PostDoc Journal
Vol. 3, No. 11, November 2015

Journal of Postdoctoral Research
www.postdocjournal.com

Drawing the line – a cognitive or visual system for number extraction?

Matthias Witte, Ph.D.
Department of Psychology, University of Graz, Graz, 8010, Austria
Email: matthias.witte@uni-graz.at

Abstract

One of the most influencing theories in numerical cognition proposes a specialized cognitive system for extracting number out of visual displays. This system has been suggested to map number onto a mental representation of space, the mental number line. While initially number extraction was said to occur independent of visual features, recent evidences challenge this view. After introducing the basics of numerical cognition, the current article will briefly outline this ongoing dispute based on literature coming from the line bisection task. Finally, directions for future research are proposed.

Keywords: approximate number system, line bisection, numerical cognition

Numerical cognition

Since the ancient Greeks, a tight linkage between numbers and space has been assumed. This linkage has driven mathematics as for example reflected in Cartesian coordinate system. Besides formal mathematics, we also see behavioral evidence for a number-space mapping. The spatial-numerical association of response codes (SNARC) effect (Dehaene et al. 1993) is probably the most known example here. Responses to smaller numbers are quicker when they are presented in spaces on the left side, while for larger numbers the right side results in faster responses.

This mapping between number and space has led to the concept of a mental number line (Dehaene 2001; Hubbard et al. 2005): Western cultures seem to automatically follow a left-to-right orientation of increasing numbers. The underlying processes are assumed automatic and behavioral effects can be observed even when numerical magnitude is not task relevant: The original experiment showing the SNARC effect simply asked participants to judge whether a number is even or odd.

Recent findings reported on the existence of a mental number line in newborn chicks (Rugani et al. 2015). This supports one of the main theories in numerical cognition that postulates a non-verbal approximate number system (Barth et al. 2003; Halberda and Feigenson 2008; Dehaene and Cohen 1997; Dehaene et al. 1993). In this cognitive system, numbers are approximated as numerosities, i.e. a continuous mental representation of magnitude (Cantlon et al. 2009). In this way, a quick estimation or comparison of number is achieved. The approximate number system therefore builds the basis for arithmetic abilities from early life on (Barth et al. 2003; Halberda and Feigenson 2008; Dehaene 2009). It also allows us to extract non-symbolic number of objects out of visual scenes. The ability to quantify such sets of items is highly relevant in natural settings. In fact, we often have to separate smaller from larger magnitudes instead of identifying the precise number. In summary, there is evidence for a fast and automatic number sense that makes use of a tight coupling between number and space.

The line bisection task

One of the best described clinical scenarios of deficits in number-space interactions is seen in hemispatial neglect (for a review see Jewell and McCourt 2000). Patients suffer from damage to (usually right) parietal cortices and consequently tend to ignore the contralesional (left) hemispace. The classical test to study this neglect is the line bisection task where the midpoint of a physical line has to be indicated (Albert 1973; Driver and Vuilleumier 2001). Patients with left neglect bisect lines markedly to the right of the true midpoint. Interestingly, when asked to tell the midpoint of a number interval they also tend to respond with numbers to the right, i.e. numbers that are too large (Zorzi et al. 2002). This finding again suggested the spatial characteristics of the mental number line.

When using line bisection tasks in healthy subjects, one can also observe misjudgments of the true midpoint (Bowers and Heilman 1980). This time the bisection bias is to the left and is referred to as pseudoneglect. Moreover, the bias in bisecting a physical line is positively correlated with the same task using a mental number interval (Longo and Lourenco 2007). This number-space interaction is also evident for strings of Arabic digits instead of a line: Fisher (2001) showed a leftwards bias for strings of small numbers like 2222222, while a rightwards bias can be seen for larger numbers (e.g. 8888888). The overall proposed explanation for the effects described so far is that spatial attention influences bisection performance.

