Perception, 2006, volume 35, pages 837 – 845

DOI:10.1068/p5539

Savant-like numerosity skills revealed in normal people by magnetic pulses

Allan Snyder¶§, Homayoun Bahramali§, Tobias Hawker§, D John Mitchell¶
¶ Centre for the Mind, Australian National University, Canberra, ACT 0200, Australia; § University of Sydney, NSW 2006, Australia; e-mail: allan@centreforthemind.com
Received 3 August 2005, in revised form 19 October 2005; published online 3 May 2006

Abstract. Oliver Sacks observed autistic twins who instantly guessed the exact number of matchsticks that had just fallen on the floor, saying in unison "111". To test the suggestion that normal individuals have the capacity for savant numerosity, we temporarily simulated the savant condition in normal people by inhibiting the left anterior temporal lobe of twelve participants with repetitive transcranial magnetic stimulation (rTMS). This site has been implicated in the savant condition. Ten participants improved their ability to accurately guess the number of discrete items immediately following rTMS and, of these, eight became worse at guessing as the effects of the pulses receded. The probability of as many as eight out of twelve people doing best just after rTMS and not after sham stimulation by chance alone is less than one in one thousand.

1 Introduction

In 1871 the acclaimed economist W Stanley Jevons wrote: "It is well known that the mind is unable through the eye to estimate any large number of objects without counting them successively. A small number, for instance three or four, it can certainly comprehend and count by an instantaneous and apparently single act of mental attention".

Those early observations have stood the test of time and have been augmented by elegant contemporary investigations (Burgess and Barlow 1983; Boles 1986; Ginsburg and Goldstein 1987; Dehaene 1997; Butterworth 1999, 2005; Piazza et al 2002, 2004; Dehaene et al 2004; Feigenson et al 2004; Colvin et al 2005). However, reports over time about the ability of autistic savants to accurately guess large numbers of objects remain enigmatic (Scripture 1891; Sacks 1986; Treffert 2000). For instance, Oliver Sacks (1986) observed autistic twins who instantly guessed the exact number of matchsticks that had just fallen on the floor, saying in unison "111". Such reports motivated our present study.

The extraordinary skills of savants have been hypothesised to be due to their privileged access to lower levels of sensory information prior to it being integrated into the holistic picture. This lower level, more literal, information is suggested to exist in everyone (Snyder and Mitchell 1999), but is not normally accessible except by artificial means (Snyder et al 2003; Young et al 2004).

We tested this hypothesis on the ability of normal individuals to guess a large number of discrete elements, by artificially simulating the savant condition in twelve people. To do this, we applied low-frequency (1 Hz) repetitive transcranial magnetic stimulation (rTMS) to the left anterior temporal lobe for 15 min (see section 2.3). This site is implicated in the savant syndrome for both autistic savants and savants who emerge late in life as a result of frontotemporal lobe dementia (Miller et al 1998, 2000; Hou et al 2000). Low-frequency rTMS is known to temporarily inhibit neural activity in a localised area of the cerebral cortex, thereby creating 'virtual lesions' (Pascual-Leone et al 1999; Walsh and Cowey 2000; Hoffman and Cavus 2002).

Our study directly addresses the question whether rTMS improves a person's ability to accurately guess the absolute number of discrete elements displayed on a monitor.

We offer conclusive evidence that it does. And, importantly, that the improvement comes without the participants having any feedback of their accuracy or any prior knowledge of the range of numbers of objects to be displayed.

Participants were presented with between 50 and 150 discrete elements on a monitor (figure 1) in rTMS and sham conditions. Both the spatial position of the elements and their number were randomly generated by computer for every presentation. Each session involved 60 trials, that is 20 opportunities to guess the number of elements before, immediately after, and 1 h after rTMS. The exposure time was 1.5 s: too short for anyone to count the number of elements, but sufficiently long to resemble exposure times in real-life situations. Apart from rTMS trials, participants did not show a systematic improvement in their accuracy of guessing over time, thus excluding their adoption of learning strategies. They did show a significant on-average improvement in their ability to guess the number of elements immediately following rTMS and that ability receded after 1 h.

