A spelling device for the paralysed

When Jean-Dominique Bauby suffered from a cortico-subcortical stroke that led to complete paralysis with totally intact sensory and cognitive functions, he described his experience in *The Diving-Bell and the Butterfly*[1] as "something like a giant invisible diving-bell holds my whole body prisoner". This horrifying condition also occurs as a consequence of a progressive neurological disease, amyotrophic lateral sclerosis, which involves progressive degeneration of all the motor neurons of the somatic motor system. These 'locked-in' patients ultimately become unable to express themselves and to communicate even their most basic wishes or desires, as they can no longer control their muscles to activate communication devices. We have developed a new means of communication for the completely paralysed that uses slow cortical potentials (SCPs) of the electroencephalogram to drive an electronic spelling device.

The neurophysiological basis and behavioural functions of SCPs have been described[2], and operant conditioning has been used to bring them under voluntary control. We have shaped the voluntary control of SCPs in two locked-in patients with amyotrophic lateral sclerosis who were able to learn to operate a spelling device by regulating their brain responses. The spelling device drives a cursor on a video screen, allowing the subjects to select letters of the alphabet. Previous interfaces between brains and computers have used different brain responses, such as certain frequency bins or event-related brain potentials[3,4], but these have not yet been tested with locked-in patients.

Both subjects suffer from advanced amyotrophic lateral sclerosis and have been artificially respirated and fed for four years. Sustained voluntary control of the musculature was not possible in either patient, so they were unable to use a muscle-driven communication device. They were trained to produce changes voluntarily in their SCPs lasting 2–4 seconds. Each trial consisted of a 2-second baseline and a response period lasting 2–4 seconds, the length of which was adapted to suit the patient. A training day consisted of 6–12 sessions (depending on the condition of the patient), each of which comprised about 70 to 100 trials and lasted about 5–10 minutes.

During the response period, the subjects were required to produce either negativity or positivity greater than a specific criterion amplitude in random order. The baseline and response periods were signalled by two clearly different tones, and whether positivity or negativity was required was indicated

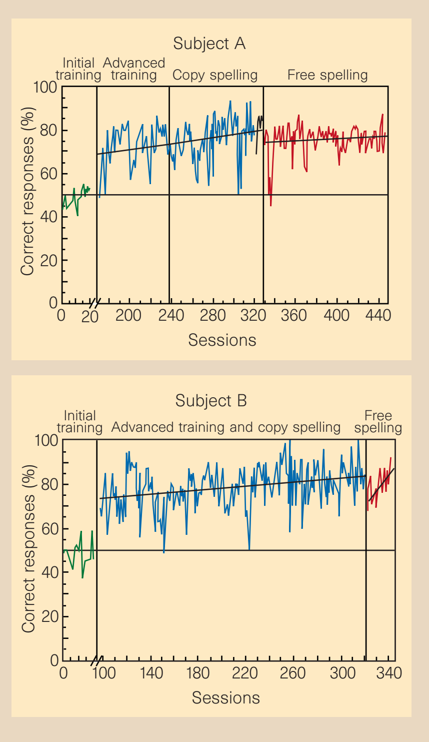

Figure 1 Response accuracy of subjects using the new spelling device. Subject A began with feedback training of SCP amplitude (initial and advanced training; 71.3% correct selections, 75.0% correct rejections, based on 'go-back' responses), proceeded to copy spelling (copying of letters and then words; 78.7%, 75.3%) and finally to free spelling (self-selected letters; 66.4%, 82.9%). Subject B began with initial training, then switched to a combination of advanced training (77.5%, 68.8%) and copy spelling (77.5%, 67.6%) and finally to free spelling (86.2%, 73.7%).

by a box being highlighted in either the upper (negativity) or the lower (positivity) half of the screen. Visual feedback of SCPs, which was updated every 64 ms, was provided by a ball that moved towards or away from the box, depending on the direction in which the SCP deviated from baseline. The response criterion was progressively increased from 5 to 8 μV.

