The Neuroscientist
http://nro.sagepub.com/

Exceptional Abilities in the Spatial Representation of Numbers and Time: Insights from Synesthesia

Roi Cohen Kadosh, Limor Gertner and Devin Blair Terhune

Neuroscientist 2012 18: 208 originally published online 12 May 2011
DOI: 10.1177/1073858411402835

The Neuroscientist
18(3) 208–215

DOI: 10.1177/1073858411402835
http://nro.sagepub.com
SAGE

Exceptional Abilities in the Spatial Representation of Numbers and Time: Insights from Synesthesia

Roi Cohen Kadosh[1], Limor Gertner[2], and Devin Blair Terhune[3]

Abstract

In the study of basic and high-level cognitive functions, neuroscientists, psychologists, and philosophers have tended to focus on normal psychological processes and on deficits in these processes, whereas the study of exceptional abilities has been largely neglected. Here the authors emphasize the value of researching exceptional abilities. They make the case that studies of exceptional representations, such as of time, number, and space in synesthesia, can provide us with insights regarding the nature of the neurocognitive mechanisms of these dimensions, as well as their developmental, evolutionary, and cultural origins.

Keywords

synesthesia, exceptional abilities, development, evolution, neuronal specialization, cognitive cost

Studies on psychological processes such as perception, emotion, cognition, and action have provided considerable understanding of these faculties in the average human, whereas neuropsychological research has focused on acquired and congenital deficits in humans and lesion studies in animals. In contrast, relatively little attention has been devoted to the mechanisms underlying the exceptional expression of human abilities, such as superior mathematical or language abilities. In this article, we focus on such enhanced abilities. We attempt to demonstrate how the study of enhanced abilities can advance our knowledge about psychological processes and brain function and organization, using the examples of time, number, and space. By providing a window onto a wider spectrum of human abilities, such research will allow us to examine questions pertaining to cognitive and neural processes in a more comprehensive fashion that moves away from a categorical design (impaired abilities in function $X <$ normal abilities in function X) toward a parametric modulation (low abilities in function $X <$ average abilities in function $X <$ high abilities in function X) and, in turn, provide a finer understanding and characterization of human abilities.

We start by introducing the phenomena of explicit visualization of time and/or number in space (henceforth, TNS synesthesia), a neurological condition with a genetic basis that leads to an overbinding of different features (Asher and others 2009). This is followed by an overview of its cognitive and neural mechanisms, together with the gains and costs of such exceptional experiences. We conclude by discussing why this exceptional binding occurs and suggest plausible developmental and evolutionary origins at the brain level.

TNS Synesthesia

Do you see numbers vividly in certain locations in space? For example, do you see the numbers 1 to 10 running from the right to the left and then exhibiting an upward 30° trajectory? Do you disagree with this description because you see numbers in another shape? Perhaps you can see instead numbers, different units of time, such as hours, days of the week, months, or even years in a specific spatial location (Figure 1)? If yes, you are probably one out of approximately five people who possesses a distinct condition in which numerical sequences are represented as spatial arrays (Mann and others 2009; Sagiv and others 2006),

[1]Department of Experimental Psychology and the Centre for Functional Magnetic Resonance Imaging of the Brain, University of Oxford, Oxford, England
[2]Department of Psychology and Zlotowski Center for Neuroscience, Ben-Gurion University of the Negev, Beer-Sheva, Israel
[3]Department of Experimental Psychology, University of Oxford, Oxford, England

Corresponding Author:
Roi Cohen Kadosh, Department of Experimental Psychology, University of Oxford, Tinbergen Building, South Parks Road, Oxford, OX1 3UD
Email: roi.cohenkadosh@psy.ox.ac.uk

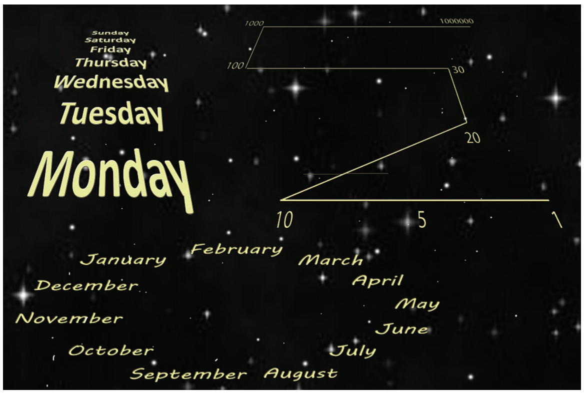

Figure 1. An example of three-dimensional representations of time units (months, days of the week) and numbers in mental space, as depicted by different time, number, and space (TNS) synesthetes. Modified from Cohen Kadosh and Gertner, 2011, with permission from Elsevier.

an ability that is implicit in the average population (Bueti and Walsh 2009; Cantlon and others 2009; Walsh 2003). This phenomenon of overbinding different features is termed *synesthesia* (Box 1). Recently, a number of studies have investigated TNS synesthesia (e.g., Eagleman 2009; Gertner and others 2009; Hubbard 2009; Mann and others 2009; Piazza and others 2006; Price 2009; Price and Mentzoni 2008; Sagiv and others 2006; Simner 2009; Simner and others 2009; Smilek and others 2007; Tang and others 2008). These studies provide important insights into the ways that time, number, and space are represented by TNS synesthetes and nonsynesthetes.

