Cite as: Brogaard, B. (2012). “Color Synesthesia”, in Kimberly A. Jameson (ed.), Cognition & Language, *Encyclopedia of Color Science and Technology*, Springer, forthcoming.

Color Synesthesia

Berit Brogaard
brogaardb@gmail.com
July 1, 2012

Synesthesia is a condition in which stimulation in one sensory or cognitive stream involuntarily, or automatically, leads to associated internal or external (illusory or hallucinatory) experiences in a second unstimulated sensory or cognitive system (Baron-Cohen, et al., 1987; Cytowic, 1989; Ramachandran, et al., 2001; Grossenbacher and Lovelace 2001; Hubbard and Ramachandran 2005; Sperling, et al., 2005; Hubbard et al. 2005; Ward, et al., 2006; Hubbard 2007). Although most cases of synesthesia are developmental and run in families, acquired cases have also been reported following traumatic brain injury, demyelination, ischemia, tumors, post-traumatic total ocular blindness and neuropathology involving the optic nerve and/or chiasm (Beauchamp and Ro, 2008; Afra, et al. 2009, Brogaard, et al. 2012).

Color synesthesia is a special kind of synesthesia that comprises cases of synesthesia in which a non-colored sensory or cognitive stimulus involuntarily leads to internal or external color experiences. The prevalence of color synesthesia is unknown. Estimates range from 1 in 200 to 1 in 250,000 (Sagiv, et al. 2006; Cytowic, 1997) Some speculate that color synesthesia may be present in more than 4 percent of the population. (Hubbard and Ramachandran 2005)

One of the best-known forms of color synesthesia is grapheme-color synesthesia, in which numbers or letters are seen as colored. But lots of other forms of color synesthesia have been identified, including week-color synesthesia, sound-color synesthesia, taste-color synesthesia, fear-color synesthesia, etc. (Hubbard and Ramachandran 2005) For lack of space I shall here focus primarily on grapheme-color synesthesia.

One mark of color synesthesia is that the synesthetic colors are seen either as projected out onto the world (“projector synesthesia”) or in the mind's eye (“associator synesthesia”) (Dixon et al. 2004). Another mark is that it exhibits test-retest reliability (Baron-Cohen, et al. 1987, Eagleman, et al. 2007): Colors identified by the subject as representative of her synesthetic experiences relative to a given stimulus in the initial testing phase are nearly identical to colors identified by the subject as representative of her synesthetic experiences relative to the same stimulus in a retesting phase at a later time (see **Fig 1**).

Age/graph	0	1	2	3	4	5	6	7	8	9
3	/	B	Y	G	P	R	Bl	W	Br	R
4	/	B	Y	G	P	R	Bl	W	Br	R
5	Go	B	Y	G	P	R	DBr	W	Br	R
6	Go	B	Y	G	P	R	DBr	W	Br	R
7	B	B	Y	G	P	R	Br	W	Br	R
8	B	B	Y	G	P	R	Bl	W	Br	R

Figure 1: Example of test-retest reliability of synesthetic experience in one of our associator grapheme-color synesthetes from ages 3 to 8 (Go = gold, B = blue, Y = yellow, G = green, P = purple, R = red, Bl = black, DBr = dark brown, Br = brown, W = white).

Because of the automatic nature of synesthesia and its test-retest reliability, color synesthesia is not to be confused with memory associations or stereotypical colors of objects. For example, there is no evidence that color synesthetes simply remember the colors of entities or images they were exposed to earlier in their lives or associate stimuli with their stereotypical colors (Eagleman, et al. 2007).

Synesthetic color experience is unique for each synesthete. For example, the letter A may trigger the color red in one grapheme-color synesthete but trigger the color blue in another. In fact, each grapheme has been found to trigger each of the 11 Berlin and Kay colors in different synesthetes (red, pink, orange, yellow, green, blue, purple, blown, black, white, gray). Despite the uniqueness of synesthetic color experience, synethetic colors sometimes fall into certain clusters. For example, grapheme-color synesthetes tend to associate A with red, E with yellow or white, I with black or white and O with white (Baron-Cohen et al, 1993; Simner 2005).

