Inducing a virtual hand ownership illusion through a brain–computer interface

Daniel Perez-Marcos[a], Mel Slater[b,c] and Maria V. Sanchez-Vives[a,b]

The apparently stable brain representation of our bodies is easily challenged. We have recently shown that the illusion of ownership of a three-dimensional virtual hand can be evoked through synchronous tactile stimulation of a person's hidden real hand and that of the virtual hand. This reproduces the well-known rubber-hand illusion, but in virtual reality. Here we show that some aspects of the illusion can also occur through motor imagery used to control movements of a virtual hand. When movements of the virtual hand followed motor imagery, the illusion of ownership of the virtual hand was evoked and muscle activity measured through electromyogram correlated with movements of the virtual arm. Using virtual bodies has a great potential in the fields of physical and neural rehabilitation, making the understanding of ownership of a virtual body highly relevant. *NeuroReport* 20:589–594 © 2009 Wolters Kluwer Health | Lippincott Williams & Wilkins.

NeuroReport 2009, **20**:589–594

Keywords: body illusion, body perception, body representation, body scheme, brain–computer interface, rehabilitation, virtual environments, virtual reality

[a]Institut d'Investigacions Biomèdiques August Pi i Sunyer, [b]Institució Catalana de Recerca i Estudis Avançats and [c]Centre de Realitat Virtual, Universitat Politècnica de Catalunya, Barcelona, Spain

Correspondence to Maria V. Sanchez-Vives, IDIBAPS, Villarroel,
170, Barcelona 08036, Spain
Tel: +93 2275400 x4301; e-mail: msanche3@clinic.ub.es

Received 6 January 2009 **accepted** 30 January 2009

Introduction

A variety of illusions have shown that body image representation is highly malleable. Multisensory correlations can generate the illusion of changes to one's body, or indeed a feeling that external objects might be part of one's body [1–3]. In the rubber-hand illusion [1], tactile stimulation of a person's hidden real hand in synchrony with touching a substitute rubber hand placed in a plausible position results in an illusion of ownership of the rubber hand. There is also a measurable proprioceptive displacement of the location of the arm towards the location of the rubber one. If the multisensory input provided is asynchronous, the illusion does not occur.

We recently demonstrated that even a computer-generated three-dimensional (3D) virtual arm could be integrated into the body representation when similar synchronous multisensory correlations are provided [2]. We found that not only is the perceptual system deceived by this 'virtual hand illusion', but also that the strength of the illusion was correlated with the degree of motor activity in the real arm following movement of the virtual arm. This is also a powerful illustration of presence in virtual environments, that is the tendency for people to respond to virtual situations and events as if these were real [4] – in this case their feeling of ownership of a virtual limb that apparently replaces their real limb.

Brain–computer interfaces (BCI) support communication with external objects using different brain signals, for example, slow cortical potentials [5,6], event-related desynchronization [7,8], or P300 [9], among others. Here we explore what happens when visuotactile correlations are replaced by synchrony between the thought of moving the hand (motor imagery) and the seen movements of a virtual hand and arm that is apparently attached to the person's body. Our experiment explores whether the control of a virtual arm through a noninvasive BCI can induce the illusion of ownership, proprioceptive displacement, and agency towards that arm, in the absence of tactile sensory stimulation. Motor agency, understood as the sense of intending and executing actions including the feeling of controlling own body movements, has been suggested as an important factor for the coherence experience of the body [10], while activity in the premotor cortex has been proposed to underlie ownership of a seen hand [11].

Methods

Virtual reality system

The virtual reality set-up was composed of a tracking system (Intersense Bedford, Massachusetts, USA) with a six-degrees-of-freedom head tracker and a 2 × 2.7 m screen, where stereoscopic 3D images are back projected from two projectors. The virtual environment was developed under the XVR platform (VRMedia, Pontedera, Italy). Participants wore polarized glasses for passive stereo vision.

Mel Slater is currently an ICREA Research Professor at the University of Barcelona

0959-4965 © 2009 Wolters Kluwer Health | Lippincott Williams & Wilkins

DOI: 10.1097/WNR.0b013e32832a0a2a

Recording system

Data were acquired with the g.USBamp amplifier (Guger Technologies, Graz, Austria). The high-speed online processing toolbox (Guger Technologies) running under Simulink/MATLAB (Mathworks Inc., Natick, Massachusetts, USA) was used for real-time parameter extraction and saving.