Box 1. Synesthesia

Synesthesia is not restricted to TNS and is present for a wide variety of psychological processes (e.g., listening to music, seeing a grapheme) that automatically trigger ancillary, exceptional experiences (e.g., color, taste, smells, pain) in the absence of any direct stimulation pertaining to the secondary experience (Cohen Kadosh and Henik 2007; Cytowic and Eagleman 2009; Hochel and Milan 2008; Hubbard and Ramachandran 2005; Rich and Mattingley 2002; Robertson 2003; Robertson and Sagiv 2004; Ward and Mattingley 2006). For example, for some people who see digits in colors (termed digit-color synesthesia), an achromatic 7 will appear in a distinct color such as turquoise (Cohen Kadosh, Cohen Kadosh, and Henik 2007).

Reports on TNS synesthesia already had appeared at the end of the 19th century by scholars such as Galton (1880a, 1880b) and Flournoy (1893). These studies were based on introspection and, together with the

(continued)

Box 1. (continued)

idiosyncrasy of synesthesia (but see Cohen Kadosh, Henik, and Walsh 2007; Rich and others 2005; Simner and others 2005; Ward and others 2006), stimulated little scientific interest. With the recent adoption of behavioral research methods together with rigorous neuroscientific techniques, synesthesia research has gained a greater empirical footing and undergone a revival in the past 15 years. Nevertheless, the study of synesthesia has been biased toward specific types of synesthesia, such as sound-color or grapheme-color synesthesia (Hochel and Milan 2008; Hubbard and Ramachandran 2005; Rich and Mattingley 2002; Robertson 2003; Ward and Mattingley 2006), a trend that has been somewhat reversed in the recent years with a multitude of studies published on TNS synesthesia (e.g., Eagleman 2009; Gertner and others 2009; Hubbard 2009; Mann and others 2009; Piazza and others 2006; Price 2009; Price and Mentzoni 2008; Sagiv and others 2006; Simner 2009; Simner and others 2009; Smilek and others 2007; Tang and others 2008; for an exception, see Seron and others 1992).

Cognitive Processes of Time, Number, and Space

Can synesthesia inform cognitive processes and neural mechanisms in nonsynesthetes? Many studies have answered this question positively by showing that the synesthetic experience is quantitatively, rather than qualitatively, different from that of nonsynesthetes. That is, the processes underlying synesthesia appear to be present in all people to varying extents, albeit at a different level of awareness (Cohen Kadosh and Henik 2007), but may result from different factors in synesthetes such as the magnitude of cortical inhibition and/or white matter brain connectivity (Bargary and Mitchell 2008; Cohen Kadosh and Walsh 2008; Grossenbacher and Lovelace 2001; Rouw and Scholte 2007; Weiss and Fink 2009).

For example, there is a striking resemblance between the explicit representation of number and space in TNS synesthetes and their implicit representation in nonsynesthetes. Studies from different countries and educational systems have shown that between 62% and 66% of TNS synesthetes report representing small numbers on the left side and large numbers on the right side (Eagleman 2009; Sagiv and others 2006; Seron and others 1992). This prevalence is similar to the percentage of nonsynesthetes (65%) who similarly represent numbers implicitly from left to right as the numbers increase, as indicated by the spatial-numerical association of response codes (SNARC) effect (Wood and others 2006). Yet, TNS synesthetes are singled out by their enhanced ability to consistently and automatically consciously associate time and/or numbers with space

(Eagleman 2009; Gertner and others 2009; Hubbard 2009; Mann and others 2009; Piazza and others 2006; Price 2009; Price and Mentzoni 2008; Sagiv and others 2006; Seron and others 1992; Simner 2009; Simner and others 2009; Smilek and others 2007; Tang and others 2008).

But what advantage, if any, would be carried by an enhanced ability to represent time, number, and space explicitly? This question can provide us with insights into the functionality of the interaction between these dimensions in nonsynesthetes. Recent studies indicate that there are clear benefits from an explicit representation of these dimensions. For example, it has been revealed that people with time-space synesthesia have enhanced abilities in tasks that relate to time (e.g., month sequences) or space (e.g., mental rotation) (Mann and others 2009; Simner and others 2009). Critically, these synesthetes did not show enhanced abilities in tasks that were unrelated to their synesthesia (e.g., reading) (Simner and others 2009). Another study has shown that when time-space synesthetes are asked to learn a new time-space arrangement, their performance is superior to nonsynesthetes (Brang and others 2010).