Low-Level Vs. High-Level Perception

An open question about color synesthesia is whether it is a form of low-level or high-level perception. According to Ramachandran and Hubbard (2003), synesthesia is a form of low-level perception, a “sensory” phenomenon. As they put it:

> Work in our laboratory has shown that synaesthesia is a genuine sensory phenomenon ... The subject is not just ‘imagining the colour’, nor is the effect simply a memory association (e.g. from having played with coloured refrigerator magnets in childhood). (2003: 51)

Some of the evidence listed in favor of treating color synesthesia as a kind of low-level perception is that some color-grapheme synesthetes appear to experience a pop-out effect in visual search paradigms in which some characters elicit synesthetic experience. For example, if a cluster of 2s is embedded in an array of randomly placed 5s, normal subjects take several seconds to find the shape formed by the 2s, whereas grapheme–color synesthetes who experience a pop-out effect instantly see the shape (see **Fig 2**) (Ramachandran & Hubbard, 2001; Smilek et al., 2001).

Visual search paradigms are supposed to be indicators of whether synesthetic experience requires focal attention. If synesthetic experience does not require focal attention, then digits with unique synesthetic colors should capture attention, which would lead to highly efficient identification of inducing digits. If, on the other hand, synesthetic experience requires focal attention, then synesthetic colors do not capture attention and the identification process should be inefficient (Edquist et al., 2006). Perceptual features must be processed early enough in the visual system for them to attract attention and lead to pop-out and segregation (Beck, 1966; Treisman, 1982). So the appearance that synesthetic experience can lead to pop-out and segregation indicates that synesthesia is a low-level perceptual phenomenon Ramachandran & Hubbard, 2001; Ramachandran & Hubbard, 2003).

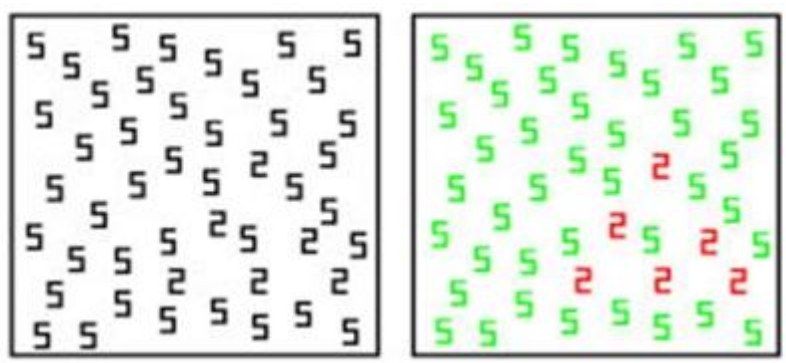

Figure 2 When normal subjects are presented with the figure on the left, it takes them several seconds to identify the hidden shape. Some grapheme–color synesthetes instantly see the triangular shape because they experience the 2s and the 5s as having different colors.

However, while a significant number of grapheme-color synesthetes are more efficient in visual search paradigms than controls, this does not clearly show that attention is not required for synesthetic experience. In one subject PM, it was shown that quick identification of graphemes occurred only when the graphemes that elicit synesthetic experience were close to the initial focus of attention (Laeng et al., 2004). Smilek et al. (2003) used a variation on the standard visual search paradigm to test subject J's search efficiency. J was shown an array of black graphemes on a colored background, some of which induced synesthetic experience. The colored background was either congruent or incongruent with the synesthetic color of the target. The researchers found that J was more efficient in her search when the background was incongruent than when it was congruent. This indicates that the synethetic colors attracted attention only when they were clearly distinct from the background.

Edquist et al. (2006) carried out a group study involving 14 grapheme-color synesthetes and 14 controls. Each subject performed a visual search task in which a target digit differed from the distractor digits in terms of its synesthetic color or its display color. Both synaesthetes and controls identified the target digit efficiently when the target had a unique display color but the two groups were equally inefficient when the target had a unique synesthetic color. The researchers concluded that for most grapheme-color synesthetes, graphemes elicit synesthetic color only once the subject attends to them. This indicates that synesthetic colors cannot themselves attract attention because they are not processed early enough in the visual system.

