included as covariates of no interest.
328 High-pass filtering was implemented in the design matrix using a cut-off period of 128 s to
329 remove slow drifts from the time series. Linear contrasts tested the main effect of each
330 condition ([Subtraction], [Multiplication], [Letter]), the main effect of arithmetic ([Subtraction \cap
331 Multiplication>Letter]), the main effect of the Subtraction condition
332 ([Subtraction>Multiplication]) and the main effect of the multiplication condition
333 ([Multiplication>Subtraction]). These linear contrasts generated statistical parametric maps
334 [SPM(T)]. The resulting contrast images were then further spatially smoothed (Gaussian kernel
335 8 mm FWHM) and entered in a second-level analysis, corresponding to a random effects

336 model, accounting for inter-subject variance. For each contrast, one-sample t-tests were
337 carried out in each group separately. Two-sample t-tests were then computed to identify
338 group differences for each separate contrast. Group effects [Blind>Sighted] and
339 [Sighted>Blind] were inclusively masked ($p < 0.001$ uncorrected for multiple comparisons) by
340 the main effect in the blind and the sighted group, respectively. Statistical inferences were
341 performed at a threshold of $p < 0.05$ after correction for multiple comparisons (Family Wise
342 Error method) over the entire brain volume or over small spherical volumes (10 mm radius)
343 located in regions of interest (SVC). To select the coordinates of interest, we consulted a body
344 of literature examining brain activations related to numerical processing in sighted individuals
345 and related to functionally specific cross-modal plasticity in the blind. Before performing any
346 small-volume correction (SVC), peaks reported in Talairach space (Talairach and Tournoux
347 1988) were transformed to Montreal Neurological Institute space using Matthew Brett's
348 bilinear transformation (<http://imaging.mrc-cbu.cam.ac.uk/imaging/MniTalairach>). Standard
349 stereotactic coordinates (x,y,z) used for SVC are listed in supplemental material (in MNI space).

350

351 **Resting-State Functional Connectivity Analysis.**

352 To control for possible motion artifacts, a scrubbing approach was implemented using
353 Artifact detection tools (ART; www.nitrc.org/projects/artifact_detect) to identify outlier
354 volumes that had a difference in scan-to-scan global intensity more than 9 standard deviations
355 away from the mean global brain signal, or volumes that had more than 2 mm of scan-to-scan
356 composite motion. The outlier time points were used as a first level covariate. Afterwards, the
357 functional volumes were spatially smoothed with a 4-mm full-width half-maximum (FWHM)
358 Gaussian kernel. To rule out the possibility that any connectivity changes could be attributed

359 to motion (Power et al. 2012; Satterthwaite et al. 2012; Van Dijk et al. 2012), we compared
360 the average and maximum motion between groups using a two-sample t-test, and found no
361 significant difference between the 2 groups in the average ($t(22)=0.35$, $p=0.73$) or the
362 maximum motion ($t(22)=0.67$, $p=0.508$).

363 Functional connectivity analysis was performed in CONN functional connectivity
364 toolbox (Whitfield-Gabrieli and Nieto-Castanon 2012); <http://www.nitrc.org/projects/conn>). A
365 component-based noise correction (Compcorr) (Behzadi et al. 2007) strategy was
366 implemented to control for nuisance effects and physiological noise. Motion parameters and
367 their first derivatives, and outlier time points from ART toolbox were included as first level
368 covariates to remove the variance related to head motion. Linear de-trending and a band-
369 pass filter of 0.008-0.09Hz was applied to the functional data. First level analysis was
370 performed in the CONN framework to investigate functional connectivity changes within-
371 subject. Pearson's correlation coefficient was used as a measure of functional connectivity. A
372 seed-based correlation analysis using a voxel-wise approach was performed. We used the left
373 and right middle occipital gyri as our seed regions because these regions showed cross-modal
374 plasticity for the contrasts [CB>SC][Subtraction \cap Multiplication>Letter] and
375 [CB>SC][Subtraction>Multiplication] – see results section.

376 The time series from each seed region was extracted by averaging the signal from all
377 the voxels in the seed ROI. The time series from each seed was then correlated with each
378 voxel in the rest of the brain. The correlation coefficients were fisher transformed to perform
379 second-level statistical comparison across groups. One-sided two-samples t-test was
380 performed to assess differences in the functional connectivity between groups [CB > SC].

381 Results were thresholded at $p < 0.001$ at the voxel level and FDR-corrected $p < 0.05$ at the
382 cluster level.

383

384 **Acknowledgments**

385 The authors are grateful to Giulia Dormal for her help in implementing the design of this
386 study. This research and the authors were supported by the Canada Research Chair Program
387 (FL), the Canadian Institutes of Health Research (FL), the Belgian National Funds for Scientific
388 Research (OC, MPN), a WBI.World grant (VC), the European Union's Horizon 2020 research
389 and innovation program under the Marie Skłodowska-Curie grant agreement No 700057 (VC)
390 and the 'MADVIS' European Research Council starting grant (OC; ERC-StG 337573).

391

392 **Competing financial interests**

393 The authors declare that they have any financial interests that could be construed to have
394 influenced their paper.

395

396 **References**

397

398 Amedi, A., Hofstetter, S., Maidenbaum, S., & Heimler, B. 2017. Task selectivity as a
399 comprehensive principle for brain organization. *Trends Cogn Sci.* 5: 307-310.

400

401 Amedi A, Raz N, Pianka P, Malach R, Zohary E. 2003. Early "visual" cortex activation correlates
402 with superior verbal memory performance in the blind. *Nat Neurosci.* 6(7): 758-766.

403

404 Andres M, Michaux N, Pesenti M. 2012. Common substrate for mental arithmetic and finger
405 representation in the parietal cortex. *Neuroimage*. 62: 1520-1528.

406

407 Arsalidou M, Taylor MJ. 2011. Is $2+2 = 4$? Meta-analyses of brain areas needed for numbers
408 and calculations. *NeuroImage*. 54: 2382-2393.