Other studies have observed the costs that accompany these cognitive advantages. For example, TNS synesthetes use less flexible strategies to solve a given task if it is not commensurate with their explicit representation. The performance of month-space synesthetes is better when the external stimuli are consistent with their month-space perception. Namely, synesthetes who visualize early months on the left and late months on the right were faster to make left-hand responses to the former and right-hand responses to the latter than vice versa, whereas synesthetes who represent early months on the right and late months on the left showed the opposite pattern (Price and Mentzoni 2008; Smilek and others 2007). Similarly, number-space synesthetes respond slower when asked to compare the quantity of two numbers when the spatial relationship between the presented numbers is incongruent with their representation compared to congruent presentation of the numbers (Gertner and others 2009; Hubbard 2009; Piazza and others 2006; Sagiv and others 2006). For example, a TNS synesthete, S.M., represents numbers in ascending order from bottom to top. She was slower when comparing the magnitude of a pair of digits that were presented in descending relative to ascending order on a computer monitor (Gertner and others 2009). In addition, although their general arithmetic abilities seem to be intact, number-space synesthetes display rigidity that leads to underperformance when the most efficient way to solve an arithmetic problem requires a strategy that is not based on a visuospatial process (Ward and others 2009) (e.g., small multiplication problems such as 3×3, which are based on rote retrieval, rather than visuospatial abilities, as in the case of subtraction problems; Dehaene and others 2004). These studies illustrate how, despite TNS synesthetes' enhanced experience of time, number, and space, this tangible vivid representation can carry not only some advantages but also some costs (see also Box 2).

Box 2. The Cost of Exceptional Abilities

Autism is a neurodevelopmental disorder characterized by three major symptoms: impairment in communication, deficits in social interactions, and repetitive behavior. Yet, about 10% of those with autism also display remarkably superior skills, known as savant skills (Happe 1999). A person with autism, who may be intellectually disabled in many cognitive and social aspects, may possess an exceptional memory for dates, outstanding mathematical ability, or extraordinary talent for music (Snyder 2001).

Recently, a delicate genetic link between synesthesia and savant autism was suggested (Asher and others 2009; Baron-Cohen and others 2007; Bor and others 2007; Parker and others 2006; Simner and others 2009). Similarities between the conditions are that both display superior performance in a very specific domain (Simner and others 2009; Snyder 2001) and that autism involves perceptual abnormalities that might involve synesthetic-like experiences (Baron-Cohen and others 2007; Bor and others 2007).

It has been suggested that the level of coherence in processing the world might account for the deficits and assets that savant autistics show, both in experimental tasks and daily life. Specifically, people from the autistic spectrum have a superior ability to attend to local elements while easily ignoring the whole (Happe 1999), whereas nonautistic individuals present a preference for holistic processing or no preference at all (Kimchi 1992).

What might be the preferential level of processing for TNS synesthetes? Is it reasonable to assume that because TNS synesthetes are able to spatially represent very detailed images of time and numbers, they might also be, to some extent, detail biased like people with autism? Recent studies seem to provide a positive answer. TNS synesthetes who performed a numerical Navon task (Navon 1977)—that is, identifying a large digit (global) composed of small digits (local) and vice versa—were faster at identifying a digit at the local level and were less distracted by interference from the global level compared to controls, who showed no preference for either processing level (L. Gertner, S. Naparstek, and A. Henik unpublished).

These results are in line with a recent study of D.T., a man with Asperger syndrome (i.e., a subtype of the

(continued)

Box 2. (continued)

autistic spectrum), who has a savant memory for numbers and exceptional skill for mathematical calculations. In addition, he also has a form of synesthesia in which he experiences numbers in specific shapes, colors, and textures (Bor and others 2007).

In conclusion, the ability to focus on local details might be a common denominator of both savant autistics and TNS synesthetes. This propensity might serve as a platform through which we can learn more about these two types of exceptional abilities, their relation to each other, and the benefits and costs of cognitive and perceptual enhancements.