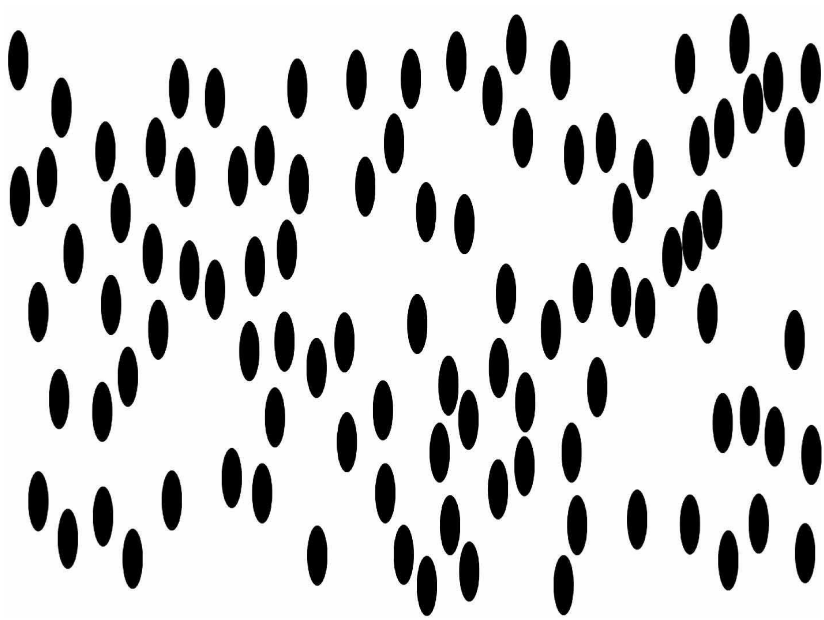

Figure 1. A typical trial. This example contains 100 discrete elements. At no time were the participant or the experimenter informed of the number, or range of numbers, of elements.

2 Methods

2.1 *Participant recruitment*

Twelve right-handed volunteers (five males, seven females; 19 – 33 years old), who were naive to both the rTMS procedure and the hypothesis of the experiment, took part in the study. They were recruited from local university students. The study was approved by the human ethics committee at the University of Sydney. Participants gave informed consent for the rTMS protocol. They were screened according to TMS guidelines (Wassermann 1998) and the TMS Adult Safety Screen protocol (see Keel et al 1999). Participants attended experimental sessions separated by approximately 1 week.

2.2 *Transcranial magnetic stimulation protocol*

Repetitive transcranial magnetic stimulation (rTMS) was administered with a Medtronic MagPro magnetic stimulator (Dantec Medtronic), with a 70 mm Butterfly coil (MCF-B65). The resting motor threshold was determined by placing the coil over the left primary motor area and establishing the minimum amount of stimulator output required to produce a motor-evoked potential with a peak-to-peak amplitude of 50 μV in the right first dorsal interosseous muscle following at least three out of five single pulses. The left anterior-temporal cortical stimulation site was determined by measuring laterally and anteriorly from the vertex (laterally 40% of the intra-auricular distance; anteriorly 5% of the distance from inion to nasion). This point lies approximately halfway between T3 and F7 on the international 10 – 20 system for electrode placement (Blom and Anneveldt 1982). In the real stimulation condition, the intensity of stimulation was 90% of motor threshold with duration of 15 min at a frequency of 1 Hz.

2.3 *Experimental protocol*

Experiments were carried out over separate sessions in a single-blind randomised order. rTMS was applied to the left anterior temporal lobe. In the sham session (Robertson et al 2003), the magnet was inverted and placed over parietal site Pz, in the international 10 – 20 system (Blom and Anneveldt 1982). The magnetic stimulation was insignificant in the sham sessions, but the rTMS apparatus was active and produced audible clicks identical to those produced during the real rTMS sessions. Typically one week separated visits to the lab by each subject. In all sessions, the participants undertook estimation performance tests three times: before rTMS, immediately after 15 min of rTMS, and 1 h after rTMS had ceased.

2.4 *Task description*

Before the tests commenced, participants were seated in front of a computer monitor, and informed that they would be shown a series of images, each made up of a number of discrete elements. The participants were asked to give a verbal report of the number of items they saw on the screen in each trial. Test batteries comprised 20 trials of computer-generated stimuli for each session. Participants made 120 guesses by the time they completed both real and sham sessions. Each stimulus consisted of a number of uniformly sized, shaped, and coloured (blue) ellipses on a white background. The number of ellipses presented at each trial was chosen from the interval (50 to 150) with a uniform distribution, as shown in figure 1. The spatial distribution of ellipses in each image was determined from uniform random selection in both horizontal and vertical dimensions, and was independent for each image. The ellipses presented did not overlap, and were all entirely contained within the borders of the monitor. Each stimulus was presented for 1.5 s. After the entire screen was made blank, the participant verbally provided their estimation. This was entered into the testing software by the experimenter. Neither the participant nor the experimenter had knowledge of the number of objects, nor the range of numbers, presented on the monitor throughout all testing sessions.