409

410 Bavelier D, Neville, HJ. 2002. Cross-modal plasticity: where and how? *Nat Rev Neurosci*. 3:
411 443-452.

412

413 Bedny M. 2017. Evidence from blindness for a cognitively pluripotent cortex. *Trends Cogn
414 Sci*. 21(9): 637-648.

415

416 Bedny M, Pascual-Leone A, Dodell-Feder D, Fedorenko F, Saxe R. 2011. Language
417 processing in the occipital cortex of congenitally blind adults. *Proc Natl Acad Sci USA*. 108(11):
418 4429-4434.

419

420 Behzadi Y, Restom K, Liao J, Liu TT. 2007. A component based noise correction method
421 (CompCor) for BOLD and perfusion based fMRI. *Neuroimage*. 37(1): 90-101.

422

423 Bi, Y., Wang, X., & Caramazza, A. 2016. Object domain and modality in the ventral visual
424 pathway. *Trends Cogn Sci*. 20(4): 282-290.

425

426 Büchel C, Price C, Frackowiak RSJ, Friston K. 1998. Different activation patterns in the visual
427 cortex of late and congenitally blind subjects. *Brain*. 121(3): 409-419.

428

429 Büchel C, Price C, Friston K. 1998. A multimodal language region in the ventral visual
430 pathway. *Nature*. 394: 274-277.

431

432 Burr D, Ross J. 2008. A visual sense of number. *Curr Biol*. 18: 425-428.

433

434 Burton H, Snyder AZ, Raichle ME. 2014. Resting state functional connectivity in early blind
435 humans. *Front Syst Neurosci*. 8: 51.

436

437 Campbell JID, Xue Q. 2001. Cognitive arithmetic across cultures. *J Exp Psychol Gen*. 130 (2):
438 299-315.

439

440 Castronovo J. 2014. Numbers in the dark: Numerical cognition and blindness. In Cohen
441 Kadosh R and Dowker A, editors. *The Oxford Handbook of Numerical Cognition*. Oxford:
442 Oxford University Press. pp. 787-807.

443

444 Cecchetti L, Kupers R, Ptito M, Pietrini P, Ricciradi E. 2016. Are supramodality and cross-modal
445 plasticity the yin and yang of brain development? From blindness to rehabilitation. *Front Syst*
446 *Neurosci*. 10: 89.

447

448 Chochon F, Cohen L, van de Moortele PF, Dehaene S. 1999. Differential contributions of the
449 left and right inferior parietal lobules to number processing. *J Cogn Neurosci*. 11(6): 617-630.

450

451 Collignon O, Dormal G, Lepore F. 2012. Building the Brain in the Dark: Functional and Specific
452 Crossmodal Reorganization in the Occipital Cortex of Blind Individuals. In Steeves JKE, Harris
453 LR, editors. *Plasticity in sensory systems*. Cambridge University Press. pp 73-96.

454

455 Collignon O, Lassonde M, Lepore F, Bastien D, Veraart C. 2007. Functional cerebral
456 reorganization for auditory spatial processing and auditory substitution of vision in early blind
457 subjects. *Cereb Cortex*. 17(2): 457-465.

458

459 Collignon O, Vandewalle G, Voss P, Albouy G, Charbonneau G, Lassonde M, Lepore F. 2011.
460 Functional specialization for auditory-spatial processing in the occipital cortex of congenitally
461 blind humans. *Proc Natl Acad Sci USA*. 108(11): 4435–4440.

462

463 Collignon O, Voss P, Lassonde M, Lepore F. 2009. Cross-modal plasticity for the spatial
464 processing of sounds in visually deprived subjects. *Exp Brain Res*. 192(3): 343-358.

465

466 Cooney JB, Swanson HL, Ladd SF. 1988. Acquisition of mental multiplication skill: Evidence
467 for the transition between counting and retrieval strategies. *Cognition & Instruction*. 5: 323-
468 345.

469

470 Corbetta M, Shulman GL, Miezin FM, Petersen SE. 1995. Superior Parietal Cortex Activation
471 During Spatial Attention Shifts and Visual Feature Conjunction. *Science*. 270(5237): 802-805.

472

473 Crollen V, Collignon O. 2016. Cognition numérique : que peuvent nous apprendre les
474 personnes non-voyantes ? *Med Sci*. 32: 1097-1102.

475

476 Crollen V, Collignon O, Noël MP. 2017. Visuo-spatial processes as a domain-general factor of
477 numerical development in atypical populations. *Journal of Numerical Cognition*. 3(2).
478 doi:10.5964/jnc.v3i2.68.

479

480 Crollen V, Dormal G, Seron X, Lepore F, Collignon O. 2013. Embodied numbers: The role of
481 vision in the development of number-space interactions. *Cortex*. 49: 276–283.

482

483 Crollen V, Mahe R, Collignon O, Seron X. 2011. The role of vision in the development of
484 finger-number interactions: Finger-counting and finger-montring in blind children. *J Exp Child*
485 *Psychol*. 109: 525-539.

486

487 Crollen V, Noël MP. 2015. Spatial and numerical processing in children with high and low
488 visuo-spatial abilities. *J Exp Child Psychol*. 132: 84-98.

489

490 Crollen V, Noël MP, Seron X, Mahau P, Lepore F, Collignon O. 2014. Visual experience
491 influences the interactions between fingers and numbers. *Cognition*. 133: 91-96.