Neural Processes of Time, Number, and Space

Previous studies that examined the neural bases of time, number, and space in healthy nonsynesthetic adults concur that the parietal lobes, particularly the intraparietal sulcus, play a crucial role in processing these dimensions, probably via overlapping neuronal populations that encode time, number, and space (Bueti and Walsh 2009; Cantlon and others 2009; Cohen Kadosh and others 2008; Walsh 2003). On the basis of these findings, one can predict that if TNS synesthetes' enhanced ability to spatially represent time and numbers is quantitatively different from nonsynesthetes, then the parietal lobes will also show local modulation of activations in these participants that differs from nonsynesthetes. A study on number-space synesthetes gave support to this idea by finding increased activation of the parietal lobes in synesthetes as compared to nonsynesthetes in an ordinal task with numbers (Tang and others 2008). Another study found that damage to the left inferior parietal lobe and the superior temporal lobe led to elimination of TNS synesthesia (Spalding and Zangwill 1950). In this case, A.L., a 24-year-old man who had several types of TNS synesthesia, was wounded as a metallic foreign body entered the left side of his brain. A.L. reported several difficulties, including the disappearance of his synesthetic experiences of number-space and time-space. In addition, he also exhibited severe acalculia that was not attributable to verbal deficits. Remarkably, his acalculia was different from the acalculic behavior that is exhibited by nonsynesthetic patients with similar damage (Lemer and others 2003; Willmes 2008), who tend to exhibit a dissociation between multiplication and subtraction. However, his acalculic performance is predictable if he and other TNS synesthetes calculate different arithmetic problems, including multiplication and subtraction, via their number-space forms. This is in line with recent findings that we described in the previous section (Ward and others 2009). These results indicate that the parietal lobe is both sufficient and necessary for TNS synesthesia. In the next section, we focus on plausible causes for the development of a TNS synesthetic experience.

Evolutionary and Developmental Neural Reuse as the Basis of TNS Synesthesia

Previous theories of synesthesia rooted its origin in excess connectivity between brain areas (Bargary and Mitchell 2008), probably due to a lack of pruning during infancy (Spector and Maurer 2009) or a lack of inhibition from other cortical areas (e.g., the prefrontal cortex; Cohen Kadosh and others 2009) to downstream brain areas (Grossenbacher and Lovelace 2001). Although these theories can explain some types of synesthesia such as grapheme-color, they might not be sufficient to explain TNS synesthesia, which appears to be based in the parietal lobe, a region responsible for encoding time, number, and space (Bueti and Walsh 2009; Cantlon and others 2009; Cohen Kadosh and others 2008; Walsh 2003). Evidence for the idea that TNS synesthesia is distinct from other synesthesias is garnered from a recent factor analysis of different forms of synesthesia, which found that TNS synesthesia was only weakly related to other forms (Eagleman 2010), as well as other studies demonstrating a notably higher prevalence of TNS (Eagleman 2010; Mann and others 2009) than other synesthesias in the general population (Simner and others 2006).

The solution as to the origin of TNS synesthesia might be rooted in neuronal reuse theories. In recent years, the idea of neuronal reuse has provided some important implications and insights into the function-structure of brain organization (Anderson 2010). For example, the massive redeployment hypothesis (Anderson 2007) and the neuronal recycling hypothesis (Dehaene and Cohen 2007) suggest that neuronal reuse constitutes a fundamental evolutionary (Anderson 2007) or developmental (Dehaene and Cohen 2007) strategy for realizing cognitive functions.

More specifically, the massive redeployment hypothesis suggests that brain areas that evolved initially for other functions reuse these existing structures during evolutionary development to acquire new capabilities (e.g., in this case, the understanding of numerical and time units; Anderson 2007). Similarly, the neuronal recycling hypothesis proposes that cognitive capacities that are culturally invented, such as the representation of numerical and time units, must be learned and that the brain structures that support these capacities must therefore be assigned and/or shaped during development.

As both representations of time and number are assumed to emerge phylogenically and onthogenically later than