2.5 *Statistical analysis*

Statistical analysis of within-subjects effects was performed with SPSS for Windows version 12. The effect of the rTMS and sham protocol on participants' performance was compared with the aid of repeated-measures analysis of variance, with Mauchly's test used to ensure that sphericity assumptions were not violated. This yielded the results described below.

For each experimental session, the probability of a participant guessing the number of elements within an accuracy of 5 more often during the second test (post-treatment) than during the first (pre-treatment) and third (1 h after) tests by random chance alone is 31%. This follows provided no strong relationship is found between test repetition and test performance. The probability is slightly less than a one-in-three chance because of the possibility of equal scoring. The likelihood of having this pattern under rTMS and not under sham is $P[= 31\%]$ multiplied by $1 - P$, yielding an overall probability of around 21%. We can treat each participant's results as a Bernoulli trial and calculate the likelihood of obtaining the observed results or better from a binomial distribution.

3 Results

We investigated savant-like ability to normal individuals to accurately guess numbers of discrete elements, before and after magnetic pulse stimulation (rTMS). We found that participants presented their answers to the nearest 5. Specifically, 99% of estimates were multiples of 5, and in fact 82% were even multiples of 10. Consequently, we used a 'bulls-eye' measure of within-5 as the indication of high accuracy estimates. This is the most stringent and conservative measure for evaluating accuracy given these response patterns. A measure that varied depending on the number shown would accept less accurate guesses for trials involving more items, and be subject to severe quantisation error throughout the range. We have confirmed that our bulls-eye measure is not especially sensitive to the choice of 5. Even if we expand the bulls-eye band to 10, thus including many less-accurate estimates, we still find statistically significant increases in the number of bulls-eyes immediately following rTMS.

3.1 *Individual performance*

Of our twelve participants, ten improved their ability to accurately guess the number of discrete elements immediately following magnetic pulse stimulation. Of these ten, eight became worse 1 h later, as the effects of the magnetic pulses receded. None of those eight participants exhibited that pattern during the sham session. The probability of as many as eight out of twelve people doing best just after rTMS and not just after the sham by chance alone is less than 1 in 1000 [$p = 0.001$]; analogous to rolling a five-sided dice 12 times and obtaining a 'one' eight or more of those times. This holds because we found approximate independence between repetitions of the test and the number of bulls-eyes attained [$R^2 < 0.005$; $p > 0.5$] (see section 2).

Figure 2 presents the responses of four representative participants. The left graph for each participant shows the accuracy of guessing before, just after, and 1 h after rTMS. The right graph displays the results for the sham control. rTMS clearly improves accurate guessing. For example, before rTMS and 1 h later, participant AB (figure 2a) was unable to guess the number of items within an accuracy of 5 for any of the 20 exposures presented to her. Yet, immediately after rTMS, 6 of her 20 guesses were within the bulls-eye criterion of 5. During the sham control, none of her guesses were bulls-eyes, as shown on the right graph of figure 2a.

Taking the last example, participant DL had 3 guesses within an accuracy of 5 before rTMS and 10 immediately after—more than tripling the number of his bulls-eyes; 1 h after rTMS, his accuracy at guessing was significantly reduced. Participant DL is unusual in showing a slight improvement after his sham stimulation, by having 1 additional guess within an accuracy of 5. But, this was insignificant compared to his improved accuracy immediately following rTMS and, unlike the real rTMS session, his accuracy of guessing increased marginally, by 1 again, 1 h after sham stimulation (figure 2d).

3.2 *Aggregate changes*

Figure 3 presents the averaged results of all twelve participants, reinforcing the above conclusion that magnetic pulse stimulation significantly improves a person's ability to guess within the bulls-eye criterion of 5. This is quantified statistically by a repeated-measures analysis of variance test of the interaction effect between treatment type (rTMS and sham) and stimulation condition (before, just after, 1 h after) ($F_{2,10} = 5.2$, $p = 0.014$). Multifactorial analysis of variance shows even stronger effects ($F_{2,10} = 9.0$, $p = 0.006$).