492

- 493 Crollen V, Vanderclausen C, Allaire F, Pollaris A, Noël MP. 2015. Spatial and numerical
494 processing in children with non-verbal learning disabilities. *Res Dev Disabil.* 47: 61-72.
495
- 496 Damarla, S.R., Cherkassky, V.L., & Just, M.A. 2016. Modality-independent representations of
497 small quantities based on brain activation patterns. *Hum Brain Mapp.* 37(4), 1296-1307.
498
- 499 Dehaene S, Cohen L. 1997. Cerebral pathways for calculation: double dissociation between
500 rote verbal and quantities knowledge of arithmetic. *Cortex.* 33 (2): 219-250.
501
- 502 Dehaene S, Cohen L. 2007. Cultural recycling of cortical maps. *Neuron.* 56(2): 384-398.
503
- 504 Dehaene S, Piazza M, Pinel P, Cohen L. 2003. Three parietal circuits for number processing.
505 *Cogn Neuropsychol.* 20 (3-6): 487-506.
506
- 507 Dormal G, Collignon O. 2011. Functional selectivity in sensory-deprived cortices. *J*
508 *Neurophysiol.* 105(6): 2627-2630.
509
- 510 Dormal G, Lepore F, Collignon O. 2012. Plasticity of the dorsal « spatial » stream in visually
511 deprived individuals. *Neural Plast.* 2012:687659.
512
- 513 Dormal G, Rezk M, Yakobov E, Lepore F, Collignon O. 2016. Auditory motion in the sighted
514 and blind: early visual deprivation triggers a large-scale imbalance between auditory and
515 « visual » brain regions. *Neuroimage.* 134: 630-644.

516

517 Dormal V, Crollen V, Baumans C, Lepore F, Collignon O. 2016. Early but not late blindness
518 leads to enhanced arithmetic and working memory abilities. *Cortex*. 83: 212-221.

519

520 Dormal V, Schuller AM, Nihoul J, Pesenti M, Andres M. 2014. Causal role of spatial attention
521 in arithmetic problem solving: evidence from left unilateral neglect. *Neuropsychologia*. 60: 1-
522 9.

523

524 Eger, E., Sterzer, P., Russ, M.O., Giraud, A.L., & Kleinschmidt, A. 2003. A supramodal number
525 representation in human intraparietal cortex. *Neuron*. 37(4): 719-725.

526

527 Geary DC, Hamson CO, Hoard MK. 2000. Numerical and arithmetical cognition: a longitudinal
528 study of process and concept deficits in children with learning disability. *J Exp Child Psychol*.
529 77(3): 236-263.

530

531 Gougoux F, Zatorre RJ, Lassonde M, Voss P, Lepore F. 2005. A functional neuroimaging study
532 of sound localization: Visual cortex activity predicts performance in early-blind individuals.
533 *PLoS Biol*. 3: e27.

534

535 Grabner RH, Ansari D, Reishofer G, Stern E, Ebner F, Neuper C. 2007. Individual differences
536 in mathematical competence predict parietal brain activation during mental calculation.
537 *Neuroimage*. 38: 346–356.

538

539 Hannagan T, Amedi A, Cohen L, Dehaene-Lambertz G, Dehaene S. 2015. Origins of the
540 specialization for letters and numbers in ventral occipitotemporal cortex. *Trends Cogn Sci.*
541 19(7): 374-382.

542

543 Harvey BM, Dumoulin SO. 2017. A network of topographic numerosity maps in human
544 association cortex. *Nat Hum Behav.* 1: 0036. doi:10.1038/s41562-016-0036.

545

546 Harvey BM, Klein BP, Petridou N, Dumoulin SO .2013. Topographic representation of
547 numerosity in the human parietal cortex. *Science.* 341(6150): 1123-1126.

548

549 Hasson U, Andric M, Atilgan H, Collignon O. 2016. Congenital blindness is associated with
550 large-scale reorganization of anatomical networks. *Neuroimage.* 128: 362-372.

551

552 Heimler B, Striem-Amit E, Amedi A. 2015. Origins of task-specific sensory-independent
553 organization in the visual and auditory brain: neuroscience evidence, open questions and
554 clinical implications. *Curr Opin Neurobiol.* 35: 169-177.

555

556 Jiang F, Stecker GC, Boynton GM, Fine I. 2016. Early blindness results in developmental
557 plasticity for auditory motion processing within auditory and occipital cortex. *Front Hum*
558 *Neurosci.* 10: 324.

559

560 Kanjlia S, Lane C, Feigenson L, Bedny M. 2016. Absence of visual experience modifies the
561 neural basis of numerical thinking. *Proc Natl Acad Sci U S A.* 113(40): 11172-11177.

562

563 Knops A, Thirion B, Hubbard EM, Michel V, Dehaene S. 2009a. Recruitment of an area
564 involved in eye movements during mental arithmetic. *Science*. 324: 1583–1585.

565

566 Knops A, Viarouge A, Dehaene S. 2009b. Dynamic representations underlying symbolic and
567 non-symbolic calculation: Evidence from the operational momentum effect. *Atten Percept*
568 *Psychophys*. 71 (4): 803–821.

569

570 Lane C, Kanjlia S, Omaki A, Bedny M. 2015. “Visual” cortex of congenitally blind adults
571 responds to syntactic movement. *J Neurosci*. 35(37): 12859-12868.

572

573 Loetscher T, Bockish CJ, Nicholls MER, Brugger P. 2010. Eye position predicts what number
574 you have in mind. *Curr Biol*. 20(6): R264-R265.

575

576 Masson N, Pesenti M. 2014. Attentional bias induced by solving simple and complex addition
577 and subtraction problems. *Q J Exp Psychol*. 67(8): 1514-26.

578

579 McCrink K, Dehaene S, Dehaene-Lambertz G. 2007. Moving along the mental number line:
580 operational momentum in nonsymbolic arithmetic. *Percept Psychophys*. 69 (8): 1324–1333.

581

582 McLean JF, Hitch GJ. 1999. Working memory impairments in children with specific arithmetic
583 learning difficulties. *J Exp Child Psychol*. 74(3): 240-260.

584

585 Mizuhara H, Wang LQ, Kobayashi K, Yamaguchi Y. 2005. Long-range EEG phase
586 synchronization during an arithmetic task indexes a coherent cortical network simultaneously
587 measured by fMRI. *Neuroimage*. 27(3): 553-563.