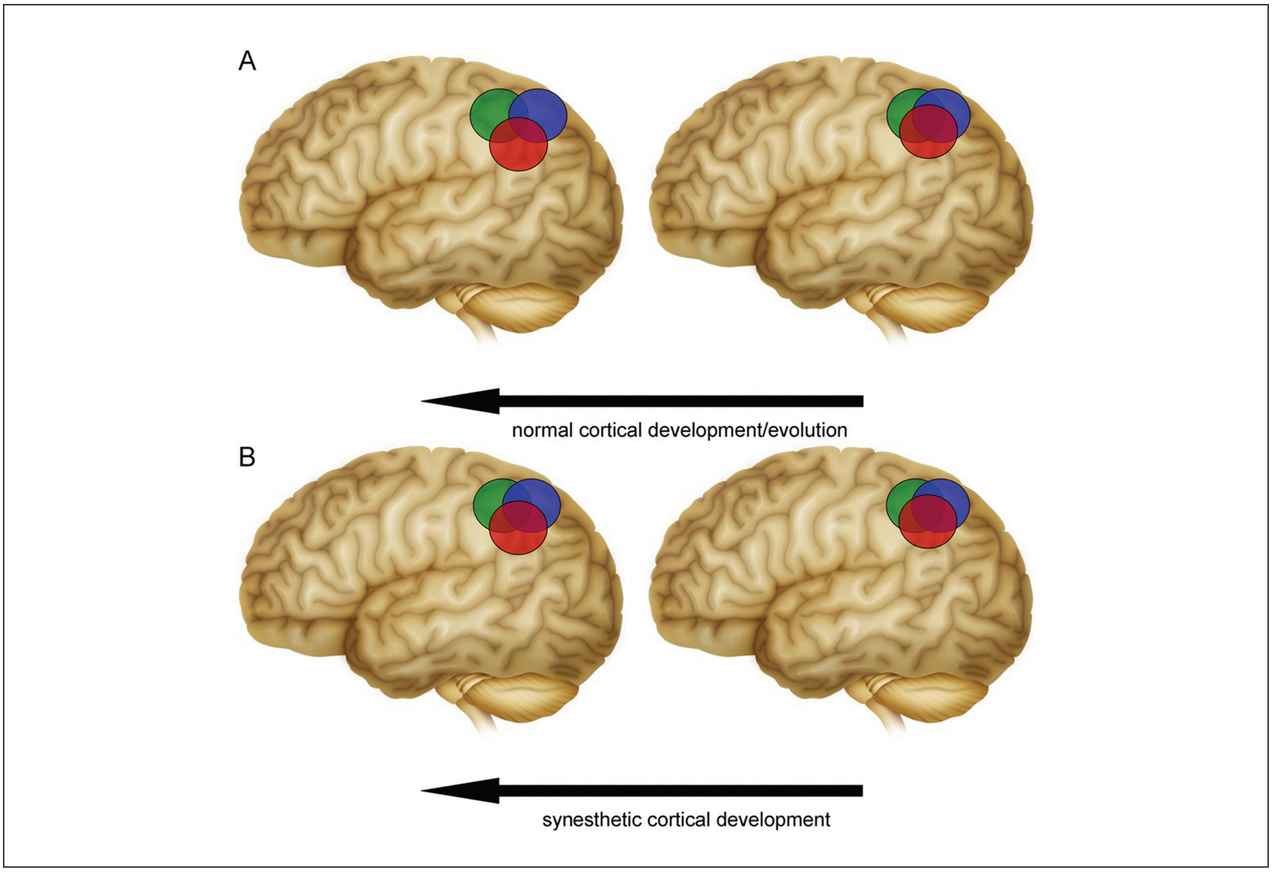

Figure 2. Evolutionary and developmental neural reuse as the basis of time, number, and space (TNS) synesthesia. The colors red, green, and blue represent the overlap between space, time, and number in the parietal lobe. The greater the overlap between these colors, the greater the overlap between these dimensions at the neural level. (*A*) In infants and animals, this overlap seems to be quite extensive. However, it seems to still exist but to a lesser degree in adults due to neural specialization (Bueti and Walsh 2009; Cantlon and others 2009; Cohen Kadosh and others 2008; Feigenson 2007; Nieder and others 2006; Walsh 2003). (*B*) In the case of synesthetes, it might be that this neural reuse/specialization does not exist or at least exists to a lesser degree, therefore leading to the strong coupling between these dimensions. The brain figure has been modified from Maurizio De Angelis, Wellcome Images.

spatial representations, they will be based on the same neuronal substrates that are dedicated to space. These regions, in turn, will slowly emerge to represent time and numbers. In this view, the origin of TNS synesthesia may result from a failure of the full implementation of this reuse. That is, the foundation of TNS synesthesia is based on a lack of neuronal specialization (to a certain degree) in the parietal lobes for processing number or time as opposed to space. Such a hypothesis can also explain why there is a strong relationship between number, time, and space in nonsynesthetes (Brang and others 2010; Bueti and Walsh 2009; Cantlon and others 2009; Cohen Kadosh and others 2008; Hubbard and others 2005; Walsh 2003). That is, these abilities are initially built on a common mechanism and specialize as a function of development. Moreover, in nonsynesthetes, there might still be some commonalities in the shape of neuronal populations that code time, number, and space indifferently, although to a lesser extent than in TNS synesthetes (Figure 2). This idea is supported by the behavioral and neuroimaging evidence discussed here and elsewhere (Brang and others 2010; Bueti and Walsh 2009; Cantlon and others 2009; Cohen Kadosh and others 2008; Hubbard and others 2005; Walsh 2003).