It is important to note from figure 3 that, on average, the participants' performance slightly worsened just after the sham session. This may reflect the pejorative effects associated with being subjected to 15 min of the rTMS protocol, which only underscores the significance of the observed improvement just after the genuine rTMS.

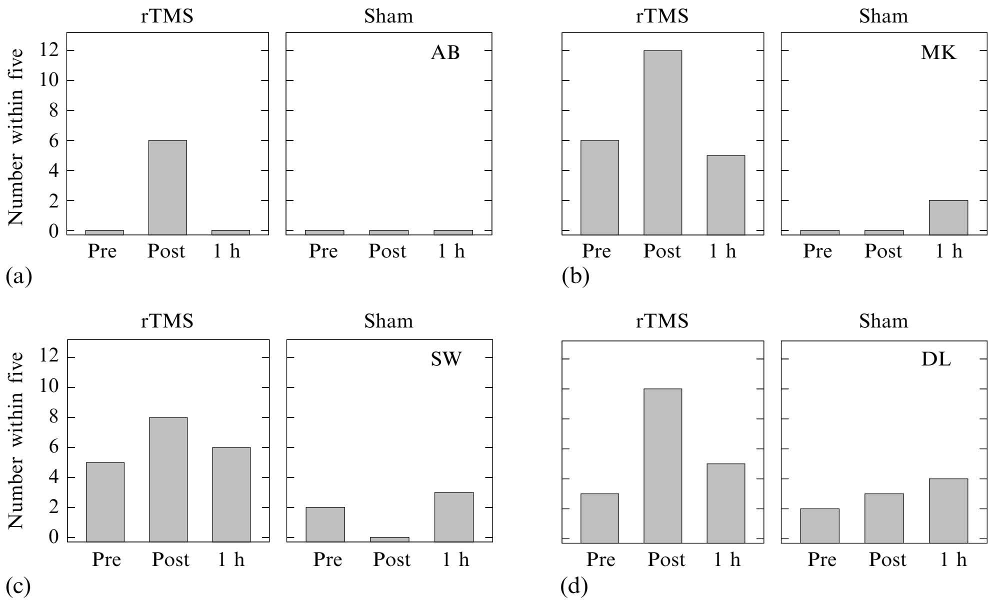

Figure 2. The ability of four participants to guess the number of elements within the bulls-eye criterion of 5. Each left panel shows the ability before (Pre), immediately after (Post), and 1 h after rTMS. Right panels show sham in the same order. Each bar represents the number of trials, out of 20, that were accurately guessed to within 5. Participants' initials are shown on the top right of graphs. For participants AB and DL, the rTMS session preceded the sham session; for participants MK and SW, sham preceded rTMS.

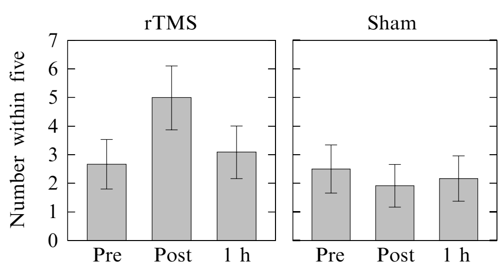

Figure 3. Mean ability across all participants to make guesses within the bulls-eye criterion of 5. Error bars represent 95% confidence intervals.

The stand-out performance just after rTMS, visible in figure 3, can be verified by a paired t-test showing that the mean is significantly different from the means both before the application of rTMS and 1 h later ($t_{11} = 3.0$, $p = 0.01$, and $t_{11} = 2.3$, $p = 0.04$, respectively). The small differences in performance under the sham condition are not significant ($t_{11} = 1.3$, $p = 0.2$, and $t_{11} = 0.4$, $p = 0.7$).

The worsening in task performance, after the effect of rTMS had receded, is also apparent in figure 3. Standard analysis of variance shows that the effect of rTMS on the likelihood that an estimate is a bulls-eye is significant ($F_{2,239} = 6.4$, $p = 0.002$). t-Tests confirm that an estimate is more likely to be a bulls-eye following rTMS than either before or long after rTMS application ($t_{478} = 3.3$, $p = 0.001$, and $t_{478} = 2.6$, $p = 0.009$, respectively), while there is no significant change under the sham condition ($t_{478} = 1.0$, $p = 0.3$, and $t_{478} = 0.5$, $p = 0.7$).

