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Abstract

Finger gnosis is the ability to mentally represent one's fingers as distinct from one another in the absence of visual feedback. In the current paper, we conducted a quantitative meta-analysis of imaging data, using activation likelihood estimation, to determine the neural correlates of finger gnosis. Fourteen studies contributed 294 activated foci from 225 participants for analysis. The meta-analysis yielded seven peaks of activation located within the frontal-parietal network (i.e., medial frontal gyrus, pre- and post-central gyrus, and inferior parietal lobule) and cerebellum (i.e. culmen). A qualitative comparison of the findings of our meta-analysis with single-experiment fMRI investigations of finger gnosis (Andres et al., 2012; Rusconi et al., 2014) suggests that experimentalists' choices of primary and control tasks have influenced our understanding of the neural substrate underlying finger gnosis. Our results may aid in the design and interpretation of behavioural and imaging experiments as well as inform the development of computational models.

Keywords: Finger gnosis; finger localization; finger differentiation; ALE; meta-analysis.

Introduction

Finger gnosis is defined as *the presence of an intact finger schema* (Gerstmann, 1940), or the ability to mentally represent one's fingers as distinct from one another, in the absence of visual feedback. Finger gnosis is operationalized as performance on finger localization tasks (Baron, 2004; Benton, 1959; Noël, 2005) or finger differentiation tasks (Kinsbourne & Warrington, 1962). In a typical finger localization task (Baron, 2004), the participant's hand is shielded from their view, the experimenter touches one or two fingers, and the participant is asked to report which fingers were touched. Reporting methods vary and can be verbal (i.e., indicating a finger name or associated number) or non-verbal (i.e., pointing). Commonly used finger differentiation tasks (Kinsbourne & Warrington, 1962) include the in-between test and the finger block test. In the in-between test, two fingers are touched on the same hand while the participant's eyes are closed and the participant is asked to verbally report the number of fingers in between the two touched fingers (i.e., 0, 1, 2). In the finger block test, the experimenter places a wooden block (with grooves that induce a particular pattern of flexion/extension across the fingers) in the participant's hand while the participant's eyes are closed. The block is then removed and the participant is asked to open their eyes and select the block that was held from four possible options. Finger gnosis tasks were originally designed for diagnostic use in neuropsychological cases (e.g., finger agnosia and lesions of the left angular gyrus; Gerstmann, 1940; Kinsbourne & Warrington, 1962), but have since been adapted for use in non-clinical populations to assess individual differences in finger representation.

Individual imaging experiments have been conducted to identify the neural correlates of finger gnosis (Andres, Michaux, & Pesenti, 2012; Rusconi et al., 2014) using different tasks. Andres et al. (2012) used a novel variant of the finger block test where the participant held an unseen block with grooves in two finger positions. While holding the block, the participant was shown a line drawing of a hand with one finger outlined in red. The participant was to verbally answer (i.e., yes, no) whether the indicated finger was down (i.e., in a groove). In the control task, participants saw the same line drawing of a hand, but outlined entirely in either black or red. The participant was to verbally answer (i.e., yes, no) whether the hand colour was red. Rusconi et al. (2014) used a variant of the in-between test (Rusconi, Gonzaga, Adriani, Braun & Haggard, 2009) where two fingers were stimulated on each hand and the participant was to respond, using foot pedals, whether the number of fingers in between was the same or different across hands. In the control task, two fingers were stimulated on each hand and the participant was to respond, using foot pedals, whether the intensity of stimulation was the same or different across hands.

Both Andres et al. (2012) and Rusconi et al. (2014) noted bilateral premotor cortex (Brodmann area [BA] 6) activation as well as unilateral (left) activation of the precuneus (BA 7) and inferior parietal lobule (BA 40). However, likely due to variation in the tasks used to assess finger gnosis ability (block pose vs. finger vibration) as well as the medium by which participants reported (verbal vs. pedal action), each study described unique (to their study) areas of activation. For example, Andres et al. noted activation of the left fusiform gyrus (BA 37) as well as the right precuneus and middle occipital gyrus (BA 19), which have been shown to be involved in higher order visual processing such as colour perception (Lafer-Sousa, Conway, & Kanwisher, 2016) and visual-spatial imagery (Cavanna & Trimble, 2006). In contrast, Rusconi et al. noted bilateral activation of the dorsal lateral prefrontal cortex (BA 9), which has been shown to be involved in self-generated speech and finger movements (Frith, Friston, Liddle, & Frackowiak, 1991), visuospatial control of actions, and working memory (Levy & Goldman-Rakic, 2000).