In addition, our hypothesis can explain why it is so rare (if not impossible) to find number-time synesthesia, as both are processing mechanisms acquired later in life and are evolutionarily younger. Moreover, it provides an account as to why only some stimulus types are more likely to trigger ancillary experiences, rather than the opposite; the directionality of most types of synesthesia, including TNS synesthesia, seems to be from "newer" functions (e.g., word) to "older" abilities (e.g., color perception). That is, representations in a newer domain are more likely to be mapped onto representations in an older domain, an idea that may account for the low prevalence of bidirectionality among synesthetes (Cohen Kadosh and Henik 2007). To conclude, we suggest here that TNS synesthesia might originate from a failure to reuse the neuronal substrates for space to acquire the representation of *accurate* number and time units. This demonstrates an ironic case of a superior/enhanced cognitive ability caused by a failure of the neural system.

Conclusions

We have described here an exceptional ability—to represent number and/or time in space. We suggest that a better grasp of this ability can enhance our understanding of the cognitive and neural processes underlying time, number, and space in the average human and in those with acquired or congenital deficits. We show how synesthesia provides a quantitative difference of implicitly occurring processes in nonsynesthetes. Future integration of scientific evidence of exceptional abilities with our knowledge of normal and impaired functioning will allow for a fuller characterization of time, number, and space, as well as many other cognitive functions. Moreover, a better understanding of the development of TNS synesthesia will yield insights into the phylogenic and onthogenic principles of brain organization for time, number, and space. Extending the research on synesthesia to other domains, such as research in anthropology, or on typical and atypical neurodevelopmental conditions (Boxes 2 and 3), can provide valuable information that will advance our knowledge of the connections between time, number, and space.

Box 3. Questions for Future Research

- Are there subtypes of TNS synesthesia? Previous studies have shown that TNS synesthesia might appear in conjunction with grapheme-color synesthesia (Sagiv and others 2006). Might it be that this type of synesthesia is based on the inferior temporal rather than the parietal lobe (Eagleman 2009)?
- Is TNS synesthesia influenced by the dominancy of number and time in Western culture? For example, will it appear in indigenous cultures in which number (Gordon 2004; Pica and others 2004) or time (Everett 2005) does not play a fundamental role in daily life?
- Is the prevalence of TNS synesthesia smaller in groups who suffer from developmental disabilities for processing numbers or space, such as developmental dyscalculia (Rubinsten and Henik 2009) and Williams syndrome (Karmiloff-Smith 2007)?

(continued)

Box 3. (continued)

- What is the connection between mental imagery and TNS (Price 2009)?
- Will the operational momentum effect, a bias toward larger presented outcome values for addition and smaller values for subtraction problems (Knops and others 2009; McCrink and others 2007; Pinhas and Fischer 2008), be modulated according to the direction of the synesthetic experience, and will it be stronger in TNS synesthetes as compared to nonsynesthetes?
- Is there some additional cost for having TNS synesthesia? For example, people with time-space synesthesia use less time-number mapping (e.g., May → 5) relative to nonsynesthetes to improve their performance in cognitive tasks (Mann and others 2009). Does this indicate that the processing of numbers will be less proficient (e.g., automaticity) in time-space synesthetes than in nonsynesthetes? Similarly, perhaps number-space synesthetes will show impairments in the encoding or processing of temporal information compared to nonsynesthetes.

Acknowledgments

We thank Ed Hubbard and Kathrin Cohen Kadosh for helpful comments.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interests with respect to the authorship and/or publication of this article.

Financial Disclosure/Funding

The author(s) disclosed receipt of the following financial support for the research and/or authorship of this article: RCK is supported by the Wellcome Trust (WT88378). DBT is supported by the Cogito Foundation.

References

Anderson ML. 2007. Evolution of cognitive function via redeployment of brain areas. Neuroscientist 13:13–21.

Anderson ML. 2010. Neural re-use as a fundamental organizational principle of the brain. Behav Brain Sci 33:245–313.

Asher JE, Lamb JA, Brocklebank D, Cazier JB, Maestrini E, Addis L, and others. 2009. A whole-genome scan and fine-mapping linkage study of auditory-visual synesthesia reveals evidence of linkage to chromosomes 2q24, 5q33, 6p12, and 12p12. Am J Hum Genet 84:279–85.

Bargary G, Mitchell KJ. 2008. Synaesthesia and cortical connectivity. Trends Neurosci 31:335–42.

Baron-Cohen S, Bor D, Billington J, Asher JE, Weelwright S, Ashwin C. 2007. Savant memory in a man with colour form-number synaesthesia and asperger syndrome. J Conscious Stud 14:237–51.

Bor D, Billington J, Baron-Cohen S. 2007. Savant memory for digits in a case of synaesthesia and Asperger syndrome is related to hyperactivity in the lateral prefrontal cortex. Neurocase 13:311–9.

Brang D, Teuscher U, Ramachandran VS, Coulson S. 2010. Temporal sequences, synesthetic mappings, and cultural biases: the geography of time. Conscious Cogn 19:311–20.

Bueti D, Walsh V. 2009. The parietal cortex and the representation of time, space, number and other magnitudes. Philos Trans R Soc B Biol Sci 364:2369–80.