4 Discussion

This research was motivated by the reported numerosity feats of savants (Scripture 1891; Sacks 1986; Treffert 2000). We demonstrated an enhanced ability of healthy normal individuals to guess the absolute number of discrete elements by attempting to artificially simulate the savant condition. We did this by using rTMS to create a virtual lesion (Pascual-Leone et al 1999; Walsh and Cowey 2000) in the left anterior temporal lobe, a site implicated in the savant condition (Miller et al 1998, 2000; Hou et al 2000). Our numerosity findings are consistent with previously reported rTMS enhanced savant-like skills in drawing (Snyder et al 2003; Young et al 2004) and proofreading (Snyder et al 2003). They are predicted by an earlier theoretical framework (Snyder and Mitchell 1999; Snyder et al 2004). The robustness of our results is noteworthy. There are many variables in the administration of rTMS (Robertson et al 2003), including magnetic field configuration, intensity and pulse frequency, target location, and variability of brain structure. But recognising these uncertainties only serves to increase the significance of our positive findings.

4.1 *Savant skills as privileged access to raw sensory details*

Savants are extremely rare individuals who, although often severly brain impaired, frequently by autism, can display islands of astonishing excellence in the same peculiarly restricted areas, across all cultures. Their skills are literal, non-symbolic, and apparently not derived from practice. They often emerge 'spontaneously' and do not improve qualitatively with time, even though the skill might be better articulated. Savants typically have no idea how they do it (Rimland 1963; Treffert 2000, 2005).

In the words of one pioneering researcher, their "gift springs so to speak from the ground, unbidden, apparently untrained and at the age of somewhere between five and eight years of age. There is often no family history of the talent" and it "is apparently not improved with practice" (O'Connor 1989, page 4).

It has been hypothesised (Snyder and Mitchell 1999) that savants have privileged access to raw sensory details, before these details are assembled into concepts, meaningful labels, and holistic pictures. All brains possess this same raw information but, without some sort of brain dysfunction, or altered states of mind (Humphrey 2002; Sacks 2003), it is normally beyond conscious access. We tend to see the whole and not the parts (Howe 1989, page 83). Savants tend to see the parts and not the whole. They are literal with an inclination to focus on local, rather than global aspects of the scene, and to recall detail without meaning (Rimland 1963; Frith and Hill 2003; Snyder 2004).

4.2 *Why does being literal enhance numerosity?*

How does being literal enhance numerosity? We argue that it removes our unconscious tendency to group discrete elements into meaningful patterns, like grouping stars into constellations, which would normally interfere with accurate estimation. By being literal, a savant sees elements as discrete and disconnected, thus removing this interference.

This explanation is consistent with the fact that the accuracy of estimating numbers of elements depends on their arrangement (Ginsburg 1976, 1991; Boles 1986; Ginsburg and Goldstein 1987; Dehaene 1997) and even on the sensory properties of the stimulus (Barth et al 2003). As Krueger (1984) concluded, "...perceived numerosity depends more on higher level cognitive factors...than on lower level perceptual or sensory factors".

Indeed, the healthy normal brain makes hypotheses in order to extract meaning from the sensory input, hypotheses derived from prior experience (Gregory 1970, 2004; Snyder and Barlow 1988; Snyder et al 2004). If perceived numerosity depends on higher-level cognitive factors, then the estimation of number is likely to be performed on this hypothesised content, not on the actual raw sensory input, thus exaggerating errors in estimation that would otherwise be absent.

In sum, we argue that the estimation of number by normal people is performed on information after it has been processed into meaningful patterns. The unconscious meaning we assign to these patterns interferes with our accuracy of estimation, whereas savants, by virtue of being literal, have less interference. This, together with the fact that it takes only a handful of precise measurements to calibrate our number estimation system (Dehaene 1997, page 71), could explain the reported numerosity feats of savants.

4.3 *The role of the left anterior temporal lobe in the savant syndrome*
Why did we apply rTMS to the left anterior temporal lobe? The savant syndrome is often associated with some form of left-brain dysfunction together with right-brain compensation, leading to a predilection for literal, non-symbolic skills (Treffert 2000, 2005). This is consistent with the role of the left hemisphere in hypothesis formation: the left, but not the right, hemisphere tends to search for patterns, and match them to prior experience (Wolford et al 2000). Furthermore, most savants are autistic and autism is associated with a right-hemispheric bias (Herbert et al 2005; Koshino et al 2005), as well as superior visual-discrimination abilities (O'Riordan et al 2001; O'Riordan 2004).