The goal of the current paper is to conduct a first, quantitative meta-analysis of brain imaging data for finger gnosis, looking across studies to find regions of common activation. Activated likelihood estimation (ALE) is a quantitative meta-analytic technique originally developed by Turkeltaub et al. (2002) and later refined by Eickhoff et al. (2009, 2012) and Turkeltaub et al. (2012). ALE identifies commonalities across imaging studies by using the standardized coordinates from multiple studies and synthesizing them into a statistical map, displaying probable locations of cortical activation for a given experimental task. Each study's coordinates are input into voxels, 2-mm cubes that divide the brain into a 3-dimensional grid. Each voxel is given an ALE score based on the number of coordinates entered into that voxel, and analyses are conducted to determine if a voxel is significantly activated. This process results in a map of the brain displaying the common areas of activation for a given task.

Thus, in the current study, we conducted an ALE meta-analysis in order to systematically identify common regions of activation for finger gnosis across the literature. We expected that common areas identified across Rusconi et al. (2014) and Andres et al. (2012) would be similarly identified in the ALE map, particularly in the premotor cortex, precuneus, and the inferior parietal lobule.

Methods

In order to determine the neural correlates of finger gnosis, we conducted an ALE analysis following the methodology that Sokolowski et al. (2017) used to describe the neural correlates of symbolic and non-symbolic number comparison. This methodology involved three broad steps: 1) literature search; 2) manuscript evaluation; and 3) ALE analysis.

Step 1: Literature Search. We searched the PubMed and PsycINFO databases using the keywords "finger" AND ("localization", "representation", "gnosis", "gnosia", "agnosia", "knowledge", "recognition", "proprio*") AND ("pet", "fmri", "positron", "functional magnetic resonance", "neuroimag*", and "imaging") along with filters that specified the inclusion of only scholarly journal articles and research that used adult, human participants. These database searches yielded 393 and 307 manuscripts from PubMed and PsycINFO, respectively. The search outputs were combined, with duplicates removed, resulting in a list of 585 peer-reviewed manuscripts. These articles were retrieved from their respective databases for further evaluation.

Step 2: Manuscript Evaluation. Each article was evaluated based on six inclusion/exclusion criteria. Each article had to include: 1) at least one task involving finger representation that required participants to discriminate between fingers either on the same hand or across hands, without visual feedback; 2) a sample of healthy, human adults; 3) results from brain imaging completed using either fMRI or PET; 4) whole-brain analyses that described brain regions (foci) in either Talairach/Tournoux or Montreal Neurological Institute (MNI) coordinate frames; 5) a sample size greater than five; and 6) be written in English. Of the aforementioned 585 articles yielded from our database search, only 14 (2.4%) of the studies met these criteria (see Table 1) and could be used in the ALE analysis.

Step 3: ALE Analysis. Three pieces of software, developed by BrainMap (www.brainmap.org) for the purposes of conducting brain imaging meta-analyses, were used for our ALE analysis: *Scribe*, *Sleuth*, and *GingerALE* (Fox & Lancaster, 2002). Data (e.g., activated brain regions, task description, subject demographics, etc.) from the 14 manuscripts meeting our criteria were encoded using Scribe and submitted to the BrainMap database. Sleuth was used to convert data from the relevant experiments into a file properly formatted to be accepted by GingerALE. The GingerALE analysis was a cluster-level inference with 1000 threshold permutations, a cluster-level threshold of $p < 0.01$, and a cluster-forming (uncorrected) threshold of $p < .001$, following Sokolowski et al. (2017).

