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Somatosensory attention identifies both overt and covert awareness in disorders of consciousness

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1 **Somatosensory attention identifies both overt and covert awareness in**
2 **disorders of consciousness**

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1 **Abstract**

2 *Objective:* Some patients diagnosed with disorders of consciousness retain sensory and cognitive
3 abilities beyond those apparent from their overt behaviour. Characterising these covert abilities is crucial
4 for diagnosis, prognosis, and medical ethics. This multimodal study investigates the relationship
5 between electroencephalographic evidence for perceptual/cognitive preservation and both overt and
6 covert markers of awareness.

7 *Methods:* Fourteen patients with severe brain injuries were evaluated with an electroencephalographic
8 vibrotactile attention task designed to identify a hierarchy of residual somatosensory and cognitive
9 abilities: 1) somatosensory steady-state evoked responses, 2) bottom-up attention orienting (P3a event-
10 related potential), and 3) top-down attention (P3b event-related potential). Each patient was also
11 assessed with a clinical behavioural scale and two functional magnetic resonance imaging assessments
12 of covert command following.

13 *Results:* Six patients produced only sensory responses, with no evidence of cognitive event-related
14 potentials. A further eight patients demonstrated reliable bottom-up attention orienting responses (P3a).
15 No patient showed evidence of top-down attention (P3b). Only those patients who followed commands,
16 whether overtly with behaviour or covertly with functional neuroimaging, also demonstrated event-
17 related potential evidence of attentional orienting.

18 *Interpretation:* Somatosensory attentional orienting event-related potentials differentiated patients who
19 could follow commands from those who could not. Crucially, this differentiation was irrespective of
20 whether command following was evident through overt external behaviour, or through covert functional
21 neuroimaging methods. Bedside electroencephalographic methods may corroborate more expensive and
22 challenging methods such as functional neuroimaging, and thereby assist in the accurate diagnosis of
23 awareness.

24

1 Introduction

2 Disorders of consciousness (DoC) are states that a person may enter when they emerge from
3 coma following a severe brain injury. Patients in a vegetative state (VS) do not demonstrate purposeful
4 behaviour and are considered to lack awareness^{1–3}. In contrast, patients in a minimally conscious state
5 (MCS) are considered to have fluctuating awareness and demonstrate variable, but reproducible,
6 purposeful behaviour⁴. Furthermore, the MCS can be sub-divided into MCS *Plus* or *Minus* on the basis
7 of the patient's ability to follow commands⁵. Patients who demonstrate accurate communication and/or
8 functional object use are considered *emergent* from a MCS (EMCS)⁴. However, the accurate
9 identification of a patient's diagnostic group comprises a considerable clinical challenge^{1–3,6–8}.

10 To facilitate more accurate diagnosis of the DoC, researchers have developed brain imaging
11 paradigms to assess volition and command following in the absence of outward responsiveness^{9–14}.
12 Patients who produce behaviour consistent with a VS, but who exhibit evidence of *covert* awareness
13 with functional neuroimaging – such as imagining movements to command^{6,9,10,13,15–17} – have been
14 considered to exhibit a non-behavioural MCS¹⁸. However, in both behavioural and neuroimaging-based
15 assessments, a patient may produce a false negative due to fatigue or insufficient cognitive resources to
16 successfully complete the demanding diagnostic task^{8,19}.

17 Researchers have developed assessments of brain function to place a patient along a hierarchy of
18 increasingly complex attentional information processing^{20–24}. However, there are inconsistencies in the
19 prognostic value of the event-related potentials used in these hierarchical approaches; some investigators
20 have reported positive prognostic value in these attentional markers²⁵, while others have not²⁶. These
21 inconsistencies may have occurred because multimodal assessments were not used to identify patients in
22 a non-behavioural MCS. Therefore, 15% of the patient sample considered to be VS may have possessed
23 a non-behavioural MCS and consequently misrepresented the diagnostic category²⁷. Similarly, most
24 studies of patients with DoC employ auditory stimulation because many patients lack oculomotor
25 control; however, this tendency limits the characterisation of a patient's sensory abilities to the auditory
26 domain.