Manipulating spatial attention has been used to further explore the nature of (pseudo-)neglect. The idea is to present cues at both ends of the line, so called flankers, which may modulate the observed bisection bias. Numerous studies have shown a systematic bias towards flankers signaling larger magnitude when using Arabic digits (de Hevia et al. 2008; de Hevia and Spelke 2009; Fischer 2001; Stöttinger et al. 2012), non-symbolic numerical cues like dot arrays (de Hevia and Spelke 2009; Gebuis and Reynvoet 2011, 2012b) or number words (Calabria and Rossetti 2005). Thus, representations of task irrelevant numerical magnitude are believed to overlap with representations of line length resulting in an overall estimate of magnitude (de Hevia and Spelke 2009).

An ongoing dispute

Over the last years, several studies have explored line bisection using non-symbolic flankers. This approach usually applied arrays of dots ranging from 1 dot to 9 dots. Because no cognitive resources related to language or digit processing are needed, this design is believed to reveal the very basic number-space interactions of the approximate number system. The predominant theory suggests that extracting numerosity should be independent of the visual properties of the flankers. Instead, the numerical disparity of flankers has been said to result in a cognitive illusion of line length (de Hevia and Spelke 2009; de Hevia et al. 2006; de Hevia et al. 2008; Stöttinger et al. 2012): The flanker with larger numerosity induces a relative lengthening of this hemispace. Another explanation proposed that the mental number line is logarithmic and thus a compression of the larger numerosity and its hemispace takes place (Longo and Lourenco 2007; Dehaene and Mehler 1992; Dehaene 2003).

One issue in these theoretical considerations is whether the experimental procedures controlled for potential influences of factors other than numerical cues. A meta-analysis, for example, revealed age, sex, handedness and scanning direction as moderator variables (Jewell and McCourt 2000). Besides these factors, the

features of the visual display themselves have been controversially discussed. De Hevia and Spelke (2009) showed that pseudoneglect can be seen in preschool children as young as five years. As the bias was in the same direction as in adults, they suggested a non-directional spontaneous mapping present before any education in formal mathematics. Most important, the authors found no influence of contour, surface or distance of the flanking dots on performance. It was concluded that visual properties did not influence line bisection.
Gebuis and Gevers (2011) questioned these conclusions as they argued that only a very small subset of visual cues had been considered. When controlling for the area subtended by the flankers, they observed a bias towards larger area instead of larger numerosity. Consequently, a weighing process of all the different visual features was suggested to finally result in an estimate of numerosity. This is well in line with other models proposing an intermediate step in number extraction for non-symbolic cues (Sophian and Chu 2008).

In a reply to Gebuis, de Hevia (2011) objected that the speeded visuo-spatial task design of line bisection may have prevented extraction of numerical information. Instead, non-numerical cues could have overridden number. The authors did not deny an influence of visual cues but reviewed a consistent effect of number itself in the literature (Burr and Ross 2008; Brannon 2006; Cantlon and Brannon 2007; de Hevia et al. 2006; Xu and Spelke 2000). Against this argument, a recent study corroborated a primary role of stimuli area in line bisection tasks (Cleland and Bull 2015). Importantly, this work replicated the bias to larger area (but smaller number) across different ranges and ratios of non-symbolic items and in cases where the flankers showed equal numbers. However, it is impossible to control for all visual properties of stimuli and thus number and visual information on magnitude are always confound to some extend (Gebuis and Reynvoet 2012a, 2013, 2014). For non-symbolic number in natural settings this notion is intuitively valid: Larger number usually goes along with larger size, contour or area of items. The common ground, considering both sides of this research dispute, is that numerical and non-numerical information of magnitude are closely linked.

A new agenda emerging in numerical cognition

The term “number sense” illustrates the proposed link and several findings are of interest to this definition. First, perception of numerosity is susceptible to adaptation (Arrighi et al. 2014; Burr and Ross 2008). When participants adapted to a large number of dots, subsequent number extraction underestimated the magnitude information (Burr & Ross 2008). Moreover, Arrighi and colleagues (2014) reported that serially presented flashes and tones affected the perceived numerosity. Even more, they found robust cross-modal (auditory-visual) and cross-format (sequential-simultaneous display) effects and concluded that a common representation of numerosity integrates information across time and space. The second line of support comes from findings of a topographic “numerosity map” in parietal cortex (Harvey et al. 2013): neurons were tuned to preferred numerosity in a spatially ordered way indicating a higher-order association map. Yet, also in this study the strength of tuning was not insensitive to stimulus properties like circumference of the dots. One and the same neuron could therefore encode visual properties, number or a mixture of both.