Cantlon JF, Platt ML, Brannon EM. 2009. Beyond the number domain. Trends Cogn Sci 13:83–91.

Cohen Kadosh R, Cohen Kadosh K, Henik A. 2007. The neuronal correlate of bi-directional synaesthesia: a combined ERP and fMRI study. J Cogn Neurosci 19:2050–9.

Cohen Kadosh R, Henik A. 2007. Can synaesthesia research inform cognitive science? Trends Cogn Sci 11:177–84.

Cohen Kadosh R, Henik A, Catena A, Walsh V, Fuentes LJ. 2009. Induced cross-modal synesthetic experience without abnormal neuronal connections. Psychol Sci 20:258–65.

Cohen Kadosh R, Henik A, Walsh V. 2007. Small is bright and big is dark in synaesthesia. Curr Biol 17:R834–5.

Cohen Kadosh R, Gertner L. 2011. Synesthesia: Gluing together time, number, and space. In: Dehaene S, Brannon EM, editors. Space, time and number in the brain. Toronto: Elsevier. p. 123–132.

Cohen Kadosh R, Lammertyn J, Izard V. 2008. Are numbers special? An overview of chronometric, neuroimaging, developmental and comparative studies of magnitude representation. Prog Neurobiol 84:132–47.

Cohen Kadosh R, Walsh V. 2008. Synaesthesia and cortical connections: cause or correlation? Trends Neurosci 31:549–50.

Cytowic RC, Eagleman DM. 2009. Wednesday is indigo blue. Cambridge, MA: MIT Press.

Dehaene S, Cohen L. 2007. Cultural recycling of cortical maps. Neuron 56:384–98.

Dehaene S, Molko N, Cohen L, Wilson AJ. 2004. Arithmetic and the brain. Curr Opin Neurobiol 14:218–24.

Eagleman DM. 2009. The objectification of overlearned sequences: a new view of spatial sequence synesthesia. Cortex 45:1266–77.

Eagleman DM. 2010. What has large-scale analysis taught us? Paper presented at the 5th Meeting of the UK Synaesthesia Association; 27–28 March; Brighton, UK.

Everett DL. 2005. Cultural constraints on grammar and cognition in Pirahã: another look at the design features of human language. Curr Anthropol 46:621–46.

Feigenson L. 2007. The equality of quantity. Trends Cogn Sci 11:185–7.

Flournoy T. 1893. Des phénomènes de synopsie. Geneva, Switzerland: Charles Eggimann & Co.

Galton F. 1880a. Visualised numerals. Nature 21:494–95.

Galton F. 1880b. Visualised numerals. Nature 21:252–6.

Gertner L, Henik A, Cohen Kadosh R. 2009. When 9 is not on the right: implications from number-form synaesthesia. Conscious Cogn 18:366–74.

Gordon P. 2004. Numerical cognition without words: evidence from Amazonia. Science 306:496–9.

Grossenbacher PG, Lovelace CT. 2001. Mechanisms of synesthesia: cognitive and physiological constraints. Trends Cogn Sci 5:36–41.

Happe F. 1999. Autism: cognitive deficit or cognitive style? Trends Cogn Sci 3:216–22.

Hochel M, Milan EG. 2008. Synaesthesia: the existing state of affairs. Cogn Neuropsychol 28:93–117.

Hubbard EM. 2009. What information is critical to elicit interference in number-form synaesthesia? Cortex 45:1200–16.

Hubbard EM, Piazza M, Pinel P, Dehaene S. 2005. Interactions between number and space in parietal cortex. Nat Rev Neurosci 6:435–48.

Hubbard EM, Ramachandran VS. 2005. Neurocognitive mechanisms of synesthesia. Neuron 48:509–20.

Karmiloff-Smith A. 2007. Williams syndrome. Curr Biol 17: R1035–6.

Kimchi R. 1992. Primacy of wholistic processing and global/local paradigm: a critical review. Psychol Bull 112:24–38.

Knops A, Viarouge A, Dehaene S. 2009. Dynamic representations underlying symbolic and nonsymbolic calculation: evidence from the operational momentum effect. Atten Percept Psychophys 71:803–21.

Lemer C, Dehaene S, Spelke E, Cohen L. 2003. Approximate quantities and exact number words: dissociable systems. Neuropsychologia 41:1942–58.

Mann H, Korzenko J, Carriere JSA, Dixon MJ. 2009. Time-space synaesthesia: a cognitive advantage? Conscious Cogn 18:619–627.

McCrink K, Dehaene S, Dehaene-Lambertz G. 2007. Moving along the number line: operational momentum in nonsymbolic arithmetic. Percept Psychophys 69:1324–33.

Navon D. 1977. Forest before trees: the precedence of global features in visual perception. Cogn Psychol 9:353–85.