The left anterior temporal lobe, in particular, has been implicated in the savant syndrome, both for an autistic savant as well as for individuals who become savants at the onset of frontotemporal dementia (FTD) (Miller et al 1998, 2000; Hou et al 2000). In particular, patients displayed autistic savant-like artistic skills where none existed, along with other autistic traits such as preoccupation with visual details and a loss of semantic memory. Miller et al (1998) conclude that "loss of function in the left anterior temporal lobe may lead to 'paradoxical functional facilitation' of artistic and musical skills". Application of rTMS to the left anterior temporal lobe has been previously reported to increase savant-like skills both in drawing (Snyder et al 2003; Young et al 2004) and in proofreading (Snyder et al 2003). Furthermore, Oliveri et al (2004) found that participants were less accurate in interpreting the meaning of opaque idioms, ie they became more literal after rTMS to the left temporal lobe.

Recent brain-imaging studies of normal individuals show convincingly that the parietal cortex is associated with numerosity estimation (Piazza et al 2002, 2004; Dehaene et al 2004; Butterworth 2005). These findings are not in conflict with those of ours, resulting from applying rTMS to the left anterior temporal lobe. We recognise that the parietal cortex plays a significant role in number estimation, but we argue here for the possibility that rTMS affects the information upon which that estimation is performed.

4.4 *Why does rTMS improve a person's savant-like ability to accurately guess numbers of items?*
It is interesting to speculate on how rTMS could give rise to savant-like skills. It was originally suggested that savant-like skills could be expressed in normal people by using rTMS to simulate the savant condition, possibly by inhibiting the part of the brain concerned with meaning and concepts (Carter 1999; Snyder and Mitchell 1999). One possibility is that, in the normal brain, the conceptual networks tend to inhibit networks concerned with detail (Snyder et al 2004). By inhibiting networks involved in concepts, we may facilitate conscious access to literal details, leading to savant-like skills.

The above theoretical framework accords with current neurophysiology. The possibility that cortical areas responsible for concepts could inhibit those concerned with spatial detail is consistent with evidence about hemispheric competition (Kapur 1996; Ramachandran 2004; Goldberg 2005), as is also the possibility of reversing the inhibition by suppressing the dominant cortical area with rTMS (Oliveri et al 1999, 2004; Hilgetag et al 2001; Théoret et al 2003; Sack et al 2005).

In particular, Hilgetag et al (2001) conclude that "competition between different brain structures might, thus, be a general principle of brain function (Walsh et al 1998) and may explain the paradoxical behavioural enhancement or recovery observed after various brain lesions (Kapur 1996; Hilgetag et al 1999)"; furthermore, that "... impairment induced by rTMS disinhibits the contralateral cortex and thus leads to improved attentional performance" (Hilgetag et al 2001).

In summary, the observed improvement in participants' numerosity, following the application of rTMS to the left anterior temporal lobe, is predicted by theory, is consistent with the left-brain dysfunction implicated in the savant condition, and accords with contemporary views about hemispheric competition and the disinhibiting influence of rTMS.

Acknowledgments. We thank Thor Næss, Abbie Hughes, Michael Harré, Terry Bossomaier, Sophie Ellwood, and Gerry Pallier for insightful discussions.