588

589 Nieder A. 2012. Supramodal numerosity selectivity of neurons in primate prefrontal and
590 posterior parietal cortices. *PNAS*. 109(29): 11860-11865.

591

592 Nieder A. (2016). The neuronal code for number. *Nat Rev Neurosci*. 17(6): 366-382.

593

594 Pelland M, Orban P, Dansereau C, Lepore F, Bellec P, Collignon O. 2017. State-dependent
595 modulation of functional connectivity in early blind individuals. *Neuroimage*. 147: 532-541.

596

597 Piazza M, Pinel P, Le Bihan D, Dehaene S. 2007. A magnitude code common to numerosities
598 and number symbols in human intraparietal cortex. *Neuron*. 53: 293–305.

599

600 Pinhas M, Fischer M. 2008. Mental movements without magnitude? A study of spatial biases
601 in symbolic arithmetic. *Cognition*. 109: 408–415.

602

603 Poirier C, Collignon O, Scheiber C, Renier L, Vanlierde A, Tranduy D, Veraart C, De Volder
604 AG. 2006. Auditory motion perception activates visual motion areas in early blind subjects.
605 *Neuroimage*. 31(1): 279-285.

606

607 Power JD, Barnes KA, Snyder AZ, Schlaggar BL, Petersen, SE. 2012. Spurious but systematic
608 correlations in functional connectivity MRI networks arise from subject
609 motion. *Neuroimage*. 59(3): 2142-2154.

610

611 Reich L, Szwed M, Cohen L, Amedi A. 2011. A ventral visual stream reading center
612 independent of visual experience. *Curr Biol*. 21(5): 363-368.

613

614 Ricciardi E, Tozzi L, Leo A, Pietrini P. 2014. Modality-dependent cross-modal functional
615 reorganization following congenital visual deprivation within occipital areas: a meta-analysis
616 of tactile and auditory studies. *Multisens Res*. 27(3-4): 247-262.

617

618 Ricciardi E, Vanello N, Sani L, Gentili C, Scilingo EP, Landini L, Guazzelli M, Bicchi A, Haxby
619 JV, Pietrini P. 2007. The effect of visual experience on the development of functional
620 architecture in hMT+. *Cerebral Cortex*. 17(12): 2933-2939.

621

622 Rickard TC, Romero SG, Basso G, Wharton C, Flitman S, Grafman J. 2000. The calculating
623 brain: an fMRI study. *Neuropsychologia*. 38 (3): 325-335.

624

625 Röder B, Stock O, Bien S, Neville H, Rösler F. 2002. Speech processing activates visual cortex
626 in congenitally blind humans. *Eur J Neurosci*. 16(5): 930-936.

627

628 Ross J, Burr DC. 2010. Vision senses number directly. *J Vis*. 10(2):10, 1-8.

629

630 Sadato N, Pascual-Leone A, Grafman J, Ibanez V, Deiber MP, Dold G, Hallett M. 1996.
631 Activation of the primary visual cortex by Braille reading in blind subjects. *Nature*. 380: 526-
632 528.
633
634 Sathian K, Simon TJ, Peterson S, Patel GA, Hoffman JM, Grafton ST. 1999. Neural evidence
635 linking visual object enumeration and attention. *J Cogn Neurosci*. 11(1): 36-51.
636
637 Satterthwaite TD, Wolf DH, Loughead J, Ruparel K, Elliott MA, Hakonarson H, Gur RC, Gur
638 RE. 2012. Impact of in-scanner head motion on multiple measures of functional connectivity:
639 relevance for studies of neurodevelopment in youth. *Neuroimage*. 60(1): 623-632.
640
641 Shum J, Hermes D, Foster BL, Dastjerdi M, Rangarajan V, Winawer J, Miller KJ, Parvizi J. 2013.
642 A brain area for visual numerals. *J Neurosci*. 33(16): 6709-6715.
643
644 Siegler RS, Shrager J. 1984. Strategy choices in addition and subtraction: how do children
645 know what to do? In Sophian C, editor. *The origins of cognitive skills*. Hillsdale: Erlbaum. pp.
646 229-293.
647
648 Simon TJ. 1999. The foundations of numerical thinking in a brain without numbers. *Trends*
649 *Cogn Sci*. 3: 363-365.
650
651 Sladky R, Friston KJ, Tröstl J, Cunnington R, Moser E, Windischberger C. 2011. Slice timing
652 effects and their correction in functional MRI. *Neuroimage*. 58 (2): 588-594.

653 Stoianov I, Zorzi M. 2012. Emergence of a “visual number sense” in hierarchical generative
654 models. *Nat Neurosci.* 15(2): 194-196.

655

656 Talairach J, Tournoux P. 1988. Co-planar stereotaxic atlas of the human brain. Thieme: New
657 York.

658

659 Tschentscher N, Hauk O, Fischer MH, Pulvermüller F. 2012. You can count on the motor
660 cortex: Finger counting habits modulate motor cortex activation evoked by numbers.
661 *Neuroimage.* 59: 3139-3148.

662

663 van Ackeren MJ, Barbero FM, Mattioni S, Bottini R, Collignon O. 2017. Neuronal populations
664 in the occipital cortex of the blind synchronize to the temporal dynamics of speech.
665 *BioRxiv.* 186338. doi: <https://doi.org/10.1101/186338>.

666

667 Van Dijk KR, Sabuncu MR, Buckner RL. 2012. The influence of head motion on intrinsic
668 functional connectivity MRI. *Neuroimage.* 59(1): 431-438.

669

670 Walter E, Mazaika PK, Reiss, AL. 2009. Insights into brain development from neurogenetic
671 syndromes: from fragile X syndrome, Williams syndrome, Turner syndrome and
672 velocardiofacial syndrome. *Neuroscience.* 164(1): 257-271.

673

674 Weeks R, Horwitz B, Aziz-Sultan A, Tian B, Wessinger CM, Cohen LG, Hallett M, Rauschecker
675 JP. 2000. A positron emission tomographic study of auditory localization in the congenitally
676 blind. *J Neurosci.* 20(7): 2664–2672.

