Brain damage

Neglect disrupts the mental number line

A popular metaphor for the representation of numbers in the brain is the 'mental number line', in which numbers are represented in a continuous, quantity-based analogical format[1,2]. Here we show that patients with hemispatial neglect[3] misplace the midpoint of a numerical interval when asked to bisect it (for example, stating that five is halfway between two and six), with an error pattern that closely resembles the bisection of physical lines[4]. This new form of representational neglect constitutes strong evidence that the mental number line is more than simply a metaphor, and that its spatial nature renders it functionally isomorphic to physical lines.

Although few of us think of numbers in spatial terms[5], psychophysical evidence suggests that the mental representation of numbers has a spatial nature, possibly with a left–right orientation[6]. First, both humans[7] and primates[8] are quicker and more accurate in selecting the greater of two numbers when the numerical distance between them is large than when it is small. Second, smaller numbers are responded to faster with the left hand and larger ones with the right hand[6,9].

Patients with unilateral neglect resulting from a (right) parietal lesion show a spatial deficit for left-side stimuli, which also extends to mental images[3]. When asked to mark the midpoint of a line, they miss the midpoint and place it to the right. The misplacement increases as a function of line length, with a crossover effect (leftward displacement) for very short lines[4]. We therefore investigated whether these patients show the same form of distortion when bisecting the mental number line.

We tested four right-brain-damaged patients with persistent left neglect, four right-brain-damaged patients without spatial neglect, and four healthy control subjects. All patients showed intact numerical and arithmetic skills. In particular, they achieved near-perfect scores in subtraction and number comparison, two tasks that tap the core deficit in parietal acalculia[10] after lesion of the language-dominant hemisphere. Participants heard two numbers that defined a number interval and were asked to state the midpoint number without making calculations. The size of the interval could be three (for example, 1–3), five, seven or nine. Each interval was presented using the units (for example, 1–5), the teens (11–15) and the first tens (21–25), giving a total of 48 trials. Two neglect patients and all control subjects repeated the task using reverse presentation of the same number pairs (for example, 9–1).

Neglect patients made many errors (individuals' error rates: O.V., 39.58%; G.Z.A., 37.5%; G.Z.E., 31.25%; G.S., 35.41%). Performance was significantly affected by the size of the number interval (Fig. 1a). For the three patients who made errors at the smallest interval, their midpoint answers were significantly shifted to the 'left' in the number line (for example: interval, 11–13; suggested midpoint, 10). For longer intervals, right-shifted errors were more common (for example, 11–19; 17); this phenomenon increased as a function of interval size. Reverse presentation produced the same pattern, showing that the number line is canonically orientated[11] in a left-to-right manner. Control subjects made few errors and their performance was not affected by interval size (Fig. 1b). The magnitude of numbers used did not influence the performance of any of the groups of participants.

The systematic midpoint shift observed here is indeed produced by neglect — one control patient had a comparable error rate (31%) to that of the neglect patients, but his errors were not modulated by interval size and were randomly distributed between leftward and rightward shifts (16 left, 14 right). Moreover, the pattern of errors shown by neglect patients does not resemble that of parietal acalculics[10,12] (the only other patients known to experience difficulty with this task), who fail in a variety of tasks that require manipulation of numerical quantities and can perform extremely poorly in number bisection (error rates can be as high as 77%; ref. 12).

The performance of neglect patients closely mirrors their difficulty in bisecting physical lines[4]. This demonstrates the spatial nature of the mental number line and its striking functional isomorphism to physical lines. Although most people focus on symbolic aspects of numbers, and few seem to be aware of the intimate relationship between numbers and visuo-spatial representations, thinking of numbers in spatial terms (as has been reported by great mathematicians[13]) may be more efficient because it is grounded in the actual neural representation of numbers.