Participants

Sixteen male participants (26.1 ± 9.4 years old) were selected for the experiment, all but one was right handed. They read and signed a consent form, in accordance with the regulations of the Comité Ético de Investigación of the Hospital Universitario de San Juan de Alicante, Spain. Participants were novices both with respect to BCI training and the virtual/rubber hand illusion.

Experimental design

The experiment was divided into two stages: training and testing. In both, participants completed a standard motor imagery task where they carried out repetitive imaginary left hand or right foot movements, while their electroencephalographic (EEG) activity was recorded (Fig. 1a). The experiment was carried out in a dark room, the only light coming from the screen.

Training stage

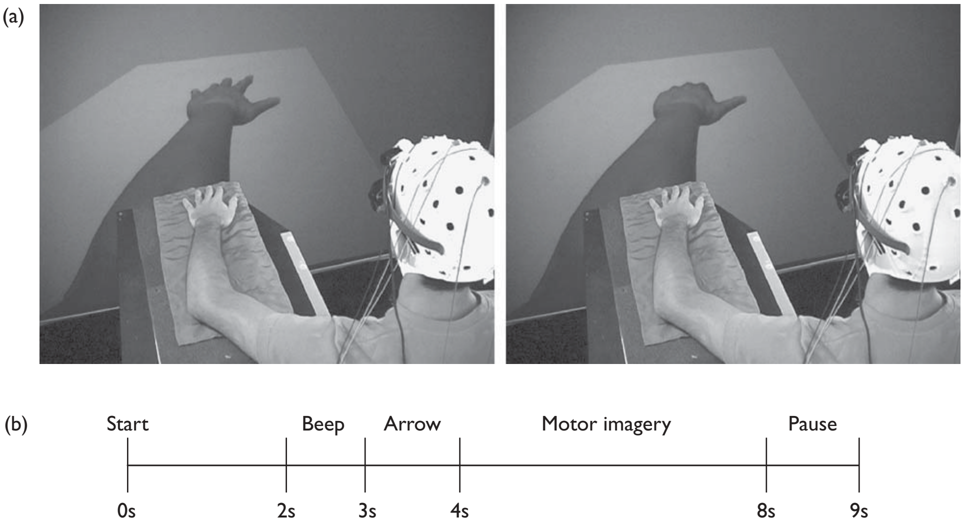
First, participants completed a short training session. Volunteers sat by a desk, with their arms relaxed on their lap. One run of the training session lasted 40 trials. Each trial started with a blue cross at the centre of a computer monitor, followed by a beep and an arrow indicating the movement to be imagined during the next 4 s (Fig. 1b). A left arrow meant that participants had to do an imaginary movement of their left hand (e.g. opening and closing it several times). A right arrow meant that participants had to do an imaginary movement of their right foot (e.g. pressing car brake several times). The order of arrow direction was pseudo-random and the trials counter-balanced (20 trials for each direction). All runs finished with a left-hand motor imagery trial. Each trial lasted 8 s and after a 1 s pause, the next trial began. Participants did not get any feedback about performance and were asked to concentrate on the cross during the task. Participants were trained until they achieved a performance ≥ 70%, (percentage of correctly classified trials at each time point during the motor imagery interval; 4–8 s). Most participants reached this performance in the first run.

Virtual environment-test stage

Volunteers sat on a chair next to a shoulder-high hollow box (adjustable height) and rested their left arm (hand flat with palm down) on it, the arm being out of view. They wore stereo glasses and a head tracker. Volunteers saw a stereo 3D projection of an arm out of their left shoulder in the virtual environment, which was displayed as resting on a virtual table (Fig. 1a).

During this stage, participants completed the same task as in the training stage, but now they were asked to concentrate their attention on the back of the virtual hand in order to receive visual feedback of their performance in real time. Imaginary movements of their left hand and right foot corresponded to closing or opening movements of the

Fig. 1



Experimental set-up. (a) The participant sat in front of the screen with his left arm resting on a shoulder-high box. A virtual left arm is displayed in 3D pointing straight ahead. From the participant's point of view (according to the head-tracker), the virtual arm appears as if coming out from his left shoulder. The virtual hand closes or opens according to participant's motor imagery. In the illustration, the partition hiding the participant's own arm has been removed to illustrate the position of the real and virtual arm. (b) The 9 s of a brain–computer interface trial (see Methods).

virtual hand, respectively. Immediately after finishing the final trial, the virtual table and arm suddenly fell down together and continued falling until they disappeared from the screen, which took 4 s to complete.