Nieder A, Diester I, Tudusciuc O. 2006. Temporal and spatial enumeration processes in the primate parietal cortex. Science 313:1431–5.

Parker ES, Cahill L, McGaugh JL. 2006. A case of unusual autobiographical remembering. Neurocase 12:35–49.

Piazza M, Pinel P, Dehaene S. 2006. Objective correlates of an unusual subjective experience: a single-case study of number-form synaesthesia. Cogn Neuropsychol 23:1162–73.

Pica P, Lemer C, Izard V, Dehaene S. 2004. Exact and approximate arithmetic in Amazonian indigene group. Science 306: 499–503.

Pinhas M, Fischer MH. 2008. Mental movements without magnitude? A study of spatial biases in symbolic arithmetic. Cognition 109:408–15.

Price MC. 2009. Spatial forms and mental imagery. Cortex 45: 1229–45.

Price MC, Mentzoni RA. 2008. Where is January? The month-SNARC effect in sequence-form synaesthetes. Cortex 44: 890–907.

Rich AN, Bradshaw JL, Mattingley JB. 2005. A systematic, large-scale study of synaesthesia: implications for the role of early experience in lexical colour associations. Cognition 98:53–84.

Rich AN, Mattingley JB. 2002. Anomalous perception in synaesthesia: a cognitive neuroscience perspective. Nat Rev Neurosci 3:43–52.

Robertson LC. 2003. Binding, spatial attention and perceptual awareness. Nat Rev Neurosci 4:93–102.

Robertson LC, Sagiv N, editors. 2004. Synesthesia: perspectives from cognitive neuroscience. New York: Oxford University Press.

Rouw R, Scholte HS. 2007. Increased structural connectivity in grapheme-color synesthesia. Nat Neurosci 10:792–7.

Rubinsten O, Henik A. 2009. Developmental dyscalculia: heterogeneity may not mean different mechanisms. Trends Cogn Sci 13:92–99.

Sagiv N, Simner J, Collins J, Butterworth B, Ward J. 2006. What is the relationship between synaesthesia and visuo-spatial number forms? Cognition 101:114–28.

Seron X, Pesenti M, Noel MP, Deloche G, Cornet JA. 1992. Images of numbers, or "When 98 is upper left and 6 sky blue." Cognition 44:159–96.

Simner J. 2009. Synaesthetic visuo-spatial forms: viewing sequences in space. Cortex 45:1138–47.

Simner J, Mayo N, Spiller MJ. 2009. A foundation for savantism? Visuo-spatial synaesthetes present with cognitive benefits. Cortex 45:1246–60.

Simner J, Mulvenna C, Sagiv N, Tsakanikos E, Witherby SA, Fraser C, and others. 2006. Synaesthesia: the prevalence of atypical cross-modal experiences. Perception 35:1024–33.

Simner J, Ward J, Lanz M, Jansari A, Noonan K, Glover L, and others. 2005. Non-random associations of graphemes to colour in synaesthetic and non-synaesthetic populations. Cogn Neuropsychol 22:1069–85.

Smilek D, Callejas A, Dixon MJ, Merikle PM. 2007. Ovals of time: time-space associations in synaesthesia. Conscious Cogn 16:507–19.

Snyder A. 2001. Paradox of the savant mind. Nature 413:251–2.

Spalding JMK, Zangwill OL. 1950. Disturbance of number-form in a case of brain injury. J Neurol Neurosurg Psychiatry 13:24–9.

Spector F, Maurer D. 2009. Synesthesia: a new approach to understanding the development of perception. Dev Psychol 45:175–89.

Tang J, Ward J, Butterworth B. 2008. Number forms in the brain. J Cogn Neurosci 20:1547–56.

Walsh V. 2003. A theory of magnitude: common cortical metrics of time, space and quantity. Trends Cogn Sci 7:483–8.

Ward J, Huckstep B, Tsakanikos E. 2006. Sound-colour synaesthesia: to what extent does it use cross-modal mechanisms common to us all? Cortex 42:264–80.

Ward J, Mattingley JB. 2006. Synaesthesia: an overview of contemporary findings and controversies. Cortex 42:129–36.

Ward J, Sagiv N, Butterworth B. 2009. The impact of visuo-spatial number forms on simple arithmetic. Cortex 45:1261–5.

Weiss PH, Fink GR. 2009. Grapheme-colour synaesthetes show increased grey matter volumes of parietal and fusiform cortex. Brain 132:65–70.

Willmes K. 2008. Acalculia. Handb Clin Neurol 88:339–58.

Wood G, Nuerk H-C, Willmes K. 2006. Crossed hands and the SNARC effect: a failure to replicate Dehaene, Bossini and Giraux (1993). Cortex 42:1069–79.