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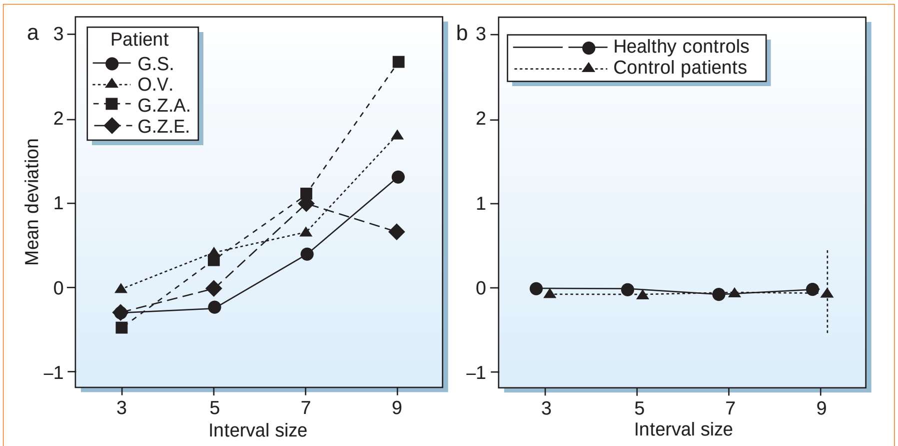

Figure 1 Displacement error with respect to the midpoint (0) of a numerical interval as a function of interval size. Positive values indicate rightward shifts of the midpoint along the number line; negative values represent leftward shifts. **a,** Performance of neglect patients (mean age, 63 yr; education, 9 yr). All had single, hypodense brain lesions limited to the right hemisphere (fronto-temporo-parietal lesion, $n=3$; fronto-parietal lesion, $n=1$; mean time since lesion, 78 days). Regression analyses revealed that the performance of all patients was significantly affected by interval size (G.S., $\beta=0.40$, $P<0.001$; O.V., $\beta=0.54$, $P<0.001$; G.Z.A., $\beta=0.62$, $P<0.001$; G.Z.E., $\beta=0.36$, $P<0.01$). For G.S., G.Z.A. and G.Z.E., the occurrence of a leftward midpoint shift for the smallest interval was significant (16 out of 18 trials, $P=0.001$, binomial test). The magnitude of the numbers used was not a significant factor in the regressions (G.S., $\beta=0.09$, n.s.; O.V., $\beta=0.08$, n.s.; G.Z.A., $\beta=0.08$, n.s.; G.Z.E., $\beta=0.04$, n.s.). **b,** Mean performance ($\pm$standard error) of control patients (mean age, 58 yr; education, 5.2 yr) and healthy controls (mean age, 63 yr; education, 9 yr). Two control patients and three healthy controls made no errors (0 out of 96 trials). One healthy control and one control patient made some errors (error rates, 5.2% and 12.5%, respectively); these were all shifted to the left of the midpoint. The performance of the control patient who made a considerable number of errors (error rate, 31.2%) was not spatially biased (16 leftward shifts, 14 rightward) and was not affected by interval size ($\beta=0.07$, n.s.) or numerical magnitude ($\beta=0.01$, n.s.).

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Electrochemistry

Building on bubbles in metal electrodeposition

In the electrodeposition of metals, a widely used industrial technique, bubbles of gas generated near the cathode can adversely affect the quality of the metal coating. Here we use phase-contrast radiology with synchrotron radiation to witness directly and in real time the accumulation of zinc on hydrogen bubbles. This process explains the origin of the bubble-shaped defects that are common in electrodeposited coatings.