27 We report a hierarchical cognitive assessment in a sample of fourteen patients with severe brain
28 injuries using vibrotactile stimulation. The assessment employed an oddball paradigm to elicit steady-
29 state evoked responses of sensory processing and event-related potential (ERP) markers of bottom-up
30 and top-down attention (the P3a and P3b, respectively)²⁸. As with previous hierarchical designs, this

1 approach discretizes a patient's sensory and cognitive abilities. A novel aspect of our method is the
2 assessment of a patient's ability to sense and attend to touch. Importantly, patients were also evaluated
3 using two previously established neuroimaging-based assessments of covert command following –
4 mental imagery^{6,9,10,13,15–17} and selective auditory attention^{29,30} – and a clinical behavioural assessment³¹.
5 By identifying patients with covert command following abilities, these additional assessments ensured a
6 more accurate representation of each patient's level of awareness. Furthermore, we were in a position to
7 test the divergence and convergence of these methods. It was expected that ERP markers of higher-order
8 attention would be evident in patients who were aware, either expressed overtly in their behaviour, or
9 covertly by wilful modulations of brain activity detected with neuroimaging.

10 **Materials and methods**

11 **Participants**

12 Fourteen patients [mean age 41 (range: 19 to 58) years] contributed sufficient data for inclusion
13 in this investigation. Seven patients were diagnosed as VS³, four patients were diagnosed as MCS, two
14 patients were diagnosed as EMCS⁴, and one patient was diagnosed with Locked-In Syndrome (LIS)³².
15 Six patients had sustained traumatic brain injuries from motor vehicle accidents. The remaining eight
16 patients had sustained non-traumatic brain injuries from different aetiologies including cardiac arrest (3
17 cases) and near-drowning (1 case; see Supplementary Table 1). Each patient's surrogate decision maker
18 provided informed, written consent for the patient's participation in the study. Ethical approval was
19 obtained from the University of Western Ontario's Health Sciences Research Ethics Board (London,
20 Canada).

21 As a scientific control, a sample of fifteen healthy volunteers also participated in the
22 somatosensory selective attention task. These participants ranged in age from 17 to 23 years (mean age
23 18 years). All healthy volunteers provided informed written consent and received course credit for their
24 participation. The Psychology Research Ethics Board of the University of Western Ontario (London,
25 Canada) provided ethical approval for the control study. Control studies of the other neuroimaging
26 paradigms have been reported elsewhere^{15,30,33}.

27 **Procedure**

28 For each patient, participation in this study comprised assessments with: (1)
29 electroencephalography (EEG) during their completion of a somatosensory selective attention paradigm;

1 (2) functional magnetic resonance imaging (fMRI) during their completion of a mental imagery
2 paradigm^{6,9,10,13,15-17}; (3) fMRI during their completion of an auditory selective attention paradigm^{29,30};
3 and (4) the Coma Recovery Scale-Revised (CRS-R³¹; see Supplementary Tables 1 and 2). fMRI data
4 from Patient EMCS2 could not be analysed due to excessive motion artefacts. However, this patient was
5 included in this investigation because his ability to follow simple commands and communicate was
6 evident from his overt behaviour. Similarly, the data for Patient VS7 from one fMRI session (selective
7 auditory attention) were discarded due to excessive movement. This patient was included in the current
8 investigation because useable data were obtained from this patient for the other three paradigms.

9 All patients completed the two fMRI paradigms within a two-day period. Ten patients completed
10 the fMRI assessments within two days of their EEG assessments (see Supplementary Table 2). The other
11 four patients completed the EEG assessments after the fMRI assessment with the following delay: 1.5-
12 months (EMCS1); 7.5-months (MCS3); 1-year (VS3); and 3.5-years (VS7). Only Patient MCS3
13 demonstrated a clinical status change between assessments with EEG and fMRI (MCS- to MCS+).
14 Given the aetiology, age, and time *post-ictus* of those patients with a year or more between assessments
15 (Supplementary Table 2), it is unlikely (although not impossible) that either of these patients underwent
16 a change in their conscious states between assessments¹⁻³. Indeed, Patients VS3 and VS7 demonstrated
17 overt behaviour consistent with a VS at all assessments.