Results

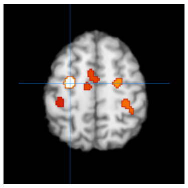
The 14 studies (see Table 1) that met our exclusion/inclusion criterion yielded 294 activated foci from 225 participants for analysis using the GingerALE software. GingerALE's cluster analysis revealed seven distinct clusters (see Table 2 and Figure 1):

Cluster 1 was the largest cluster in terms of both brain volume and number of contributing foci (23 from 10 separate studies). Although the center of mass for this cluster was located in the left parietal lobe (BA 40), this cluster had six peaks of activation distributed across both the left frontal (precentral gyrus) and parietal (postcentral gyrus and inferior parietal lobule) lobes. *Cluster 2* had a center of mass located within the frontal lobe (BA 6), two peaks of activation located in the left medial frontal gyrus, and consisted of 14 foci taken from six studies. *Cluster 3* had center of mass located in the right postcentral gyrus (BA 3), had two peaks located in the right postcentral gyrus and inferior parietal lobule, and was derived from 16 foci taken from seven studies; *Cluster 4* had both a center of mass and a singular peak located in the sub-gyral gray matter (BA 6) of the right frontal lobe and was derived from eight foci taken from six studies. *Cluster 5* had a center of mass and peaks located in the left precentral gyrus (BA 6) and was derived from eight foci taken from six studies. *Cluster 6* had both its peak and center of mass located in the right culmen of the anterior lobe of the cerebellum and was derived from eight foci from six studies. *Cluster 7*, the smallest cluster by volume, had a center of mass and a singular peak located in the left precentral gyrus and was derived from six foci from four studies.

a) Cluster 1: -38, -36, 42 **b)** Cluster 2: -6, -10, 58

c) Cluster 3: 32, -32, 46 **d)** Cluster 4: 24, -10, 54

e) Cluster 5: -54, -2, 40 **f)** Cluster 6: 20, -48, -22



g) Cluster 7: -26, -10, 50

Figure 1. Horizontal slices of cluster peaks detected by ALE with their respective coordinates.

In summary, our ALE meta-analysis of published imaging data provides support for the perspective that finger gnosis is the result of a distributed frontal-parietal-cerebellar network. Furthermore, this network contains regions involved in finger sensation (postcentral gyrus and posterior parietal cortex; Iwamura, 1998), action (precentral gyrus, posterior parietal cortex, and anterior cerebellum; Chan, Huang & Di, 2009; Isa et al., 2007), and cognition, including working memory, attention, sequence planning, and body schema development (posterior parietal cortex; Battaglia-Mayer, 2019; Tumati et al., 2019). Lastly, the activation pattern observed from our meta-analytical dataset matches those expected for a predominately (96%) right-handed sample of participants performing dexterous tasks requiring individuated finger movements.

Discussion

The goal of the current study was to identify the neural correlates of finger gnosis by conducting a quantitative meta-analysis of brain imaging data using activation likelihood estimation (ALE). Based on the common results of individual experiments (Andres et al., 2012; Rusconi et al., 2014) we predicted shared activation across studies in the premotor cortex, precuneus, and inferior parietal lobule, as well as differences across studies based on task-specific requirements. In line with previous observations, our ALE analysis yielded peaks of activation within the inferior parietal lobule bilaterally. However, our analysis did not yield activation peaks in the precuneus, dorsolateral prefrontal, premotor, or associative visual cortices, which had been noted previously. Moreover, our analysis yielded additional peaks in the left pre- and post-central gyrus, left medial frontal gyrus, and medial cerebellum (Table 2). Activation within these additional brain regions is not wholly unexpected given that our dataset consisted of a predominately right-handed participant sample whose task performance was tied, either explicitly or implicitly, to their ability to discriminate tactile sensation of, and/or produce responses using, individuated movements of fingers of the right hand.

Differences in the distribution of activation peaks across the current meta-analysis, Andres et al. (2012) and Rusconi et al. (2014) likely resulted from the variability and quality of control tasks as well as differing levels of cognitive engagement (e.g. working memory and/or attentional load) between primary task variants. Behaviorally, performance on finger localization and finger differentiation tasks has been shown to correlate significantly in clinical populations, suggesting that these different task variants index the same underlying ability (Brewer, 1966). The adaptations used in some experiments in the current meta-analysis, however, were more complex and included additional requirements that may not be subtracted out without appropriate control tasks.