677
678 Whitfield-Gabrieli S, Nieto-Castanon A. 2012. Conn: A functional connectivity toolbox for
679 correlated and anticorrelated brain networks. *Brain Connectivity.*
680 doi:10.1089/brain.2012.0073.

681
682 Wu S, Chang TT, Majid A, Caspers S, Eickhoff SB, Menon V. 2009. Functional heterogeneity
683 of inferior parietal cortex during mathematical cognition assessed with cytoarchitectonic
684 probability maps. *Cereb Cortex.* 19 (12): 2930-2945.

685
686 Yantis S, Serences JT. 2003. Cortical mechanisms of space-based and object-based
687 attentional control. *Curr Opin Neurobiol.* 13(2): 187-193.

688
689 Zhou X, Chen C, Zang Y, Dong Q, Chen C, Qiao S, Gong Q. 2007. Dissociated brain
690 organization for single digit addition and multiplication. *Neuroimage.* 35 (2): 871-880.

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696 **Table 1.** Functional results summarizing the main effect of groups for the different contrasts
 697 of interests

Area	Cluster Size(Φ)	x	y	z	Z	p
(A) [SC \cap CB] [Subtraction \cap Multiplication >Letter]						
L AG – L PSPL	89	-40	-74	26	3.03	0.02*
(B) [CB > SC] [Subtraction \cap Multiplication >Letter]						
L MOG	321	-34	-86	24	3.98	0.001*
(C) [SC \cap CB] [Subtraction > Multiplication]						
L FEF	426	-26	-2	54	2.63	0.04#
R FEF	124	22	-2	56	3.66	0.004*
L PSPL	2818	-20	-68	46	4.06	0.001*
R PSPL		24	-68	46	4.10	0.001*
R Middle Frontal Gyrus	53	32	36	24	3.25	0.01*
(D) [CB > SC] [Subtraction > Multiplication]						
R MOG	156	36	-82	8	3.55	0.006*

(E) [SC \cap CB] [Multiplication >

Subtraction]

R STG 104 64 -14 -8 3.48 0.007*

698 Brain activations significant ($p_{\text{corr}} < .05$ FWE) after correction over (*) small spherical
699 volumes (SVC, 10 mm radius) or (#) over the whole brain. (Φ) Number of voxels in specific
700 clusters when displayed at $p(\text{uncorr}) < 0.001$ SC: sighted controls, CB: congenitally blind, L:
701 left, R: Right, AG: angular gyrus; STG: superior temporal gyrus; PSPL: posterior superior
702 parietal lobule; FEF : frontal eye field; MOG : middle occipital gyrus.

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714 **Table 2.** Brain regions correlated with left and right middle occipital gyrus at rest.

Area	Cluster Size(Φ)	x	y	z	Cluster P_{FDR}
<u>Correlation with L MOG in blind ></u>					
<u>sighted</u>					
Lingual gyrus	176	0	-34	42	0.000132
L angular gyrus	151	-50	-52	48	0.000250
L cingulate gyrus	142	-6	22	46	0.000273
R inferior precentral sulcus (premotor cortex)	115	54	8	40	0.000973
R retrosplenial cortex	105	10	-46	18	0.001427
L fusiform gyrus	78	-32	-68	-12	0.006271
L middle frontal gyrus	75	-38	8	40	0.006271
L inferior frontal gyrus	75	-44	46	6	0.006271
L thalamus	73	-8	-16	10	0.006402
L occipito-temporal cortex	59	-20	-46	-8	0.015785
L IPS	51	-32	8	28	0.024218
L posterior collateral sulcus	51	-24	-68	-8	0.024218

L inferior occipital gyrus	50	-38	-86	-12	0.024218
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Posterior cingulate	41	-2	-40	24	0.046822
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Correlation with R MOG in blind >

sighted

R inferior parietal lobule	213	48	-62	28	0.000012
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L cerebellum crus 2	207	-8	-80	-32	0.000012
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L precuneus – posterior cingulate	184	-2	-44	10	0.000025
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L inferior occipital gyrus	127	-30	-86	-18	0.000426
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R middle/inferior frontal gyrus	86	46	20	30	0.003921
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R lingual gyrus	85	12	-92	0	0.003921
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R inferior occipital gyrus	80	34	-92	-8	0.004716
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R middle frontal gyrus	78	48	16	46	0.004735
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R fusiform gyrus	76	34	-68	-14	0.004835
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L inferior LOC	61	-44	-82	-14	0.011676
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R inferior temporal cortex	61	34	-46	-18	0.011676
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R superior frontal gyrus	55	30	32	54	0.014493
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R fusiform gyrus	55	54	-62	-18	0.014493
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L fusiform gyrus	55	-48	-62	-18	0.014493
L cerebellum/posterior lobe	45	-26	-62	-32	0.030143
L thalamus	39	-8	-10	6	0.047029