To better assess this presumed continuum of responses in neural populations, I suggest transferring methodological approaches from other disciplines. The majority of studies in line bisection have relied on paper-and-pencil tasks. Besides some inaccuracy in evaluating the marked midpoint, those experiments could not explore the sensorimotor processes that led to the final output (i.e. marking the midpoint). From mouse-tracking research, however, we know that movement trajectories can reveal potential conflicts between competing mental representations (Faulkenberry 2014; Scherbaum et al. 2010; Spivey et al. 2005). For example, Faulkenberry (2014) showed continuous movement deflections to the wrong visual target in a numerical parity task. Computerized bisection tasks have already been used in healthy and diseased participants (Ozel-Kizil et al. 2012; Rolfe et al. 2008; Mendez et al. 1997; Benwell et al. 2014), although only the endpoint of movement has been analyzed. This is surprising given that Benwell (2014), for example, explored the timeline of early electroencephalographic activations in the ventral attention network. Tracking neural responses along with movement trajectories should give more insights into the processes driving the bias in line bisection.

A first step in this direction has already been realized in my laboratory: movement trajectories during computerized line bisection revealed that the bias appears during early periods of the movement and persists in a robust way throughout the remaining path (Haslbeck et al. 2015). This finding argues against higher-order cognitive processing, which would be expected to result in effects later on in time. Instead, it supports recent ideas that numerosity estimates emerge out of the visual properties of stimuli. Future studies will have to explore the details of this time-resolved processing which may contribute to resolve the current issues in numerical cognition.

References

Albert, Martin L. (1973): A simple test of visual neglect. *Neurology* 23 (6):658–664.

Arrighi, Roberto; Togoli, Irene; Burr, David C. (2014): A generalized sense of number. *Proceedings. Biological sciences / The Royal Society* 281 (1797).
DOI: 10.1098/rspb.2014.1791.

Barth, Hilary; Kanwisher, Nancy; Spelke, Elizabeth (2003): The construction of large number representations in adults. *Cognition* 86 (3):201–221.
DOI: 10.1016/S0010-0277(02)00178-6.

Benwell, Christopher S; Harvey, Monika; Thut, Gregor (2014): On the neural origin of pseudoneglect: EEG-correlates of shifts in line bisection performance with manipulation of line length. *NeuroImage* 86:370–380.
DOI: 10.1016/j.neuroimage.2013.10.014.

Bowers, Dawn; Heilman, Kenneth M. (1980): Pseudoneglect: Effects of hemispace on a tactile line bisection task. *Neuropsychologia* 18 (4-5):491–498.
DOI: 10.1016/0028-3932(80)90151-7.

Brannon, Elizabeth M. (2006): The representation of numerical magnitude. *Current Opinion in Neurobiology* 16 (2):222–229.
DOI: 10.1016/j.conb.2006.03.002.

Burr, David; Ross, John (2008): A visual sense of number. *Current biology* 18 (6):425–428.
DOI: 10.1016/j.cub.2008.02.052.

Calabria, Marco; Rossetti, Yves (2005): Interference between number processing and line bisection: a methodology. *Neuropsychologia* 43 (5):779–783.
DOI: 10.1016/j.neuropsychologia.2004.06.027.

Cantlon, Jessica F.; Brannon, Elizabeth M. (2007): How much does number matter to a monkey (Macaca mulatta)? *Journal of Experimental Psychology: Animal Behavior Processes* 33 (1):32–41.
DOI: 10.1037/0097-7403.33.1.32.

Cantlon, Jessica F.; Platt, Michael L.; Brannon, Elizabeth M. (2009): Beyond the number domain.

Trends in cognitive sciences 13 (2):83–91.
DOI: 10.1016/j.tics.2008.11.007.