Another reason to think that not all cases of color experience in grapheme-color synesthesia are forms of low-level perception is that their appearance seems to depend on interpretation of visual experience. In **figure 3**, for instance, synesthetes assign different colors to the middle letter depending on whether they interpret the string of letters as spelling the word 'cat' or the word 'the'. For example, one of our child subjects, a seven-year old female, experiences the middle letter as red when she reads the word 'cat' and the middle letter as brown when she reads the word 'the'. This suggests that it is not the shape of the letter that gives rise to the color experience but the category or concept associated with the letter (Cytowic & Eagleman 2009: 75).

Figure 3: Synesthetes interpret the middle letter as an A when it occurs in 'cat' and as an H when it occurs in 'the'. The color of their synesthetic experience will depend on which word the grapheme is considered part of.

The fact that the very same grapheme can elicit different color experiences in synesthetes depending on the context in which it occurs suggests that synesthetes need to interpret what they visually experience before they experience synesthetic colors. Though Ramachandran and Hubbard (2003) argue that grapheme-color synesthesia is a form of low-level perception (‚a ‘sensory phenomenon’), they grant that linguistic context can affect synesthetic experience. They presented the sentence ‘Finished files are the result of years of scientific study combined with the experienced number of years’ to a subject and asked her to count the number of ‘f’s’ in it. Most normal subjects count only three ‘f’s’ because they disregard the high-frequency word ‘of’. Though the synesthete eventually spotted six ‘f’s’ she initially responded the way normal subjects do.

Ramachandran and Hubbard (2003) suggest that these contextual effects can be explained by top-down factors. Whether this is right, however, will depend on whether color experience processed in early visual areas is indeed affected by top-down factors. If it is not, then top-down influences cannot explain the contextual effects. A better explanation of contextual influence then may be that interpretation of low-level perceptual information is required for synesthetic experience.

Another explanation of the disagreement about whether color synesthesia gives rise to pop-out effects may bear on the fact that few studies of pop-out effects have properly distinguished between projector synesthesia and associator synesthesia as well as what Ramachandran calls ‘higher synesthesia’ and ‘lower synesthesia’. Lower grapheme-color synesthesia is synesthesia (either projector or associator) that arises in response to sensory stimuli, whereas higher grapheme-color synesthesia is synesthesia (either projector or associator) that arises in response to thoughts of graphemes. It is possible that the majority of synesthetes are higher synesthetes and that only lower synesthetes experience pop-out effects.

Neural Mechanism

The precise neural mechanism underlying color synesthesia is unknown. One hypothesis, the so-called local cross-activation hypothesis, proposed by Hubbard and Ramachandran, holds that grapheme-color synesthesia arises due to cross-activation between color areas in the visual cortex and the adjacent visual word form area (Hubbard et al., 2005b; Ramachandran and Hubbard, 2001a, 2001b). This suggestion is inspired by the observation that local crossover phenomena can explain other illusory and hallucinatory experiences, such as phantom limb sensations.

A second hypothesis is that color synesthesia may be due to disinhibited feedback from an area of the brain that binds information from different senses (Armel and Ramachandran, 1999; Grossenbacher, 1997; Grossenbacher and Lovelace, 2001). The main piece of evidence cited in favor of this hypothesis comes from an analogous case in which a patient PH reported seeing visual movement in response to tactile stimuli following acquired blindness (Armel and Ramachandran, 1999). As PH was blind, he could not have received the information via standard visual pathways. It is plausible that the misperception was a result of disinhibited feedback from brain regions that receives information from other senses.

The fact that synesthetic experiences can arise when subjects are under the influence of psychedelics provides some further evidence for the disinhibited feedback hypothesis (Shanon 2002). The synesthetic effect of psychedelic substantaces may be due to an inhibition of feedback from areas of information binding. It is unknown, however, whether drug-induced synesthesia and congenital synesthesia have the same underlying mechanism.

A third hypothesis is that color synesthesia arises as a result of aberrant re-entrant processing (Myles, et al. 2003; Smilek et al. 2001). The hypothesis is similar to the disinhibited feedback hypothesis but suggests specifically that high-level information re-enters color areas in visual cortex and that it is this form of re-entrant information processing that leads to the experience of synesthetic colors. This model would explain why visual context and meaning typically influence which synesthetic colors a grapheme gives rise to (Dixon and Smilek, 2005; Myles et al., 2003).