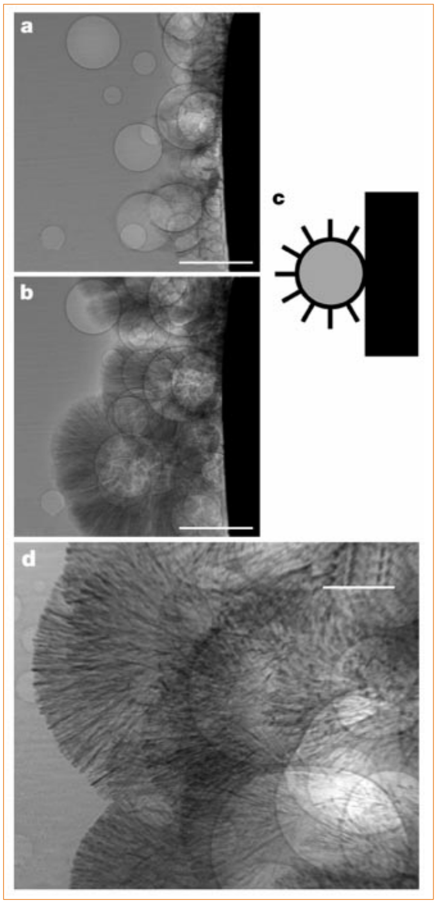

Figure 1 Phase-contrast microradiographs showing the growth of zinc on hydrogen bubbles. **a, b,** Images (taken 6 s apart) showing growth of zinc dendrites. **c,** Diagram of radial dendritic growth along the electric-field lines. **d,** Image showing the microstructure of the dendrites. Radiographs were taken at the Pohang Light Source in Korea and at the Synchrotron Radiation Research Center in Hsinchu, Taiwan. Deposition was carried out in a mini electrochemical cell with a small (about 5 mm) thickness of electrolyte solution between the windows to reduce X-ray absorption, and a variable (about 8 mm) electrode gap. The electrode was covered with epoxy, which prevented conduction, except for the X-ray-detection window. The base solution was 4.8 M KCl and 2.2 M $ZnCl_2$. Scale bars, 300 μm (**a**, **b**) and 200 μm (**d**).

Gas bubbles are an important problem in electrodeposition coating. For example, too much hydrogen typically gives rise to porous films with poor adhesion[1,2]. Surface treatments are often used to solve this problem[3–5].

The bubble phenomenon has eluded experimental clarification for decades because of a lack of probes with adequate temporal and spatial resolution and sufficient penetration to show the pattern and development of the coating's microstructural detail.

We have used a new real-time technique known as phase-contrast radiology[6,7] to demonstrate that zinc can grow directly on gas bubbles, leading to the formation of voids in the coating. The technique, which generates images that reflect differences in refractive index, is more effective than conventional absorption-based radiology.

Phase-contrast radiology depends on coherent X-rays from synchrotron sources[6,7]. Even with the best sources, however, real-time studies with high spatial resolution are difficult or impossible to carry out. We have solved this problem by using unmonochromatized synchrotron X-rays (that is, X-rays with limited longitudinal coherence)[6,7].

Previously, research on bubbles in electrodeposition processes has relied mainly on quantitative measurements of hydrogen formation and *ex situ* characterization of coatings. The presence of bowl- and tube-shaped voids suggested negative bubble fingerprints[8], but no direct evidence corroborated this possibility.

Instead, our results directly link the coating morphology with the hydrogen bubbles. For example, Fig. 1a, b shows the simultaneous formation of bubbles and zinc dendrites. The images reveal that the metal coating is formed directly on the bubble surface, with the zinc dendrites growing out radially (Fig. 1c). Figure 1d shows the microstructure of these dendrites.

Under varying experimental conditions, we found zinc growing on bubbles not only as dendrites but also as films and in other forms. We did not observe any deposition on bubbles that were not connected to the electrode (Fig. 1a), a finding that rules out electroless deposition.

On the basis of these results, we developed a model to explain the effect of bubbles on metal-coating quality. In this model, a bubble is generated and adheres to the electrode surface; zinc nucleation then occurs at high-surface-energy sites on the electrode–bubble interface, producing microstructures that perturb the local electric field. This enables zinc deposition to extend laterally over the bubble surface, covering the entire bubble. Dendrites then grow radially, following the configuration of the electric field (Fig. 1c).

The metallic film and the dendrite structure are able to stabilize the bubble-related shape. When the deposited metal becomes sufficiently dense, permanent voids are left inside the film, giving rise to defects in the coating.

This mechanism requires a charge-transfer medium. Zinc hydroxide (which, like most metal hydroxides, is an electrical conductor[9]) is the most likely candidate. $Zn(OH)_2$ can be generated as follows:

$$2H_2O + 2e^- \rightarrow H_2 + 2OH^-$$
$$Zn^{2+} + 2OH^- \rightarrow Zn(OH)_2$$

Reduction of hydrogen increases the concentration of zinc hydroxide near the cathode surface[10–13]. A similar process probably occurs near the bubble surface, resulting in deposition of zinc. We tested this idea by injecting hydrogen into the solution to form hydrogen–electrolyte–electrode interfaces. No zinc was deposited on these interfaces, ruling out the unlikely possibility that the bubbles act directly as charge carriers.

Phase-contrast radiology can be put to several other uses — for example, we have generated dynamic maps of density in the electrolytic solution. Our discovery that metal coatings can literally be built on bubbles finally confirms what has long been suspected.

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