Cleland, Alexandra A.; Bull, Rebecca (2015): The role of numerical and non-numerical cues in nonsymbolic number processing: Evidence from the line bisection task. *Quarterly Journal of Experimental Psychology.*
DOI: 10.1080/17470218.2014.994537.

de Hevia, Maria Dolores (2011): Sensitivity to number: Reply to Gebuis and Gevers. *Cognition* 121 (2):253–255.
DOI: 10.1016/j.cognition.2011.04.002.

de Hevia, Maria Dolores; Girelli, Luisa; Bricolo, Emanuela; Vallar, Giuseppe (2008): The representational space of numerical magnitude: Illusions of length. *Quarterly Journal of Experimental Psychology* 61 (10):1496–1514.
DOI: 10.1080/17470210701560674.

de Hevia, Maria Dolores; Girelli, Luisa; Vallar, Giuseppe (2006): Numbers and space: A cognitive illusion? *Experimental Brain Research* 168 (1-2):254–264.
DOI: 10.1007/s00221-005-0084-0.

de Hevia, Maria Dolores; Spelke, Elizabeth S. (2009): Spontaneous mapping of number and space in adults and young children. *Cognition* 110 (2):198–207.
DOI: 10.1016/j.cognition.2008.11.003.

Dehaene, Stanislas; Cohen, Laurent (1997): Cerebral pathways for calculation: double dissociation between rote verbal and quantitative knowledge of arithmetic. *Cortex* 33 (2):219–250.

Dehaene, Stanislas (2001): Précis of the number sense. *Mind and Language* 16 (1):16–36.

Dehaene, Stanislas (2003): The neural basis of the Weber-Fechner law: a logarithmic mental number line. *Trends in cognitive sciences* 7 (4):145–147.

Dehaene, Stanislas (2009): Origins of mathematical intuitions: The case of arithmetic. Annals of the New York Academy of Sciences, 1156:232–259.

Dehaene, Stanislas; Bossini, Serge; Giraux, Pascal (1993): The Mental Representation of Parity and Number Magnitude. *Journal of Experimental Psychology: General* 122 (3):371–396.

Dehaene, Stanislas; Mehler, Jacques (1992): Cross-linguistic regularities in the frequency of number words. *Cognition* 43 (1):1–29.
DOI: 10.1016/0010-0277(92)90030-L.

Driver, Jon; Vuilleumier, Patrik (2001): Perceptual awareness and its loss in unilateral neglect and extinction. *Cognition* 79 (1-2):39–88.
DOI: 10.1016/S0010-0277(00)00124-4.

Faulkenberry, Thomas J. (2014): Hand movements reflect competitive processing in numerical cognition. *Canadian journal of experimental psychology* 68 (3) :147–151.
DOI: 10.1037/cep0000021.

Fischer, Martin H. (2001): Number processing induces spatial performance biases. *Neurology* 57 (5):822–826.

Gebuis, Titia; Gevers, Wim (2011): Numerosities and space; indeed a cognitive illusion! A reply to de Hevia and Spelke (2009). *Cognition* 121 (2):248–252.
DOI: 10.1016/j.cognition.2010.09.008.

Gebuis, Titia; Reynvoet, Bert (2011): Generating nonsymbolic number stimuli. *Behavior Research*

Methods 43 (4):981–986.
DOI: 10.3758/s13428-011-0097-5.

Gebuis, Titia; Reynvoet, Bert (2012a): Continuous visual properties explain neural responses to nonsymbolic number. *Psychophysiology* 49 (11):1481–1491.

Gebuis, Titia; Reynvoet, Bert (2012b): The interplay between nonsymbolic number and its continuous visual properties. *Journal of Experimental Psychology* 141 (4):642–648.
DOI: 10.1037/a0026218.

Gebuis, Titia; Reynvoet, Bert (2013): The neural mechanisms underlying passive and active processing of numerosity. *NeuroImage* 70:301–307.
DOI: 10.1016/j.neuroimage.2012.12.048.

Gebuis, Titia; Reynvoet, Bert (2014): The neural mechanism underlying ordinal numerosity processing. *Journal of cognitive neuroscience* 26 (5):1013–1020.
DOI: 10.1162/jocn_a_00541.

Halberda, Justin; Feigenson, Lisa (2008): Developmental change in the acuity of the "Number Sense": The Approximate Number System in 3-, 4-, 5-, and 6-year-olds and adults. *Developmental psychology* 44 (5):1457–1465. DOI: 10.1037/a0012682.