It is plausible that different forms of color synesthesia proceed via different mechanisms. Cases of color synesthesia have been reported in which the visual cortex is not involved in generating synesthetic colors (Bor, et al. 2007, Brogaard, et. al., 2012). None of the three aforementioned hypotheses, despite their plausibility in run-of-the mill cases, can explain more unusual cases of color synesthesia.

Cognitive Advantages of Color Synesthesia

If pop-out effects require attention to the synesthetic graphemes, color-grapheme synesthesia is unlikely to give subjects much of a cognitive advantage in visual search tests. However, there may nonetheless be cognitive advantages associated with color synesthesia. For example, some case studies suggest that grapheme-color synesthetes may have greater recall ability for digits and written names when compared to non-synesthetes (Mills, et al. 2006; Smilek, et al. 2002).

In rare cases color synesthesia has been associated with extreme mathematical skills. Subject DT, for example, sees numbers as three-dimensional colored, textured forms (Bor, et al. 2007). His synesthesia gives him the ability to multiply high digits very rapidly. He reports that the product of multiplying two numbers is the number that corresponds to the shape that fits between the shapes corresponding to the multiplied numbers. Subject DT's color synesthesia also gives rise to extreme mnemonic skills. DT currently holds the European record in reciting the decimal points of the number pi. An fMRI study comparing DT to controls while attempting to locate patterns in number sequences indicated that DT's synesthetic color experiences occur as a result of information processing in non-visual brain regions, including temporal, parietal and frontal areas (Bor, et al., 2007)

Brogaard, et al. (2012) describe a case of a subject, JP, who has exceptional abilities to draw complex geometrical images by hand and a form of acquired synesthesia for mathematical formulas and moving objects, which he perceives as colored, complex geometrical figures (see **fig 4**).

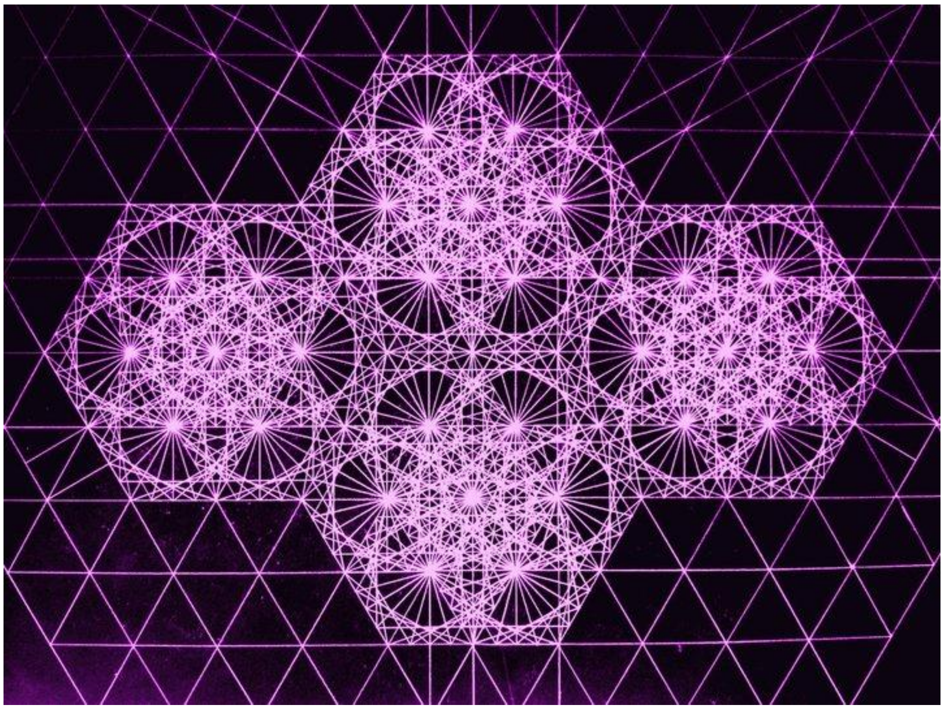

Figure 4: Image hand-drawn by subject JP

JP's synesthesia began in the wake of a brutal assault that led to unspecified brain injury. A fMRI study contrasting activity resulting from exposure to image-inducing formulas and non-inducing formulas indicated that JP's colored synesthetic images arise as a result of activation in areas in the temporal, parietal and frontal cortices in the left hemisphere. The image-inducing formulas as contrasted with the non-inducing formulas induced no activation in the visual cortex or the right hemisphere (Brogaard, et al. 2012). (see **fig 6**)