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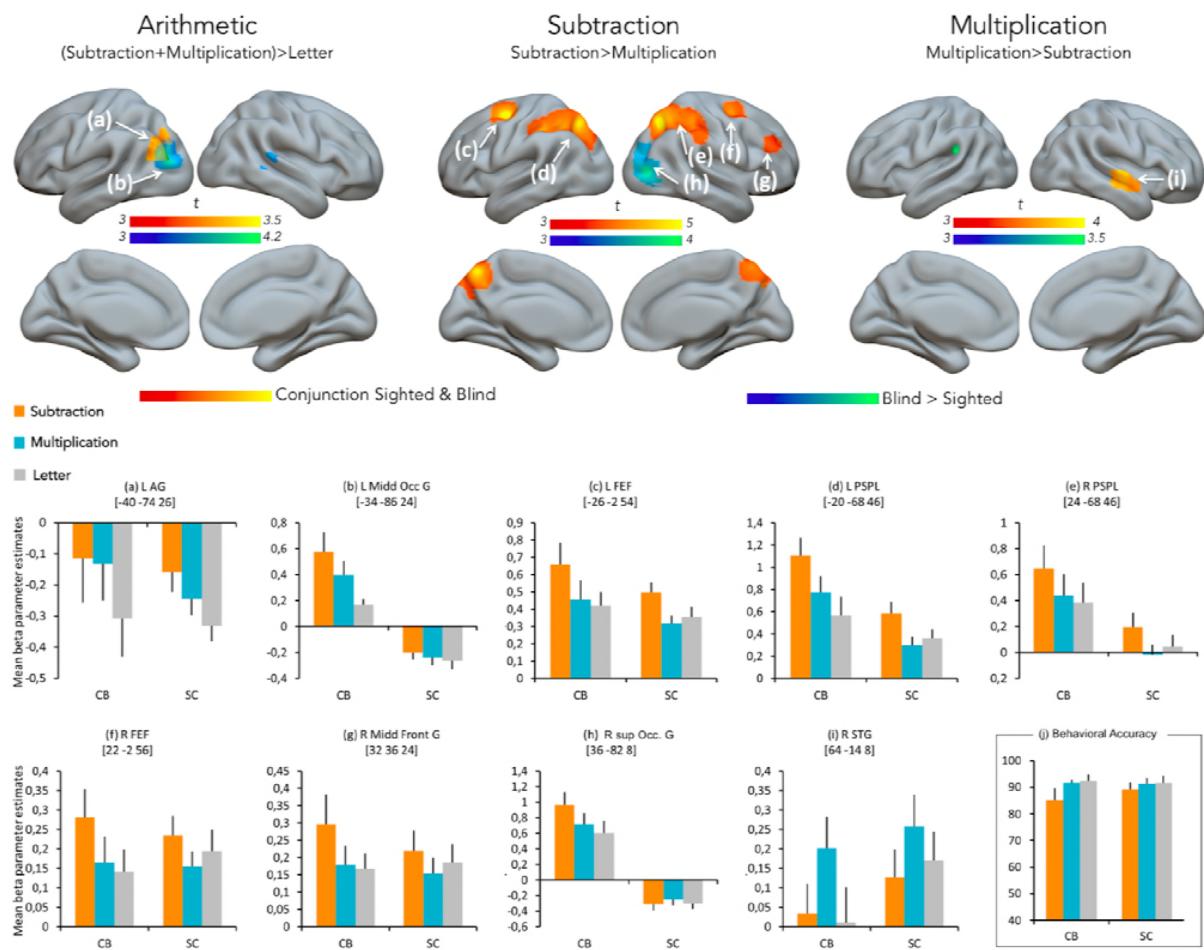
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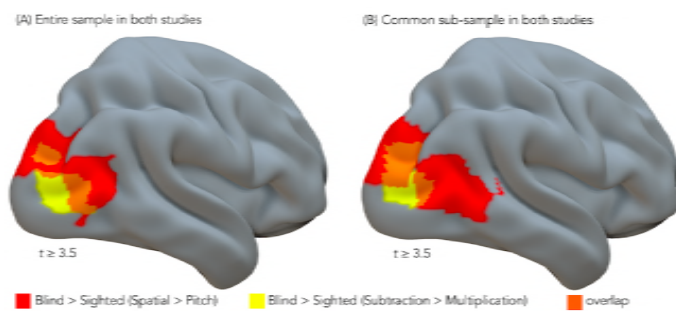
734 FIGURES



735

736 **Figure 1.** Results of the whole brain univariate analyses. Task-related brain activity common
 737 to both groups ($p_{uncorr} < .002$, $k > 15$) and specific to the blind group ($p_{uncorr} < .001$, $k >$
 738 15). There were no activations specific to the sighted group. Color bars represent t-values.
 739 Lower part (a-i): for illustration, mean activity estimates (arbitrary units \pm SEM) associated with
 740 arithmetic, subtraction and multiplication are plotted for blind and sighted at significant
 741 peaks. See Table 1 for a list of brain regions depicted in this figure. (j) Behavioral results. Mean
 742 and standard error of accuracy scores (percentage of correct responses) per condition and
 743 group.

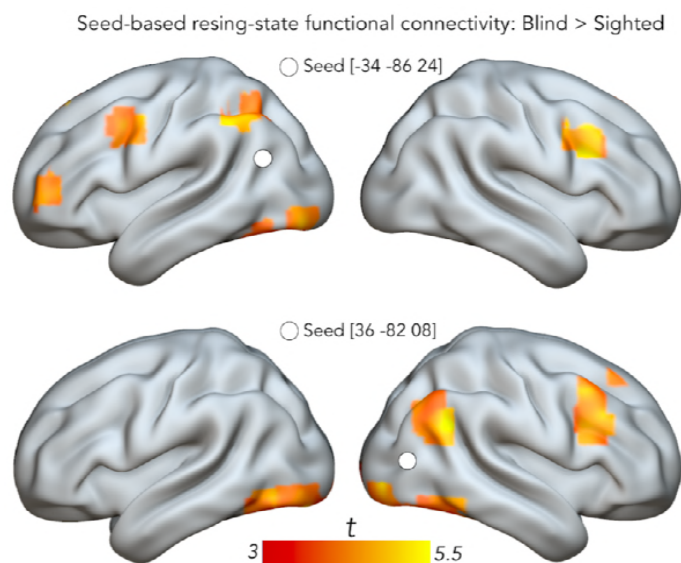
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746 **Figure 2.** Consistency across studies. The middle occipital gyrus, showing functional
747 preference for subtraction in our study overlapped in part with regions showing selective
748 tuning to auditory spatial processing in the blind (Collignon et al., 2011). Test-consistency
749 either included (A) the entire sample of blind participants in both studies or (B) only the
750 blind participants who performed both studies (N = 7).