Two different experimental conditions were presented:

(1) With correlated visual feedback ($N = 8$ participants; mean age and standard deviation: 24.00 ± 7.60 years). The virtual hand moved only during the motor imagery interval and remained still at all other times. This helped participants relax between trials.
(2) With uncorrelated visual feedback ($N = 8$ participants; mean age and standard deviation: 29.12 ± 9.43 years). The virtual hand moved randomly and independently of the participant's performance. The virtual hand movements lasted between 1 and 4 s (randomly distributed) with randomly distributed time lapses between 1 and 3 s, not only during the motor imagery interval but also during all the trials and pauses between the motor imagery trials.

Electroencephalogram recordings and analysis

Two bipolar channels placed over the sensorimotor areas (C4 and Cz, international 10–20 system) were used. A ground was placed on the forehead and reference on the right earlobe. The voltage signal was fed on the 'g.USBamp' should appear every time as a word. It is not g.US Bamp. amplifier and acquired at 600 Hz. Impedances were kept below 5 kΩ. A band-pass filter (Butterworth 5th order) was applied to extract α (8–12 Hz) and β (16–24 Hz) frequency bands. Power band changes were computed online in overlapped 1s time windows, and led into a linear discriminant analysis classifier. The result was translated into the corresponding virtual hand movement.

Electromyogram recordings and analysis

A bipolar electromyogram (EMG) was recorded from the left lateral deltoid of each participant. The ground was placed on the triceps and reference on the elbow. The voltage signal was fed on the g.USBamp amplifier at 600 Hz. A low-pass filter (250 Hz) was applied during recording. The aim was to examine the activity (root-mean-square values) in the lateral deltoid muscle during the last 4 s when the virtual arm fell down compared with resting periods, in both correlated and uncorrelated conditions. For analysis, EMG data were high-pass filtered (30 Hz) to minimize motion and electrocardiogram artefacts [12].

Questionnaire

After the experience, participants filled in a nine-item questionnaire in Spanish. Most questions were adapted and translated from Ref. [1] and new questions related to agency were added:

(1) During the experiment there were moments in which I felt that if I moved my (real) arm the virtual arm would move.
(2) During the experiment there were moments in which, when the virtual hand moved, I felt that my own arm was moving.
(3) During the experiment there were moments in which I felt as if the virtual arm was my own arm.
(4) During the experiment there were moments in which I felt my arm to be in the location of the virtual arm.
(5) During the experiments there were moments in which it seemed that my real arm was being displaced towards the right (towards the virtual arm).
(6) During the experiment there were moments in which I felt as if my real arm was becoming virtual.
(7) During the experiment there were moments in which it seemed (visually) that the virtual arm was being displaced towards the left (towards my real arm).
(8) During the experiment there had been moments in which the virtual arm started to seem like my own arm in various aspects.
(9) During the experiment there were moments in which I had the sensation of having more than one left arm.

Question 1 refers to the sense of agency; the sense that one is causing or generating the movement of the virtual arm, or that one could control it. Question 2 refers to what we define as 'inverse agency', as the feeling that when the virtual arm moves, it induces a movement in the real arm. Question 3 refers to ownership of the virtual arm, and question 4 to proprioception. The remaining questions are not concerned with the illusion and are considered as control questions. Each question was scored according to a seven-point Likert Scale, 1 meaning 'totally disagree' and 7 'totally agree'.

Behavioural measures

In addition to physiological measurements and the questionnaire, the proprioceptive drift elicited by the illusion was measured by a standard technique [1]. Participants were instructed to close their eyes and point underneath the table towards the position of their left hand (the center of the palm) with their right hand before the experiment started. To mark the position, they placed a piece of blue-tack below the tabletop. After the motor imagery task finished (40 trials), participants were asked to repeat the action with a second piece of blue-tack, which they had been holding in their right hand. The horizontal distance between both pieces of blue-tack corresponded to the proprioceptive drift.

Results

The response variables from the experiment were obtained from (i) questionnaire scores, (ii) EMG recordings and (iii) proprioceptive displacement.