18 **Somatosensory selective attention paradigm**

19 Participants completed a short somatosensory selective attention task as their EEGs were
20 recorded. One stimulator was affixed to each wrist and the upper back (three total). Each stimulator
21 administered non-painful vibrotactile stimuli via a motor housed in a rubberized casing³⁴. A similar
22 paradigm has also been evaluated for patients with LIS³⁵. The experiment comprised 14 blocks.
23 Participants were presented with a series of vibrations alternating among their wrists (10% per wrist)
24 and upper back (80%). A vibration occurred every 200ms and lasted for 50ms. The number of vibrations
25 presented to each wrist in a block was selected on a random uniform interval from 28 to 32. There was
26 always a minimum of three (maximum=21) upper back stimuli between wrist vibrations; on average,
27 49% (standard deviation=13%) of the wrist stimuli followed exactly three upper back stimuli.
28 Participants were instructed to count the vibrations presented only to the target wrist. The experimenter
29 **touch**ed the patient's target wrist after the instruction. The right wrist was always the target wrist for the
30 first block and subsequently alternated between the left and right wrists. The healthy volunteers reported

1 their count at the end of each block; these participants reported the correct number of vibrations for
2 12/14 blocks on average (all reports were within ± 3 of the true number of targets). One block of trials
3 lasted for approximately one minute.

4 **Mental imagery paradigm**

5 During an fMRI scan, patients were asked to engage in two mental imagery paradigms^{6,9,10,13,15–}
6 ¹⁷. In the motor imagery task, patients were instructed to imagine swinging their right arm to hit a tennis
7 ball. In the spatial navigation task, patients were instructed to imagine walking from room to room in
8 their house and visualise all objects they would encounter. Instructions were delivered with noise
9 cancellation headphones (Silent Scan™, Avotec Inc. for patients scanned in the Trio system, as well as
10 Patient VS6 [first visit], and Sensimetrics S14 for the patients scanned in the Prisma system, including
11 Patient VS6 [second visit]). Patients VS1, VS2, VS4, VS5, VS6 (second visit), MCS4, and EMCS1
12 completed two sessions of each task, while patients VS3, VS6 (first visit), VS7, MCS1, MCS2, MCS3,
13 and LIS1 completed only one session due to scanner availability or patient fatigue.

14 **Auditory selective attention paradigm**

15 The fMRI selective auditory attention paradigm has been previously described in healthy
16 individuals³⁰ and patients with DoC²⁹, and is designed to identify an ability to follow commands to
17 selectively attend to stimuli – *i.e.*, top-down attention. On each trial, participants were instructed to
18 either count a target word ('yes' or 'no') presented among pseudorandom distractors (spoken digits one
19 to nine), or to relax. Each trial had an on/off design: sound (~22.5s) followed by silence (10s). The scan
20 lasted five minutes, including instructions.

21 **Replication data**

22 Each task alternated five 30-second blocks of mental imagery and five 30-second blocks of rest
23 for a total of five minutes. Patients VS4, MCS3, and EMCS1 participated in second assessments with
24 the somatosensory selective attention task and the CRS-R. These assessments occurred from 2- to 3.5-
25 months following their initial participation. Patient VS6 completed a second assessment with all
26 paradigms (CRS-R, fMRI, and EEG) 22-months after her initial assessment. All four patients maintained
27 their clinical status at follow-up (Supplementary Table 2).

28 **EEG data acquisition and pre-processing**

1 EEG data were recorded at sites FC1, Fz, FC2, C3, Cz, C4, CP1, CP2, Pz, Oz, PO7, and PO8
2 using an electrode cap with the g.Gamma active electrode system (g.tec Medical Engineering GmbH,
3 Austria). This montage was selected following a previous study conducted in patients with LIS³⁵ and
4 previous work concerning optimal P300 classification³⁶. Data were sampled at 256 Hz and filtered
5 between 0.5 and 30 Hz using a digital Butterworth filter. Stimuli were presented with the g.VIBROstim
6 box (g.tec Medical Engineering GmbH, Austria) using a custom MATLAB® script for Simulink®
7 (MathWorks, Inc., Natick, MA). The recordings were referenced to the right earlobe with a forehead
8 (Fpz) ground. Impedances were kept below 5 kΩ. Data processing was conducted with EEGLAB³⁷. The
9 data were segmented into 1-second epochs with a 200ms pre-stimulus period, and linear detrending and
10 baseline correction were applied to each epoch. For artefact correction, all trials containing data with
11 voltages exceeding $\pm 100 \mu\text{V}$ were rejected. In a second step, the kurtosis of the signal across all
12 channels was calculated for each stimulus type separately, and all trials exceeding 2.5 standard
13 deviations of the mean were rejected. Final trial numbers are reported in (Table 1).