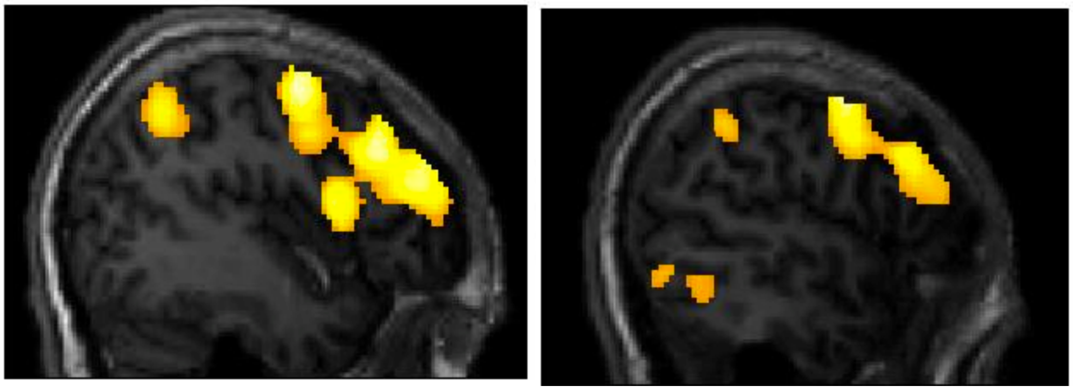

Figure 6: Sagittal slices. Activation induced by the image-inducing formula contrasted to non-inducing formulas. The SPM(T) maps were thresholded at family-wise-error-corrected p-value 0.01 and overlaid on JP's structural T1-weighted MRI which was standardized into MNI-space using SPM8. (Brogaard, et al. 2012)

These two unusual case studies suggest that at least some forms of color synesthesia can give rise to cognitive advantages in the area of mathematics. As the visual cortex does not appear to be directly involved in generating the synesthetic images in either subject, the two cases also suggest that at least some forms of color synesthesia are best characterized as forms of high-level perception that proceeds via a non-standard mechanism.

References

Afra, P., Funke, M. & Matsu, F. (2009) Acquired auditory-visual synesthesia: a window to early cross-modal sensory interactions, Psychology Research & Behaviour Management, 2, 31-37.

Armel, K.C., and Ramachandran, V.S. (1999). Acquired synesthesia in retinitis pigmentosa. Neurocase 5, 293–296.

Baron-Cohen S., Wyke, M. and Binnie, C. 1987. Hearing words and seeing colors: an experimental investigation of synesthesia, Perception 16: 761-767.

Baron-Cohen S, Harrison J, Goldstein LH, and Wyke M. (1993). "Coloured Speech Perception: Is Synaesthesia What Happens When Modularity BreaksDown?"Perception 22: 419-426.

Beck, J. (1966), "Effect of orientation and of shape similarity on perceptual grouping", Perception and Psychophysics, 1, pp. 300–2.

Beauchamp MS, Ro T. (2008). “Neural substrates of sound-touch synesthesia after a thalamic lesion.” J Neurosci. 28:13696-702.

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.

Brogaard, B, Vanni, S, Silvanto, J. (2012) “Seeing mathematics: perceptual experience and brain activity in acquired synesthesia”, Neurocase, in press.

Cytowic, R. E. 1989. Synesthesia: A Union of the Senses. New York: Springer Verlag.

Cytowic, R.E. Synesthesia: Phenomenology and Neuropsychology” (1997) in: S. Baron-Cohen. “Synesthesia: Classic and Contemporary Readings” 17-39. Blackwell Publishers, Oxford.

Cytowic, RE, Eagleman, DM 2009. Wednesday is Indigo Blue, MIT Press

Dixon, M. J., Smilek, D., and Merikle, P. M. (2004). “Not all synaesthetes are created equal: projector versus associator synaesthetes”, Cogn. Affect. Behav. Neurosci. 4: 335–343.

Eagleman, DM, Kagan, AD, Nelson, SS, Sagaram, D, Sarma, AK. (2007). “A standardized test battery for the study of Synesthesia”. Journal of Neuroscience Methods 159: 139-145.