Questionnaires

The questionnaire scores from the participants who saw a virtual arm that had movement controlled through the BCI (correlated visual feedback) were compared against those that had uncorrelated visual feedback (asynchronous motor imagery and movement) (Fig. 2). The scores on each question across the two conditions were compared using the Wilcoxon's rank-sum test ($P < 0.05$). These comparisons showed that question 6 (visual aspect of the hand) was significantly higher for the correlated condition, which was also the case in our previous study [2]. The scores for questions 2 and 3 ('inverse agency' and ownership) were significantly different with P less than 0.06, being higher for the correlated condition (Fig. 2a and b).

We analysed the questionnaire results conservatively within each condition by only considering the high scores ('6' or '7') as indicative of the illusion (Fig. 2c), as in Ref. [2]. By chance alone, the probability of a high score is 2/7. The answers to questions 1, 2 and 3 in the correlated condition have frequencies that are significantly higher than that would be expected by chance (5, 4 and 4, respectively, out of $n = 8$, with corresponding P values 0.0087, 0.0476 and 0.0476 using the binomial distribution). For the uncorrelated condition, only the number of high responses to question 1 was significantly higher than that would be expected by chance ($P = 0.0009$). The frequency of high scores for question 4 (proprioception) was low in both conditions. To conclude, the results of the questionnaire (Fig. 2) revealed significant ownership over the virtual arm and 'inverse agency' (see Methods) only in the correlated condition. The sense of agency was significantly high both in the correlated and uncorrelated conditions, probably triggered simply by the vision of a 3D arm coming off the shoulder in a feasible position (see Discussion). In contrast, participants did not report a subjective sensation of proprioceptive displacement towards the virtual arm, which is well matched with the physical measure of proprioceptive displacement (see below).

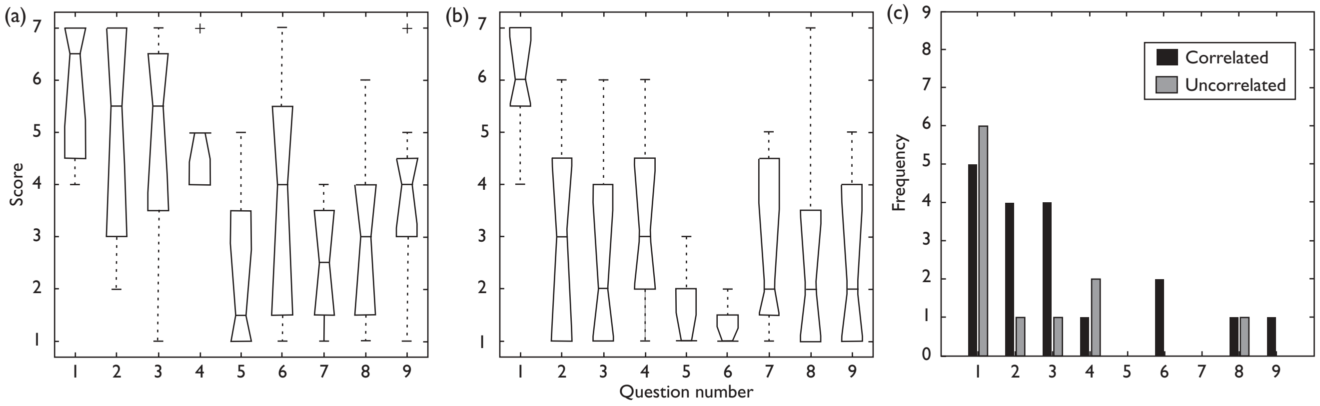
Electromyogram

To study whether events occurring to the virtual arm were sufficient to trigger muscle activity in the real arm, changes in deltoid muscle activity were measured while the virtual tabletop and arm fell. This measure was compared against a reference period, corresponding to the last resting state interval.

The analysis of the deltoid muscle activity shows higher values during the falling of the tabletop when compared with the reference interval (1 s before the arrow appeared, see Fig. 1b) in the condition with correlated visual feedback, but not in the uncorrelated visual feedback (Wilcoxon's signed-rank test, $P < 0.05$).