14 **fMRI data acquisition and pre-processing**

15 The MRI data were acquired in a 3-Tesla Siemens scanner (Siemens, Erlangen, Germany) with a
16 Siemens 32-channel head-coil at the Centre for Functional and Metabolic Mapping at Robarts Research
17 Institute, Western University, Canada. The patients were recruited over 30-months, in which time the 3-
18 T scanner was upgraded. Three patients (VS3, VS7, and MCS3) were scanned in a Magnetom Trio
19 system. All other patients were scanned in a Magnetom Prisma system. Functional echo-planar images
20 of 36 slices covering the whole brain were acquired (repetition time=2000ms, echo time=30ms, matrix
21 size=420 x 420, slice thickness=3 mm, in-plane resolution=3×3 mm, flip angle=78°; for patients VS6
22 and LIS1 only, matrix size=384x384 and flip angle=75°). High-resolution T1-weighted 3D images were
23 acquired in the same session (Trio system: repetition time=2300ms, echo time=2.98ms, inversion
24 time=900ms, matrix size=256×240, voxel size 1 × 1 × 1 mm, flip angle=9°; Prisma system: repetition
25 time=2300ms, echo time=2.32ms, inversion time=900ms, matrix size=256x256, flip angle=8°; for
26 patients VS6 and LIS1 only, matrix size=240 x 256 and flip angle=9°). Data from the mental imagery
27 paradigm were pre-processed using SPM8 (<http://www.fil.ion.ucl.ac.uk/spm>), as described elsewhere¹³.
28 For the selective attention paradigm, pre-processing was performed with the AA software³⁸.

29 **Statistical analyses**

1 EEG responses

2 The EEG data were assessed for the presence of a steady-state evoked potential to the repetitive
3 vibrotactile stimulation. As one vibration occurred every 200ms, an evoked response was considered
4 present when the averaged peak of the frequency spectrum of the data at the stimulation rate (5 Hz) and
5 its first harmonic (10 Hz) was significantly higher than the background noise³⁹. A frequency spectrum
6 was calculated with a discrete Fourier transform over the entire 1-second epoch from the average of all
7 trials using data only from site Pz^{40,41}. An F ratio ($\alpha=.05$; $F_{2,20}>=3.49$) was computed to compare the
8 power at 5 and 10 Hz with the average power in the ten adjacent ~ 1 Hz frequency bins (2-4 Hz, 6-9 Hz,
9 and 11-13 Hz)³⁹.

10 Two analyses of the EEG data were conducted to identify the attention-based event-related
11 potentials. For the bottom-up attention effect (P3a), responses to wrist (deviant) and upper back
12 (standard) stimuli were compared. A random subset of the standard stimuli (equal in number to the
13 deviant stimuli) was selected because there were many more standard than deviant stimuli. For the top-
14 down attention effect (P3b), responses to the target and non-target wrist stimuli were compared. Trial
15 numbers were matched between the target and non-target trials. Data from 50 to 750ms post-stimulus
16 were analysed using the cluster-mass procedure⁴² of the MATLAB® toolbox FieldTrip⁴³. This technique
17 has been described in detail previously^{42,44}. In the first step, data were compared at each time-point using
18 a t -test. In the second step, t -values of adjacent spatiotemporal points with $p<.05$ were clustered together
19 by summing their t -values. The largest cluster was retained. This entire procedure was repeated 1000
20 times with recombination and randomized resampling of the ERP data. This Monte Carlo method
21 generated a nonparametric estimate of the p -value representing the statistical significance of the
22 originally identified cluster.