References

Barth H, Kanwisher N, Spelke E, 2003 "The construction of large number representation in adults" *Cognition* **86** 201 – 221
Blom J L, Anneveldt M, 1982 "An electrode cap tested" *Electroencephalography and Clinical Neurophysiology* **54** 591 – 594
Boles D B, 1986 "Hemispheric differences in the judgement of number" *Neuropsychologia* **24** 511 – 519
Burgess A, Barlow H B, 1983 "The precision of numerosity discrimination in arrays of random dots" *Vision Research* **23** 811 – 820
Butterworth B, 1999 *The Mathematical Brain* (London: Macmillan)
Butterworth B, 2005 "The development of arithmetical abilities" *Journal of Child Psychology and Psychiatry* **46** 3 – 18
Carter R, 1999 "Turn off tune in" *New Scientist* **164** 30 – 34
Colvin M K, Funnell M G, Gazzaniga M, 2005 "Numerical processing in the two hemispheres: Studies of a split-brain patient" *Brain and Cognition* **57** 43 – 52
Dehaene S, 1997 *The Number Sense: How the Mind Creates Mathematics* (Oxford: Oxford University Press)
Dehaene S, Molko N, Cohen L, Wilson A J, 2004 "Arithmetic and the brain" *Current Opinion in Neurobiology* **14** 218 – 224
Feigenson L, Dehaene S, Spelke E, 2004 "Core systems of number" *Trends in Cognitive Sciences* **8** 307 – 314
Frith U, Hill E, 2003 *Autism: Mind and Brain* (Oxford: Oxford University Press) p. 9
Ginsburg N, 1976 "Effect of item arrangement on perceived numerosity: Randomness vs regularity" *Perceptual & Motor Skills* **43** 663 – 668
Ginsburg N, 1991 "Numerosity estimation as a function of stimulus organization" *Perception* **20** 681 – 686
Ginsburg N, Goldstein S R, 1987 "Measurement of visual cluster" *American Journal of Psychology* **100** 193 – 203
Goldberg E, 2005 *The Wisdom Paradox* (New York: Gotham)
Gregory R L, 1970 *The Intelligent Eye* (London: Weidenfeld and Nicholson)
Gregory R L, 2004 "Illusions", in *The Oxford Companion to the Mind* Ed. R L Gregory, 2nd edition (Oxford: Oxford University Press) pp 426 – 441
Herbert M R, Ziegler D A, Deutsch C K, O'Brien L M, Kennedy D N, Filipek P A, Bakardjiev A I, Hodgson J, Takeoka M, Makris N, Caviness V S J, 2005 "Brain asymmetries in autism and developmental language disorder: a nested whole-brain analysis" *Brain* **128** 213 – 226
Hilgetag C C, Kötter R, Young M P, 1999 "Inter-hemispheric competition of sub-cortical structures is a crucial mechanism in paradoxical lesion effects and spatial neglect" *Progress in Brain Research* **121** 121 – 141
Hilgetag C C, Théoret H, Pascual-Leone A, 2001 "Enhanced visual spatial attention ipsilateral to rtms-induced 'virtual lesions' of human parietal cortex" *Nature Neuroscience* **4** 953 – 957
Hoffman R E, Cavus L, 2002 "Slow transcranial stimulation, long-term depotentiation, and brain hyperexcitability disorders" *American Journal of Psychiatry* **159** 1093 – 1102
Hou C, Miller B L, Cummings J L, Goldberg M, Mychack P, Bottino V, Benson D F, 2000 "Artistic savants" *Neuropsychiatry, Neuropsychology and Behavioral Neurology* **13** 29 – 38
Howe M J A, 1989 *Fragments of Genius* (London: Routledge)
Humphrey N, 2002 "Comments on shamanism and cognitive evolution" *Cambridge Archaeological Journal* **12** 91 – 94
Jevons S W, 1871 "The power of numerical discrimination" *Nature* **3** 281 – 282
Kapur N, 1996 "Paradoxical functional facilitation in brain-behaviour research. A critical review" *Brain* **119** 1775 – 1790
Keel J C, Smith M J, Wassermann E M, 1999 "A safety screening questionnaire for transcranial magnetic stimulation" *Clinical Neurophysiology* **112** 720
Koshino H, Carpenter P A, Minshew N J, Cherkassky V L, Keller T A, Just M A, 2005 "Functional connectivity in an mri memory task in high-functioning autism" *Neuroimage* **24** 810 – 821