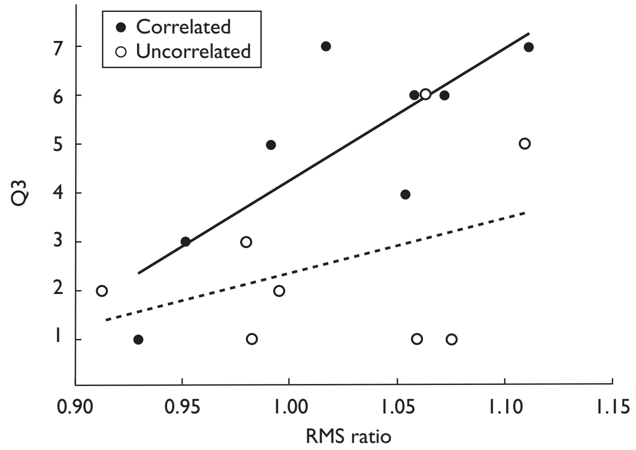
Furthermore, a strong positive relationship between this EMG activity and question 3 (ownership-related) was found in the correlated condition but not in the uncorrelated condition (Fig. 3; $r = 0.80$ and $r = 0.38$, respectively; Pearson, $P < 0.05$ for the correlated condition; this correlation was only significant for reference periods of 2–3 s duration). This positive correlation suggested that participants who experienced a stronger feeling of ownership responded physically to the virtual environment (Fig. 3).

Fig. 2



Questionnaire results represented in box plots for conditions with correlated (a) and uncorrelated (b) visual feedback. Question 1 addresses the sense of agency; Q2, inverse agency; Q3, ownership and Q4 proprioception. The medians are shown as horizontal lines and the boxes are the interquartile ranges (IQR). The whiskers represent either the extreme data points or extend to 1.5 × IQR. (c) Frequency of high scores (6 or 7) in both correlated and uncorrelated virtual hand movement and motor imagery. As the probability of giving a high score (6 or 7) is 2/7, the significance values for rejecting the hypothesis that the participants' responses were due to chance are (i) 0.0087, (ii) 0.0476, (iii) 0.0476, (iv) 0.7154, (v) 0.9322, (vi) 0.4118, (vii) 0.9322, (viii) 0.7154, (ix) 0.7154 for the correlated condition, and (i) 0.0009, (ii) 0.7154, (iii) 0.7154, (iv) 0.4118, (v) 0.9322, (vi) 0.9322, (vii) 0.9322, (viii) 0.7154, (ix) 0.9322 for the uncorrelated condition.

Fig. 3



Deltoid muscle activity during the tabletop and arm falling and the illusion of ownership. Ratio of deltoid root-mean-square (RMS) activity with respect to a 3 s time window reference period (see Methods) versus score of question 3 (ownership related): (i) correlated condition ($r=0.80^*$; $P=0.017$); linear regression, continuous line.
(ii) Uncorrelated condition ($r=0.38$; $P=0.35$); discontinuous line.

Proprioceptive drift

Proprioceptive drift refers to a displacement of the sense of position of the arm, and it has been quantified in previous studies as a measurement of the illusion [1,2]. Here, for seven of the eight participants in each condition we obtained the measure of proprioceptive drift. The two missing ones were due to the original blue-tack falling off (see Methods). We did not find any significant proprioceptive displacement of the real arm location towards the virtual one in either of the two conditions.

Discussion

The generation of motor imagery for the control of a virtual arm along with coherent and synchronous visual feedback of the virtual arm movement is enough to generate an illusion of ownership over that arm, even in the absence of additional multisensory correlations. In the virtual-hand illusion [2], tactile stimulation of the real arm (out of view) was carried out in synchrony with the virtual touch of the virtual arm, which provided the visual input to the participant. Under those conditions, an illusion of ownership of the virtual arm and a proprioceptive illusion of displacement of the real arm towards the virtual one occurred. The current experiment shows that motor imagery followed by movement of the virtual arm is sufficient to generate the subjective aspects of the illusion, but not the proprioceptive drift. However, the measurable physical response to the falling arm, as measured by EMG, was stronger here than in the study by Slater *et al.* [2] (possibly because the falling arm was a more dramatic event than the arm rotation shown in Ref. [2]).

The results of the two experiments may be different also because of the limited capacity of selective attentional mechanisms. As the participants were novices in BCI, a large part of their attention was devoted to the motor imagery task. It remains to be shown whether further BCI practice would decrease the resources devoted to the movement control and allow a stronger perceptual illusion to occur.