23 Blood oxygen level-dependent (BOLD) mental imagery responses

24 Single subject fixed-effect analyses were performed for each patient. The analysis was based on
25 the general linear model using the canonical hemodynamic response function⁴⁵ implemented with SPM8
26 (<http://www.fil.ion.ucl.ac.uk/spm>). The analysis pipeline was previously reported¹³. Linear contrasts
27 were used to obtain subject-specific estimates, and results were thresholded at a voxel level, familywise
28 error (FWE), whole-brain $p<.05$. When no significant activations were found at this level, the statistical
29 threshold was reduced to an uncorrected $p<.001$ because of the strong anatomical *a priori*

1 hypotheses^{6,9,10,13,15-17}. This less conservative threshold excluded the possibility of failing to detect more
2 subtle changes in the signal^{45,46}.

3 **BOLD auditory selective attention responses**

4 The general linear model (SPM8) was used to explore effects of interest. Two event types were
5 defined corresponding to the on/off periods (count/relax; ~22.5s, or vice-versa). The silent period (10s)
6 served as an implicit baseline for all trials. Events for these regressors were modelled by convolving
7 boxcar functions with the canonical hemodynamic response function. Also included in the general linear
8 model were the following nuisance variables: the movement parameters in the three directions of motion
9 and three degrees of rotation, and the mean of each scan. Linear contrasts were used to obtain subject-
10 specific estimates for the effect of interest. Clusters that survived the $p < .05$ threshold after the FWE
11 correction were reported as significant.

12 **Results**

13 All patient outcomes are summarized in (Figure 1) and (Supplementary Table 3).

14 **EEG responses**

15 A steady-state evoked potential was detected in the EEG data of all patients ($n=14$) and all
16 healthy volunteers ($n=15$; Figure 2).

17 **Bottom-up attention effects** (deviant versus standard stimuli) were detected from eight patients
18 and all of the healthy volunteers ($n=15$; Figure 3). All patients who demonstrated a differential response
19 to the deviant versus standard stimuli also demonstrated evidence of command following in either a
20 behavioural or a neuroimaging-based assessment (Figure 1 and Supplementary Table 3).

21 Top-down ERP attention effects (target versus non-target wrist vibrations) were not detected
22 from any of the patients. However, this ERP effect was evident for healthy volunteers at the group level
23 ($n=15$) and at the single-subject level, albeit with a hit-rate of 67% (Figure 4). Hit-rates of at least 80%
24 (12/15) and 100% (15/15) have been reported for fMRI-detected mental imagery and selective attention
25 respectively³⁰. Given the relatively lower sensitivity of the top-down attention ERP analysis (*i.e.*, 67%),
26 additional *post-hoc* comparisons were conducted. While the number of trials available after artefact
27 rejection did not differ across groups (Table 1; $\chi^2(2)=0.21$, $p=0.9$), some patients had many fewer trials
28 available than healthy individuals. The single-subject ERP analyses for the healthy volunteers were thus

1 repeated in the *post-hoc* analyses using only a pseudorandom subset of trials equal in number to the
2 minimum number of trials available in the single-subject analyses of the patient data (180 trials, in the
3 case of Patient MCS2).

4 Bottom-up attentional ERP effects were detected at the single-subject level for all healthy
5 volunteers when as few as 180 trials were included for each stimulus type. However, top-down
6 attentional ERP effects were detected from only seven healthy volunteers. Subsequent analyses revealed
7 that a minimum of 300 trials were required to detect the top-down attentional ERP effects from the same
8 10 healthy volunteers as in the *a priori* analyses. Four patients did not have enough trials available to
9 meet this criterion. Overall, these analyses indicate that the top-down attentional ERP effect may not
10 have been detected in some single-subject analyses due to low trial numbers. Nevertheless, the bottom-
11 up attentional ERP effect was robust to data loss.

12 **BOLD mental imagery responses**

13 In her first visit, Patient VS6 produced reliable, appropriate activation during the motor imagery
14 task in the supplementary motor area and cerebellum bilaterally at an uncorrected $p < .001$ (cluster level
15 FWE-corrected $p < .05$). In her second visit, Patient VS6 produced reliable, isolated clusters of activation
16 during the motor imagery and spatial navigation tasks in the left precentral gyrus at an uncorrected
17 $p < .001$ (cluster level FWE-corrected $p < .05$). The patient was thus reclassified as in a non-behavioural
18 MCS¹⁸.