Dixon, M.J., and Smilek, D. (2005). The importance of individual dif- ferences in grapheme-color synesthesia. Neuron 45, 821–823.

Edquist J, Rich AN, Brinkman C, Mattingly JB. (2006). “Do synaesthetic colours act as unique features in a visual search?” Cortex 42: 222-231.

Grossenbacher, P.G. (1997). Perception and sensory information in synaesthetic experience. In Synaesthesia: Classic and Contempo- rary Readings, S. Baron-Cohen, and J.E. Harrison, eds. (Malden, MA: Blackwell Publishers, Inc.), pp. 148–172.

Grossenbacher, P.G., and Lovelace, C.T. (2001). Mechanisms of synesthesia: cognitive and physiological constraints. Trends Cogn. Sci. 5, 36–41.

Hubbard, E. M. 2007. “Neurophysiology of synesthesia”, Current Psychiatry Reports 9: 193-199.

Hubbard, E. M. and Ramachandran, V. S. 2005. “Neurocognitive mechanisms of synesthesia”, Neuron 48: 509–520.

Hubbard, E. M., Arman, A. C., Ramachandran, V. S., & Boynton, G. M. (2005). Individual differences among grapheme-color synesthetes: Brain-behavior correlations. *Neuron, 45(6),* 975–985.

Hubbard, E.M., Manohar, S., and Ramachandran, V.S. (2005b). Con- trast affects the strength of synesthetic colors. Cortex, in press.

Laeng B, Svartdal F and Oelmann H. (2004) “Does color synesthesia pose a paradox for early-selection theories of attention?” Psychological Science, 15: 277-281.

Mills, Carol Bergfeld. Innis, Joanne. Westendorf, Taryn. Owsianiecki, Lauren. McDonald, Angela. “Effect of a Synesthete’s Photisms on Name Recall” Cortex, 2006 Vol. 42, 155-163.

Myles, K.M., Dixon, M.J., Smilek, D., and Merikle, P.M. (2003). Seeing double: the role of meaning in alphanumeric-colour synaesthesia. Brain Cogn. 53, 342–345.

Ramachandran V.S., Hubbard E.M. (2001a) Psychophysical investigations into the neural basis of synaesthesia. Proc. R. Soc. Lond. B. Biol. Sci. 268:979–983.

Ramachandran, V.S. and Hubbard, E.M. (2001b), ‘Synaesthesia: A window into perception, thought and language’, Journal of Consciousness Studies 8: 3–34.

Ramachandran, VS and Hubbard, EM. (2003). The Phenomenology of Synaesthesia, Journal of Consciousness Studies 10: 49-57.

Sagiv, Noam. Ward, Jamie. “Cross-Modal Interactions: Lessons from Synesthesia” Progress in Brain Research, 2006 Vol. 155, 259-71.

Shanon, B. (2002). Ayahuasca visualizations: a structural typology. J. Consciousness Stud. 9, 3–30.

Simner, J., Ward, J., Lanz, M., Jansari, A., Noonan, K., Glover, L., et al. (2005). Non-random associations of graphemes to colours in synaesthetic and non-synaesthetic populations. Cognitive Neuropsychology, 22(8), 1069.

Smilek, D, Dixon MJ, Cudahy C and Merikle PM (2001) “Synaesthetic photisms influence visual perception”, Journal of Cognitive Neuroscience 13: 930-936.

Smilek, Daniel. Dixon, Mike J. Cudahy, Cera. Merikle, Philip M. “Synesthetic Color Experiences Influence Memory” Psychological Science, November 2002 Vol. 13, No. 6, 548-552.

Smilek D, Dixon MJ and Merikle PM (2003). “Synaesthetic photisms guide attention”, Brain and Cognition, 53: 364-367.

Sperling, J. M., Prvulovic, D., Linden, D. E. J., Singer, W., and Stirn, A. (2005). “Neuronal correlates of graphemic colour synaesthesia: a fMRI study”, Cortex 42: 295–303.

Treisman, A. (1982), ‘Perceptual grouping and attention in visual search for features and for objects’, Journal of Experimental Psychology: Human Perception and Performance, 8 (2), pp. 194–214.

Ward J., Huckstep B., Tsakanikos E. Sound-colour synaesthesia: To what extent does it use cross-modal mechanisms common to us all? Cortex. 2006;42:264–280