One limitation of the current meta-analysis is the low number of imaging studies included. Previously, it was recommended to have ten to fifteen studies included in an ALE analysis in order to have sufficient power, but more recently this recommendation has changed to twenty studies (Eickhoff et al., 2016). Another limitation is the bias towards right-handed participants in imaging experiments. The overwhelming majority of participants in the included studies were right-handed, so the results cannot be generalized to left-handed individuals.

Stewart and colleagues have implemented a computational model of finger gnosis in spiking neurons (Stewart & Penner-Wilger, 2017; Stewart, Penner-Wilger, Waring & Anderson, 2017). To evaluate the psychological plausibility of the model, they compared model performance to human performance on a finger localization task (two-finger variant; Baron, 2004) and found that the model mirrors human performance in terms of both accuracy levels and types of errors (Stewart et al., 2017). Moreover, the same model was used to perform a number comparison task (e.g., Which is more: 3 or 4?) serving as an in-principal demonstration of the *redeployment view* (Penner-Wilger & Anderson, 2008, 2013) that number representation is grounded in sensorimotor finger representations.

Behaviorally, finger gnosis ability predicts math performance in children (Fayol, Barrouillet, & Marinthe, 1998; Noël, 2005; Penner-Wilger et al., 2007) and adults (Penner-Wilger, Waring, & Newton, 2014). On the redeployment view (Penner-Wilger & Anderson, 2008, 2013), this relation between finger gnosis and number representation reflects neural reuse (Anderson, 2014), in which one or more local brain regions have come to perform the same operation in support of finger and number representation over the course of evolution and/or development. In a single experiment, Andres et al. (2012) found overlapping activation for finger gnosis and arithmetic bilaterally in the horizontal segment of the intraparietal sulcus and posterior segment of the superior parietal lobule.

To better determine neural overlap between finger gnosis and number representation, a conjunction analysis of the current finger gnosis map and the number comparison maps of Sokolowski et al. (2017) could be conducted. This work could inform refinements of Stewart and colleagues' computational model (Stewart & Penner-Wilger, 2017; Stewart et al., 2017), leading to a more neurologically-plausible model of both finger gnosis and number representation.

Table 1. Studies included in the finger gnosis meta-analysis.

1st author	Year	Journal	N	Imaging method	Mean age	Gender	Contrast name	# of foci
Adamovich S V	2009	Restorative Neurology and Neuroscience	13	fMRI	28	9M 4F	MOVE_h > REST	14
							MOVE_e > REST	12
Andres M	2012	NeuroImage	18	fMRI	21	18M	Finger task > Rest	11
Bischoff-Grethe A	2004	Journal of Cognitive Neuroscience	24	fMRI	20	9M 15F	Learning Related Increases, Low-Recall Subjects	39
Boraxbekk C J	2016	Neuropsychologia	56	fMRI	71	26M 30F	Untrained sequence conjunction	9
							Motor training > Imagery training	1
Grafton S T	1998	The Journal of Neuroscience	20	PET		11M 9F	Sequence Encoding – Small Keyboard	8
Hanakawa T	2002	Cerebral Cortex	10	fMRI	29	9M 1F	Complex finger-tapping > Visual fixation	11
							Complex finger-tapping > simple finger tapping	5
Harrington D L	2000	Journal of Cognitive Neuroscience	15	fMRI	24	6M 9F	Common regions of activation for fingers and transitions	24
							Regions activated by fingers	5
							Regions activated by transitions	5
							Regions activated by fingers (no repeats)	2
							Regions activated by transitions (no repeats)	13
Jack A	2011	Neuropsychologia	15	fMRI	23	8M 7F	Imitation & Observation & Execution	3
Kapreli E	2007	Cortex	18	fMRI	27	18M	Fingers > Rest	17
Langner R	2014	Human Brain Mapping	36	fMRI	38	21M 15F	Encoding and Recall Epochs for both hands/delays	37
							Left > Right-hand sequences	12
							Right > Left-hand sequences	12
Rusconi E	2014	The Journal of Neuroscience	13	fMRI	27	7M 6F	Finger gnosis (IIBT) > Control (IINT)	7
Sadato N	1997	The Journal of Neuroscience	21	PET	22	21M	Mirror vs. Rest	13
							Parallel vs. Rest	15
Walz A D	2015	Behavioural Brain Research	15	fMRI	24	9M 6F	Finger sequence conjunction	12
							Writing conjunction	12
Watanabe R	2011	Neuroscience Letters	15	fMRI	23	15M	First-person anatomical > Motor control	1
							First-person specular > Motor control	6

fMRI, functional magnetic resonance imaging; PET, positron emission tomography; N, sample size of each study; M – Male, F – Female.