Harvey, B. M.; Klein, B. P.; Petridou, N.; Dumoulin, S. O. (2013): Topographic representation of numerosity in the human parietal cortex. *Science* 341 (6150):1123–1126. DOI: 10.1126/science.1239052.

Haslbeck, Jonas M.B.; Wood, Guilherme; Witte, Matthias (2015): Temporal dynamics of number-space interaction in line bisection: Comment on Cleland and Bull (2015). *Quarterly journal of experimental psychology.*
DOI: 10.1080/17470218.2015.1095773.

Hubbard, Edward M.; Piazza, Manuela; Pinel, Philippe; Dehaene, Stanislas (2005): Interactions between number and space in parietal cortex. *Nature Reviews Neuroscience* 6 (6):435–448. DOI: 10.1038/nrn1684.

Jewell, George; McCourt, Mark E. (2000): Pseudoneglect: A review and meta-analysis of performance factors in line bisection tasks. *Neuropsychologia* 38 (1):93–110.
DOI: 10.1016/S0028-3932(99)00045-7.

Longo, Matthew R.; Lourenco, Stella F. (2007): Spatial attention and the mental number line: evidence for characteristic biases and compression. *Neuropsychologia* 45 (7):1400–1407.
DOI: 10.1016/j.neuropsychologia.2006.11.002.

Mendez, Mario F.; Cherrier, Monique M.; Cymerman, Judy S. (1997): Hemispatial neglect on visual search tasks in Alzheimer's disease. *Neuropsychiatry, neuropsychology, and behavioral neurology* 10 (3):203–208.

Ozel-Kizil, Erguvan Tugba; Baskak, Bora; Gunes, Emel; Cicek, Metehan; Atbasoglu, Esref Cem (2012): Hemispatial neglect evaluated by visual line bisection task in schizophrenic patients and their unaffected siblings. *Psychiatry Research* 200 (2-3):133–136.
DOI: 10.1016/j.psychres.2012.04.025.

Rolfe, Mei H; Hamm, Jeff P.; Waldie, Karen E. (2008): Differences in paper-and-pencil versus computerized line bisection according to ADHD subtype and hand-use. *Brain and Cognition* 66 (2):188-195.
DOI: 10.1016/j.bandc.2007.07.007.

Rugani, Rosa; Vallortigara, Giorgio; Priftis, Konstantinos; Regolin, Lucia (2015): Animal cognition. Number-space mapping in the newborn chick resembles humans' mental number line. *Science* 347 (6221):534–536. DOI: 10.1126/science.aaa1379.

Scherbaum, Stefan; Dshemuchadse, Maja; Fischer, Rico; Goschke, Thomas (2010): How decisions evolve: The temporal dynamics of action selection. *Cognition* 115 (3):407–416DOI: 10.1016/j.cognition.2010.02.004.

Sophian, Catherine; Chu, Yun (2008): How do people apprehend large numerosities? *Cognition* 107 (2):460–478.
DOI: 10.1016/j.cognition.2007.10.009. Spivey, Michael J.; Grosjean, Marc; Knoblich, Günther (2005): Continuous attraction toward phonological competitors. *Proceedings of the National Academy of Sciences of the United States of America* 102 (29):10393–10398. DOI: 10.1073/pnas.0503903102.

Stöttinger, Elisabeth; Anderson, Britt; Danckert, James; Frühholz, Barbara; Wood, Guilherme (2012): Spatial biases in number line bisection tasks are due to a cognitive illusion of length. *Experimental Brain Research* 220 (2):147–152. DOI: 10.1007/s00221-012-3125-5.

Xu, Fei; Spelke, Elizabeth S. (2000): Large number discrimination in 6-month-old infants. *Cognition* 74 (1):B1-B11.
DOI: 10.1016/S0010-0277(99)00066-9.

Zorzi, Marco; Priftis, Konstantinos; Umiltà, Carlo (2002): Brain damage: neglect disrupts the mental number line. *Nature* 417 (6885):138–139. DOI: 10.1038/417138a.