SCPs were extracted from the regular electroencephalogram using a time constant of 8 s and a low-pass filter of 40 Hz. They were recorded from the vertex relative to linked mastoids at a sampling rate of 256 Hz. Vertical eye movements were simultaneously recorded with standard on-line removal of eye-movement artefacts[2]. Using an imagery strategy[5], both patients were better able to produce positivity than negativity, so training for negativity was soon discontinued. As soon as a stable performance of at least 75% correct (hitting the goal for at least 500 ms)

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Figure 2 The first full message written by subject A.

responses at the 8-μV level was achieved, the patients began to work with the spelling device. Subject A achieved this level after 327 sessions and subject B achieved it after 288 sessions (Fig. 1).

For the spelling program at level 1, the alphabet was split into two halves (letter banks) which were presented successively at the bottom of the screen for 4.5 seconds (subject A) or 6 seconds (subject B). If the subject selected the letter bank being shown by generating a SCP, it was split into two new halves, and so on until each of the two letter banks had only one letter in it. When one of the two final letters was selected, it was displayed in the top text field of the screen and then the selection began again at level 1. A 'go back' function, which appeared as an option when two successive letter banks had not been selected, allowed the speller to go back one step to the previous set of letter banks. If the speller was at level 1, selecting this function erased the last symbol written in the text field, so mistakes could be corrected. This procedure was chosen after extensive pilot work[6] involving different types of speller.

The accuracy of responses during feedback training, copy spelling and free spelling is shown in Fig. 1 for both patients over the course of 446 (subject A) and 308 sessions (subject B). Two types of error were possible: incorrect rejection was due to the SCP amplitude being too low, and incorrect selection occurred when a high SCP was made in the presence of a wrong letter or row of letters. Both subjects can now write messages. The first full message written entirely by the brain of subject A is shown in Fig. 2.

Our data indicate that patients who lack muscular control can learn to control variations in their SCPs sufficiently accurately to operate an electronic spelling device. Although writing sentences is time consuming — subject A took 16 hours to write the message in Fig. 2, a rate of about 2 characters per minute — it is reliable and precise enough to allow the patient to communicate with his or her environment. These completely paralysed individuals now have the ability to communicate, a possibility that has not previously existed for such severely affected patients.

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Insect antenna as a smoke detector

The larvae of jewel beetles of the genus *Melanophila* (Buprestidae) can develop only in the wood of trees freshly killed by fire[1]. To arrange this, the beetles need to approach forest fires from as far as 50 kilometres away[1,2]. They are the only buprestid beetles known to have paired thoracic pit organs[3], which behavioural[2], ultrastructural[4] and physiological experiments[5] have shown to be highly sensitive infrared receptors, useful for detecting forest fires. It has been suggested that *Melanophila* can sense the smoke from fires[6], but behavioural experiments failed to show that crawling beetles approach smoke sources[2]. We find that the antennae of jewel beetles can detect substances emitted in smoke from burning wood.

We connected freshly excised antennae from *M. acuminata* ($n=5$) to a gas chromatograph equipped with parallel flame ionization and electroantennographic detectors[7]. Volatiles generated by smouldering splint wood from *Pinus sylvestris* were collected on a charcoal trap, chemodesorbed by an organic solvent, and injected into the apparatus. The resulting chromatograms indicated that several components of these volatiles were biologically active (Fig. 1). Most of the volatiles perceived by the antennae are phenolic compounds, derivatives of 2-methoxyphenol (guaiacol) eliciting the greatest response.

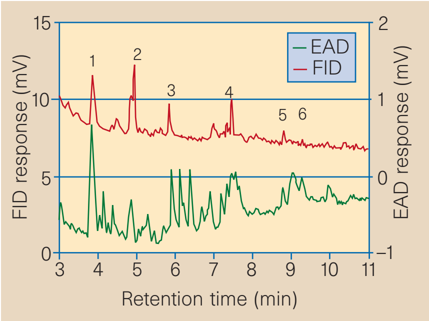

Figure 1 Typical gas chromatograms. Two detectors were used: a flame-ionization detector (FID), indicating any oxidizable compound; and an electroantennographic detector (EAD), using an isolated antenna of *Melanophila acuminata*. The sample contains volatiles released by 1 g of smouldering wood in 1 s, a quantity typically transported over long distances. The FID response indicates quantities of the mixture's components. The EAD response (amplified by a factor of 100) indicates the electrophysiological response of the antenna to: 1, α-pinene; 2, carene; 3, 2-methoxy-phenol (guaiacol); 4, 2-methoxy-4-methyl-phenol (4-methyl-guaiacol); 5, 4-acetyl-guaiacol; 6, 4-formyl-guaiacol. The two peaks only in the EAD trace (retention times of 6.0 to 6.5 min) indicate substances detected by antennae at concentrations below the detection limit of the FID: 10 ng per ml of carrier gas); presumably, they are isomers of compound 3.