Table 2. Cluster peaks and locations.

Cluster	Hemisphere	Brain area	BA	X	Y	Z	ALE	Vol/mm^3
1	L	Inferior Parietal Lobule	40	-38	-36	42	0.023	3440
1	L	Inferior Parietal Lobule	40	-34	-36	42	0.022	
1	L	Postcentral Gyrus	3	-36	-32	48	0.020	
1	L	Precentral Gyrus	4	-36	-18	56	0.020	
1	L	Postcentral Gyrus	3	-36	-28	52	0.017	
1	L	Postcentral Gyrus	2	-48	-24	44	0.013	
2	L	Medial Frontal Gyrus	6	-6	-10	58	0.021	2376
2	L	Medial Frontal Gyrus	6	-2	-6	56	0.021	
3	R	Postcentral Gyrus	3	32	-32	46	0.024	2080
3	R	Inferior Parietal Lobule	40	40	-48	44	0.016	
4	R	Sub-Gyral	6	24	-10	54	0.022	1416
5	L	Precentral Gyrus	6	-54	-2	40	0.019	1104
5	L	Precentral Gyrus	6	-50	0	34	0.019	
6	R	Culmen	N/A	20	-48	-22	0.025	1088
7	L	Precentral Gyrus	6	-26	-10	50	0.024	864

BA – Brodmann Area; X, Y and Z – x, y, z location of the peak of activation in Talairach coordinates; ALE - maximum ALE value observed in the cluster; Vol/mm^3 – volume of cluster in mm^3.

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References

Adamovich, S. V., August, K., Merians, A., & Tunik, E. (2009). A virtual reality-based system integrated with fmri to study neural mechanisms of action observation execution: a proof of concept study. *Restorative Neurology and Neuroscience*, 27(3), 209-223.

Anderson, M. L. (2014). *After phrenology: Neural reuse and the interactive brain*. Cambridge, MA: MIT Press.

Andres, M., Michaux, N., & Pesenti, M. (2012). Common substrate for mental arithmetic and finger representation in the parietal cortex. *NeuroImage*, 62(3), 1520-1528.

Baron, I. S. (2004). *Neuropsychological Evaluation of the Child.* New York, NY: Oxford University Press.

Battaglia-Mayer, A (2019). A brief history of the encoding of hand position by the cerebral cortex: implications for motor control and cognition. *Cerebral Cortex*, 29: 716-731.

Benton, A.L. (1959). *Right–Left Discrimination and Finger Localization: Development and Pathology*. Hoeber-Harper, New York, NY.

Bischoff-Grethe, A., Goedert, K. M., Willingham, D. T., & Grafton, S. T. (2004). Neural substrates of response-based sequence learning using fMRI. *Journal of Cognitive Neuroscience*, 16(1), 127-138.

Boraxbekk, C. J., Hagkvist, F., & Lindner, P. (2016). Motor and mental training in older people: transfer, interference, and associated functional neural responses. *Neuropsychologia*, 89, 371-377.

Brewer, W. F. (1966). A comparison of measures of finger recognition. *Proceedings of the Iowa Academy of Science,* 73, 318-321.

Cavanna, A.E. & Trimble, M.R. (2006). The precuneus: A review of its functional anatomy and behavioural correlates. *Brain,* 129, 564–583.

Chan, R.C.K., Huang, J., Di, X. (2009). Dexterous movement complexity and cerebellar activation: a meta-analysis. *Brain Research Reviews*, 59: 316-323.

Eickhoff S.B., Bzdok D., Laird A.R., Kurth F., Fox P.T. (2012). Activation likelihood estimation revisited. *Neuroimage,* 59, 2349-2361.