A sense of agency, the feeling of being causally involved in an action [10,13], was found both in the correlated and the uncorrelated conditions. The observations in this experiment and in a large number of pilots suggest that just seeing a virtual arm seemingly coming out of the body in a feasible position is enough to induce agency. We also explored whether any feeling of ‘inverse agency’ occurred, that is, the feeling that if the virtual hand moves, your hand will move too. A strong feeling of inverse agency was reported by participants only in the correlated condition.

Hence, the virtual arm seemed to be integrated into the body representation to some extent, even if this might have been at an unconscious, preattentive level. Future research in this direction may help us not only to understand the mechanisms that mediate representation and recognition of our own body, but also to internalize full virtual bodies, a process with broad consequences in different fields, from rehabilitation to entertainment.

Conclusion

It is generally believed that body ownership illusions require synchronous visual and tactile stimulation but here we have shown that the subjective illusion of ownership of a virtual hand can also be induced by the imagination of a motor act followed by movement of a virtual hand. Moreover, under these same conditions the spontaneous movement of that virtual hand induced measurable muscle activity in the real arm.

Acknowledgements

The authors thank R. Leeb and C. Guger for providing basic algorithms for the BCI implementation; F. Tecchia and M. Carrozzino for their help with the XVR programming system, C. Pastore for help with EMG recordings; and V. Fernandez-Descalzo, J. Abolafia and T. Gener for helpful discussions. The study was supported by EU FET Integrated Project PRESENCCIA, Contract Number 27731. Partial support was obtained from the Spanish Ministry of Science and Innovation. Part of the experimental work was carried out at Instituto de Neurociencias de Alicante, Universidad Miguel Hernández-CSIC.

References

1 Botvinick M, Cohen J. Rubber hands feel touch that eyes see. *Nature* 1998; **391**:756.

2 Slater M, Pérez-Marcos D, Ehrsson HH, Sanchez-Vives MV. Towards a digital body: the virtual arm illusion. *Frontiers Human Neurosci* 2008; doi: [Accessed 10.3389/neuro.09.006.2008]

3 Lackner JR. Some proprioceptive influences on the perceptual representation of body shape and orientation. *Brain* 1988; **111**:281–297.

4 Sanchez-Vives MV, Slater M. From presence to consciousness through virtual reality. *Nat Rev Neurosci* 2005; **6**:332–339.

5 Kubler A, Kotchoubey B, Hinterberger T, Ghanayim N, Perelmouter J, Schauer M, *et al*. The thought translation device: a neurophysiological approach to communication in total motor paralysis. *Exp Brain Res* 1999; **124**:223–232.

6 Hinterberger T, Schmidt S, Neumann N, Mellinger J, Blankertz B, Curio G, *et al*. Brain-computer communication and slow cortical potentials. *IEEE Trans Biomed Eng* 2004; **51**:1011–1018.

7 Pfurtscheller G, Aranibar A. Event-related cortical desynchronization detected by power measurements of scalp EEG. *Electroencephalogr Clin Neurophysiol* 1977; **42**:817–826.

8 Neuper C, Muller-Putz GR, Scherer R, Pfurtscheller G. Motor imagery and EEG-based control of spelling devices and neuroprostheses. *Prog Brain Res* 2006; **159**:393–409.

9 Farwell LA, Donchin E. Talking off the top of your head: toward a mental prosthesis utilizing event-related brain potentials. *Electroencephalogr Clin Neurophysiol* 1988; **70**:510–523.

10 Tsakiris M, Prabhu G, Haggard P. Having a body versus moving your body: how agency structures body-ownership. *Conscious Cogn* 2006; **15**:423–432.

11 Ehrsson HH, Spence C, Passingham RE. That's my hand! Activity in premotor cortex reflects feeling of ownership of a limb. *Science* 2004; **305**:875–877.

12 Drake JD, Callaghan JP. Elimination of electrocardiogram contamination from electromyogram signals: An evaluation of currently used removal techniques. *J Electromyogr Kinesiol* 2006; **16**:175–187.

13 Farrer C, Franck N, Georgieff N, Frith CD, Decety J, Jeannerod M. Modulating the experience of agency: a positron emission tomography study. *Neuroimage* 2003; **18**:324–333.