Krueger L E, 1984 "Perceived numerosity: a comparison of magnitude production, magnitude estimation and discrimination judgements" *Perception & Psychophysics* **35** 536 – 542
Miller B L, Boone K, Cummings J L, Read S L, Mishkin F, 2000 "Functional correlates of musical and visual ability in frontotemporal dementia" *British Journal of Psychiatry* **176** 458 – 463
Miller B L, Cummings J, Mishkin F, Boone K, Prince F, Ponton M, Cotman C, 1998 "Emergence of artistic talent in fronto-temporal dementia" *Neurology* **51** 978 – 982
O'Connor N O, 1989 "The performance of the 'idiot savant': Implicit and explicit" *British Journal of Disorders of Communication* **24** 1 – 20
Oliveri M, Romero L, Papagno C, 2004 "Left but not right temporal involvement in opaque idiom comprehension: A repetitive transcranial magnetic stimulation study" *Journal of Cognitive Neuroscience* **16** 848 – 855
Oliveri M, Rossini P M, Traversa R, Cicinelli P, Palmieri M G, Pasqualetti P, Tomaiuolo F, Caltagirone C, 1999 "Left frontal transcranial magnetic stimulation reduces contralesional extinction in patients with unilateral right brain damage" *Brain* **122** 1731 – 1739
O'Riordan M A, 2004 "Superior visual search in adults with autism" *Autism* **8** 229 – 248
O'Riordan M, Plaisted K, Driver J, Baron-Cohen S, 2001 "Superior visual search in autism" *Journal of Experimental Psychology: Human Perception and Performance* **27** 719 – 730
Pascual-Leone A, Bartres-Fox D, Keenan J P, 1999 "Transcranial magnetic stimulation: studying the brain-behaviour relationship by induction of 'virtual lesions' " *Philosophical Transactions of the Royal Society of London, Series B* **354** 1229 – 1238
Piazza M, Izard V, Pinel P, Le Bihan D, Dehaene S, 2004 "Tuning curves for approximate numerosity in the human intraparietal sulcus" *Neuron* **44** 547 – 557
Piazza M, Mechelli A, Butterworth B, Price C J, 2002 "Are subitizing and counting implemented as separate or functionally overlapping processes" *Neuroimage* **15** 435 – 446
Ramachandran V S, 2004 *A Brief Tour of Consciousness* (London: Pearson Education)
Rimland B, 1963 *Infantile Autism* (New York: Appleton-Century-Crofts)
Robertson E M, Théoret H, Pascual-Leone A, 2003 "Studies in cognition: The problems solved and created by transcranial magnetic stimulation" *Journal of Cognitive Neuroscience* **15** 948 – 960
Sack A T, Camprodon J A, Pascual-Leone A, Goebel R, 2005 "The dynamics of inter-hemispheric compensatory processes in mental imagery" *Science* **308** 702 – 704
Sacks O, 1986 *The Man Who Mistook His Wife for a Hat* (London: Picador) p. 185
Sacks O, 2003 "The minds eye" *The New Yorker*, 28 July 2003, 48 – 59
Scripture E W, 1891 "Arithmetical prodigies" *American Journal of Psychology* **4** 1 – 59
Snyder A W, 2004 "Autistic genius?" *Nature* **428** 470 – 471
Snyder A W, Barlow H B, 1988 "Revealing the artist's touch" *Nature* **331** 117 – 118
Snyder A, Bossomaier T, Mitchell D J, 2004 "Concept formation: 'object' attributes dynamically inhibited from conscious awareness" *Journal of Integrative Neuroscience* **3** 31 – 46
Snyder A, Mitchell D J, 1999 "Is integer arithmetic fundamental to mental processing? The mind's secret arithmetic" *Proceedings of the Royal Society of London, Series B* **266** 587 – 592
Snyder A W, Mulcahy E, Taylor J L, Mitchell D J, Sachdev P, Gandevia S C, 2003 "Savant-like skills exposed in normal people by suppressing the left front-temporal lobe" *Journal of Integrative Neuroscience* **2** 149 – 158
Théoret H, Kobayashi M, Valero-Cabre A, Pascual-Leone A, 2003 "Exploring paradoxical functional facilitation with tms" Supplement to *Clinical Neurophysiology* **56** 211 – 219
Treffert D A, 2000 *Extraordinary People: Understanding Savant Syndrome* (http://backinprint.com) p. 93
Treffert D A, 2005 "The savant syndrome in autistic disorder", in *Recent Developments in Autism Research* Ed. M F Cassanova (Nauppauge, NY: Science Publishers) pp 27 – 55
Walsh V, Cowey A, 2000 "Transcranial magnetic stimulation and cognitive neuroscience" *Nature Reviews Neuroscience* **1** 73 – 79
Walsh V, Ellison A, Battelli L, Cowey A, 1998 "Task-specific impairments and enhancements induced by magnetic stimulation of human visual area V5" *Proceedings of the Royal Society of London, Series B* **265** 537 – 543
Wassermann E M, 1998 "Risk and safety of repetitive transcranial magnetic stimulation: Report and suggested guidelines from the international workshop on the safety of repetitive transcranial magnetic stimulation, June 5 – 7, 1996" *Electroencephalography and Clinical Neurophysiology* **108** 1 – 16
Wolford G, Miller M B, Gazzaniga M, 2000 "The left hemisphere's role in hypothesis formation" *Journal of Neuroscience* **20**(RC64) 1 – 4
Young R L, Ridding M C, Morrell T L, 2004 "Switching skills on by turning off part of the brain" *Neurocase* **10** 215 – 222