Eickhoff, S. B., Laird, A. R., Grefkes, C., Wang, L. E., Zilles, K., & Fox, P. T. (2009). Coordinate-based activation likelihood estimation meta-analysis of neuroimaging data: A random-effects approach based on empirical estimates of spatial uncertainty. *Human Brain Mapping*, 30(9), 2907-2926.

Eickhoff, S. B., Nichols, T. E., Laird, A. R., Hoffstaedter, F., Amunts, K., Fox, P. T., ... & Eickhoff, C. R. (2016). Behavior, sensitivity, and power of activation likelihood estimation characterized by massive empirical simulation. *Neuroimage*, 137, 70-85.

Fayol, M., Barrouillet, P., & Marinthe, C. (1998). Predicting arithmetical achievement from neuro-psychological performance: A longitudinal study. *Cognition, 68,* B63-B70.

Fox, P. T., & Lancaster, J. L. (2002). Mapping context and content: the BrainMap model. *Nature Reviews Neuroscience*, 3(4), 319.

Frith, C.D., Friston, K., Liddle, P.F., & Frackowiak, R.S.J. (1991). Willed action and the prefrontal cortex in man: a study with PET. *Proc. R. Soc. Lond. B*, 244, 241-246.

Gerstmann, J. (1940). Syndrome of finger agnosia, disorientation for right and left, agraphia, and acalculia. *Arch Neurol Psychiatry, 44*, 398-408.

Grafton, S. T., Hazeltine, E., & Ivry, R. B. (1998). Abstract and effector-specific representations of motor sequences identified with PET. *Journal of Neuroscience*, 18(22), 9420-9428.

Hanakawa, T., Honda, M., Sawamoto, N., Okada, T., Yonekura, Y., Fukuyama, H., & Shibasaki, H. (2002). The role of rostral Brodmann area 6 in mental-operation tasks: an integrative neuroimaging approach. *Cerebral Cortex*, 12(11), 1157-1170.

Harrington, D. L., Rao, S. M., Haaland, K. Y., Bobholz, J. A., Mayer, A. R., Binder, J. R., & Cox, R. W. (2000). Specialized neural systems underlying representations of sequential movements. *Journal of Cognitive Neuroscience*, 12(1), 56-77.

Isa, T., Ohki, Y, Alstermark, B., Petterson, L-G., Sasaki, S (2007). Direct and indirect cortico-motoneuronal pathways and control of hand/arm movements. *Physiology,* 22, 145–1537.

Iwamura, Y. (1998). Hierarchical somatosensory processing. *Current Opinion in Neurobiology*, 8:522-528.

Jack, A., Engander, Z. A., & Morris, J. P. (2011). Subcortical contributions to effective connectivity in brain networks supporting imitation. *Neuropsychologia*, 49(13), 3689-3698.

Kapreli, E., Athanasopoulos, S., Papathanasiou, M., Van Hecke, P., Kelekis, D., Peeters, R., ... & Sunaert, S. (2007). Lower limb sensorimotor network: issues of somatotopy and overlap. *Cortex*, 43(2), 219-232.

Kinsbourne, M. & Warrington, E.K. (1962). A study of finger agnosia. *Brain,* 85, 47–66.

Lafer-Sousa, R., Conway, B.R., & Kanwisher, N.G. (2016). Color-biased regions of the ventral visual pathway lie between face-and place-selective regions in humans, as in macaques. *J. Neuroscience,* 36, 1682–1697

Langner, R., Sternkopf, M. A., Kellermann, T. S., Grefkes, C., Kurth, F., Schneider, F., ... & Eickhoff, S. B. (2014). Translating working memory into action: Behavioral and neural evidence for using motor representations in encoding visuo-spatial sequences. *Human Brain Mapping*, 35(7), 3465-3484.

Levy, R. & Goldman-Rakic, P.S. (2000). Segregation of working memory functions within the dorsolateral prefrontal cortex. *Exp Brain Res*. 133, 23–32.

Noël, M.-P. (2005). Finger gnosia: A predictor of numerical abilities in children? *Child Neuropsychology, 11,* 413-430.