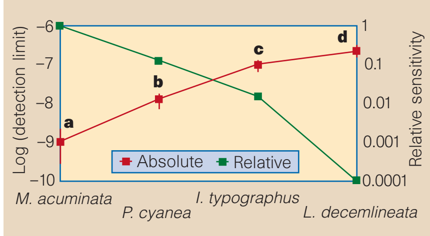

Figure 2 Absolute and relative sensitivities of pyrophilic and non-pyrophilic insects to guaiacol. Absolute detection limits were estimated by fitting logistic curves to dose–response data. The concentrations where confidence intervals (at 0.05) of average control responses did not overlap with confidence belts of fit functions were regarded as the limits of detection. Error bars show standard deviations. Letters indicate significantly differing responses (Mann–Whitney *U* test, $P<0.05$) to concentrations at detection limits. For insects infesting pine trees, α-pinene was chosen as a reference substance for obtaining relative sensitivities, as it is a typical constituent of host plant odour with a low detection limit. (*Z*)-3-hexen-1-ol was chosen for the Colorado potato beetle (*L. decemlineata*) as a sensitively detected constituent of its host plant odour.

Methoxylated phenols are released by the incomplete combustion of lignin[8] and have been identified as atmospheric markers of wood smoke. The chemical structure of the phenolic compounds in smoke is dependent on the species of tree attacked by fire[9]. Because it is particularly sensitive to guaiacol derivatives, *Melanophila* can detect remote forest fires and might even be able to use the pattern of volatiles to identify the species of tree. Our results therefore indicate that the beetles can perceive a fire-damaged *P. sylvestris* tree by olfactory cues.

The beetles' antennae can detect these guaiacol derivatives at concentrations as low as a few parts per billion (p.p.b.) (Fig. 2). We estimate[10] that this sensitivity is sufficient for the beetle to detect a single pine tree 30 cm in diameter that has smouldering bark to a height of 2 m and a bark depth of 1 cm, releasing about 7 g of guaiacol in an hour under light wind conditions (0.3 m s^{-1}), from a distance of more than 1 km.

M. acuminata shows a high absolute (1.1 ± 0.8 pg ml^{-1}, $n=14$) and relative sensitivity to guaiacol. For comparison, we also studied the sensitivity to guaiacol of three other beetles. The pulp-feeding forest pest *Phaenops cyanea* attacks weakened trees and sometimes breeds in trees that have previously been damaged by fire. It is closely related to *M. acuminata*, but its attraction to fire-damaged trees is less pronounced. Its sensitivity to guaiacol is slightly lower at 15 ± 7 pg ml^{-1} ($n=11$). The bark beetle *Ips typographus* is a pulp-feeding forest pest without detectable attraction to fire-damaged trees, but some sensitivity to guaiacols is expected because pulp also contains guaiacol. It shows only a moderate absolute (120 ± 65 pg ml^{-1}, $n=9$) and relative sensitivity to this compound. The Colorado potato beetle, *Leptinotarsa decemlineata*, is a non-pyrophilic pest that is not attracted to fire-damaged trees, although it exhibits escape behaviour in response to high concentrations of fire-generated volatiles. It does not show such specialized sensitivity (450 ± 160 pg ml^{-1}, $n=24$) to guaiacol derivatives. These values reflect the relative degree of specialization to fire detection.

In the same way that infrared-sensitive pit vipers and boid snakes use chemoreceptors on their tongue to detect volatiles released by their prey, *Melanophila* beetles use chemoreceptors sensitive to the specific volatiles of burning wood. It is unclear how the two sensory systems used by *Melanophila* to identify fire — the thoracic infrared receptors and the antennal olfactory receptors — act together to detect fire and orientate the beetle towards its source.

Understanding how the beetles detect fires could have applications in fire detection devices[11] in storehouses and public buildings, for example, as well as in early-warning detection systems for forest fires.

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