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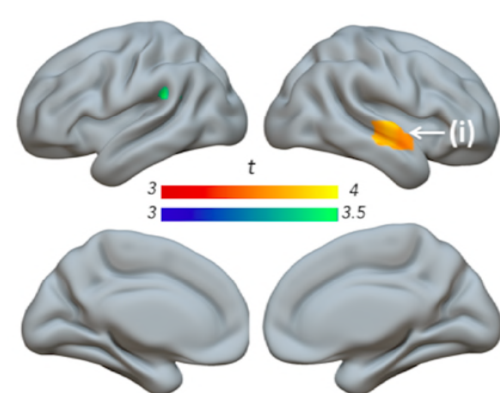
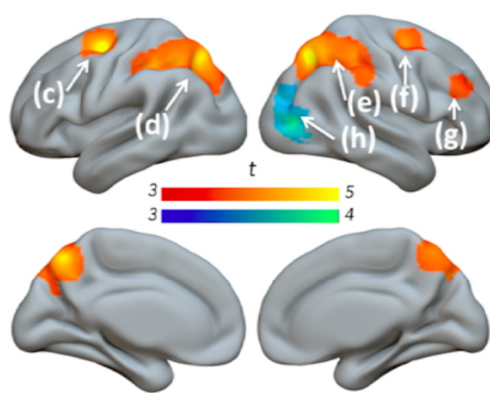
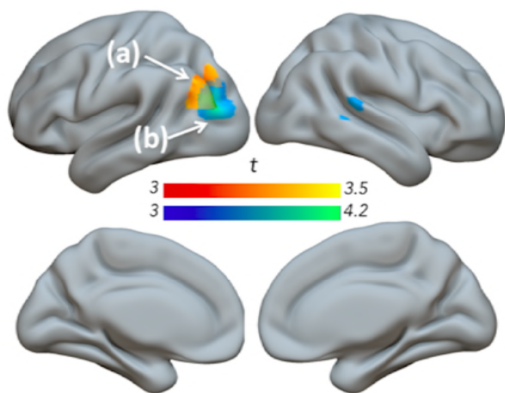
753 **Figure 3.** Brain regions more correlated with left and right MOG in blind (n = 13) relative to
754 sighted (n = 11) individuals in resting-state data ($P < 0.05$, FDR corrected). Left and right
755 MOG seeds shown in white.

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Arithmetic (Subtraction+Multiplication)>Letter