Penner-Wilger, M., & Anderson, M. L. (2008). An alternative view of the relation between finger gnosis and math ability: Redeployment of finger representations for the representation of number. *Proceedings of the 30th Annual Cognitive Science Society* (pp. 1647-1652). Austin, TX: Cognitive Science Society.

Penner-Wilger, M. & Anderson, M. L. (2013). The relation between finger gnosis and mathematical ability: Why redeployment of neural circuits best explains the finding. *Frontiers in Theoretical and Philosophical Psychology, 4,* 877.

Penner-Wilger, M., Fast, L., LeFevre, J., Smith-Chant, B. L., Skwarchuk, S., Kamawar, D., & Bisanz, J. (2007). The foundations of numeracy: Subitizing, finger gnosia, and fine-motor ability. In D. S. McNamara & J. G. Trafton (Eds.), *Proceedings of the 29th Annual Cognitive Science Society* (pp. 1385-1390). Austin, TX: Cognitive Science Society.

Penner-Wilger, M. & Waring, R. J., & Newton, A. T. (2014). Subitizing and finger gnosis predict calculation fluency in adults. In P. Bello, M. Guarini, M. McShane, & B. Scassellati (Eds.), *Proceedings of the 36th Annual Conference of the Cognitive Science Society* (pp. 1150-1155). Austin, TX: Cognitive Science Society.

Rusconi E, Gonzaga M, Adriani M, Braun C, Haggard P (2009) Know thy-self: behavioral evidence for a structural representation of the human body. *PLoS ONE* 4:e5418.

Rusconi, E., Tame, L., Furlan, M., Haggard, P., Demarchi, G., Adriani, M., ... & Schwarzbach, J. (2014). Neural correlates of finger gnosis. *Journal of Neuroscience*, 34(27), 9012-9023.

Sadato, N., Yonekura, Y., Waki, A., Yamada, H., & Ishii, Y. (1997). Role of the supplementary motor area and the right premotor cortex in the coordination of bimanual finger movements. *Journal of Neuroscience*, 17(24), 9667-9674.

Sokolowski, H. M., Fias, W., Mousa, A., & Ansari, D. (2017). Common and distinct brain regions in both parietal and frontal cortex support symbolic and nonsymbolic number processing in humans: A functional neuroimaging meta-analysis. *NeuroImage*, 146, 376-394.

Stewart, T. C., & Penner-Wilger, M. (2017). Analysis of a common neural component for finger gnosis and magnitude comparison. *Proceedings of the 15th Annual Meeting of the International Conference on Cognitive Modelling.*

Stewart, T. C., Penner-Wilger, M., Waring, R. J., & Anderson, M. L. (2017). A common neural component for finger gnosis and magnitude comparison. In G. Gunzelmann, A. Howes, T. Tenbrink, & E. J. Davelaar (Eds.), *Proceedings of the 39th Annual Conference of the Cognitive Science Society* (pp. 1150–1155). Austin, TX: Cognitive Science Society.

Tumati, S., Martens, S., de Jong, B.M., Aleman, A. (2019). Lateral parietal cortex in the generation of behavior: Implications for apathy. *Progress in Neurobiology,* 175: 20-34.

Turkeltaub, P. E., Eden, G. F., Jones, K. M., & Zeffiro, T. A. (2002). Meta-analysis of the functional neuroanatomy of single-word reading: method and validation. *NeuroImage*, 16(3), 765-780.

Turkeltaub, P. E., Eickhoff, S. B., Laird, A. R., Fox, M., Wiener, M., & Fox, P. (2012). Minimizing within experiment and within-group effects in activation likelihood estimation meta-analyses. *Human Brain Mapping*, 33(1), 1-13.

Walz, A. D., Doppl, K., Kaza, E., Roschka, S., Platz, T., & Lotze, M. (2015). Changes in cortical, cerebellar and basal ganglia representation after comprehensive long term unilateral hand motor training. *Behavioural Brain Research*, 278, 393-403.

Watanabe, R., Watanabe, S., Kuruma, H., Murakami, Y., Seno, A., & Matsuda, T. (2011). Neural activation during imitation of movements presented from four different perspectives: a functional magnetic resonance imaging study. *Neuroscience Letters*, 503(2), 100-104.