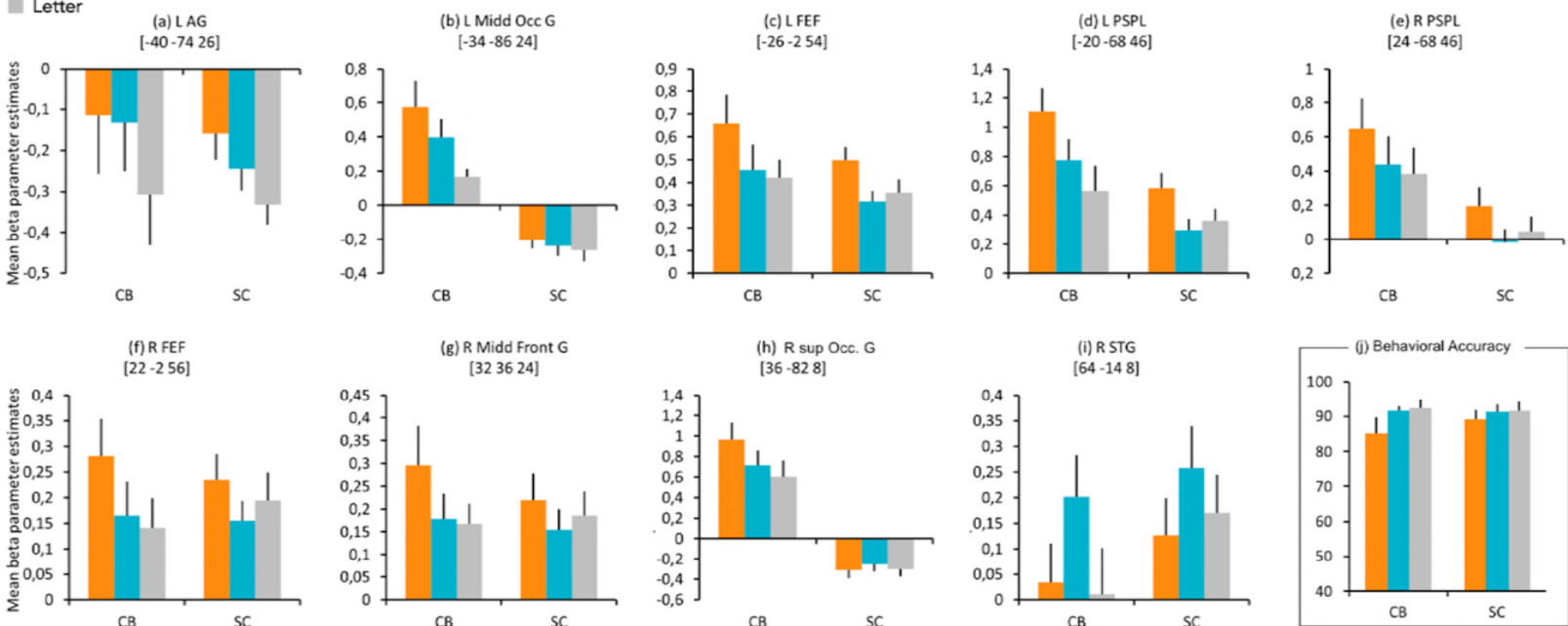
Subtraction Subtraction>Multiplication

Multiplication Multiplication>Subtraction



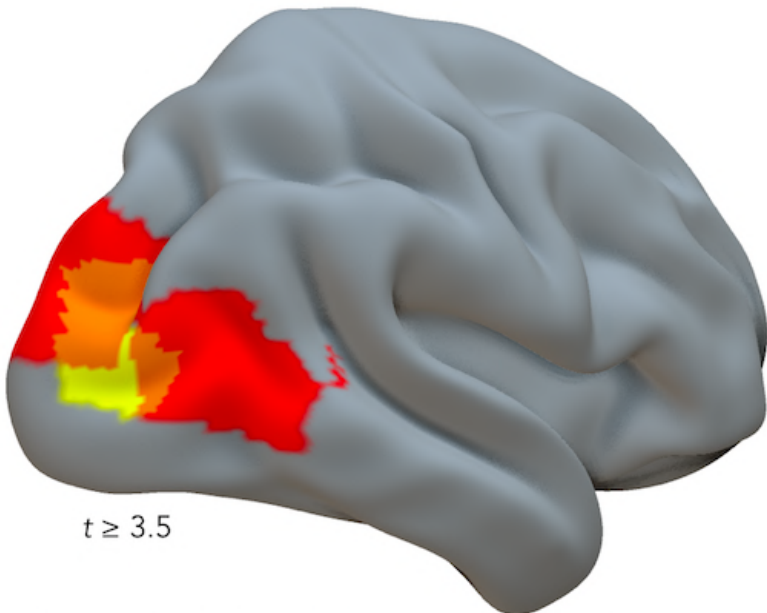
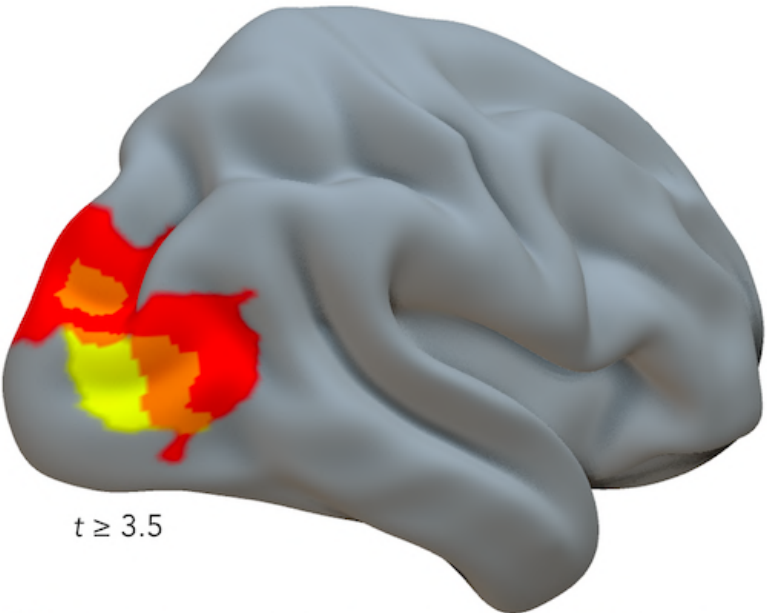
■ Subtraction
 ■ Multiplication
 ■ Letter

— Conjunction Sighted & Blind
 — Blind > Sighted



(A) Entire sample in both studies

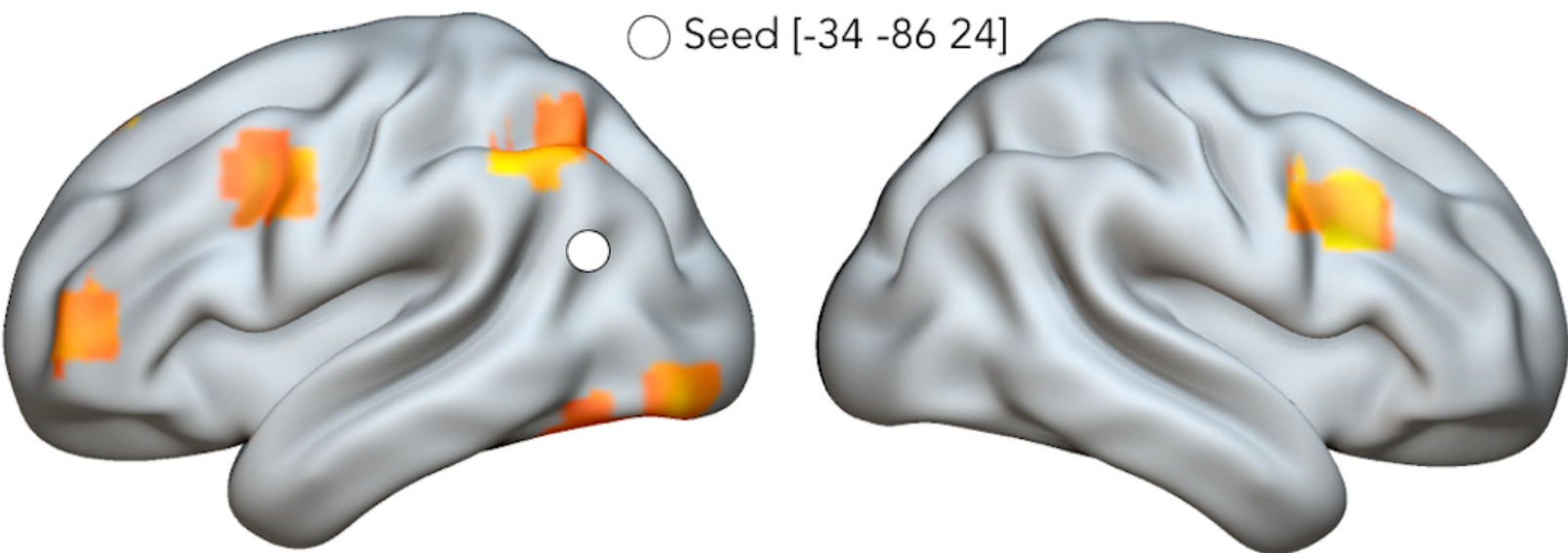
(B) Common sub-sample in both studies



■ Blind > Sighted (Spatial > Pitch) ■ Blind > Sighted (Subtraction > Multiplication) ■ overlap

Seed-based resting-state functional connectivity: Blind > Sighted

○ Seed [-34 -86 24]



○ Seed [36 -82 08]