19 Patients VS7 showed high levels of motion requiring 37% and 37.5% of his data to be discarded
20 (for motor imagery and spatial navigation respectively). The analysis of the remaining data revealed
21 appropriate activation during the spatial navigation task only (*i.e.*, the left occipito-parietal junction at
22 uncorrected $p < .001$). The patient was thus reclassified as in a non-behavioural MCS¹⁸.

23 Patients MCS3, MCS4, EMCS1, and LIS1 showed reliable activation during the spatial
24 navigation task only. This involved: bilateral occipito-parietal junction (uncorrected $p < .001$) for MCS3;
25 right temporo-occipito-parietal junction (FWE-corrected $p < .05$), as well as right dorsal premotor cortex,
26 right insular cortex, and right putamen (uncorrected $p < .001$) for MCS4; right occipito-parietal junction,
27 a region in the boundaries between right lingual gyrus/parahippocampal cortex, left precentral gyrus
28 (comprising the supplementary and pre-supplementary motor areas), as well as some less typical areas
29 such as the inferior frontal gyrus, the left superior temporal gyrus, and the left striatum (FWE-corrected

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1 $p < .05$) for EMCS1; and supplementary motor area, right precentral gyrus, occipito-parietal junction,
2 posterior temporo-occipital region, and the cerebellum (uncorrected $p < .001$) for LIS1.

3 The remaining seven patients (VS1-5, MCS1, and MCS2) showed no activation at the
4 conservative FWE-corrected statistical threshold, or at uncorrected $p < .001$.

5 **BOLD auditory selective attention responses**

6 Of the patients diagnosed as in a VS, only Patient VS6 showed significantly more activation
7 following the instruction to count than to relax. This patient showed significant activation in the
8 temporal and parietal cortex bilaterally (FWE-corrected at $p < .05$).

9 Patients MCS1-4 and LIS1 also showed significantly more activation following the instruction to
10 count than to relax. Patient MCS1 showed significant activation in the frontotemporal and parietal
11 cortex bilaterally. Patient MCS2 showed significant activation in the temporal cortex bilaterally (FWE-
12 corrected at $p < .05$). Patient MCS3 showed significant activation in the parietal cortex bilaterally. Patient
13 MCS4 showed significant activation in the frontotemporal and parietal cortex bilaterally (FWE-
14 corrected at $p < .05$). Patient LIS1 produced significant brain activity in the frontotemporal cortex
15 bilaterally (FWE-corrected at $p < .05$).

16 Of note, Patient EMCS1 did not show significant differences in activation in the command
17 following task even though she was able to follow commands with her overt behaviour immediately
18 prior to her assessment. Patients VS7 and EMCS2 were excluded from this analysis because both
19 patients moved excessively during their functional scans.

20 **Correspondence between command following and EEG responses**

21 The main hypothesis in this investigation was that patients who were aware would exhibit
22 concordant EEG markers of higher-order attention processing. While top-down processing (P3b) was
23 not detected from any patients, an interesting observation from the current data is the relationship
24 between a specific marker of awareness – command-following – and the bottom-up attention orienting
25 ERP effect, the P3a. A patient was considered to have evidence of such awareness if they demonstrated
26 evidence of command following in any one of the three non-EEG assessments (selective auditory
27 attention, mental imagery, or a behavioural assessment with the CRS-R). This approach is consistent
28 with clinical behavioural guidelines in which a diagnosis of awareness (MCS) is given if a patient
29 follows commands on one occasion across multiple assessments. A Fisher's exact test revealed a

1 significant positive association between evidence for command following and evidence for the P3a
2 ($p=.007$; note $p=.0047$ if the two observations of Patient VS6 are not included to maintain the
3 assumption of independence). This relationship is summarised in (Figure 1).

4 **Replication data**

5 The replication results are depicted in (Figure 5). All patients exhibited consistent effects across
6 assessments with the exception of Patient VS6 for whom a P3a was significant only during her initial
7 assessment.

8 **Discussion**

9 We investigated a novel EEG method for the assessment of residual sensory and cognitive
10 processing alongside two fMRI-based assessments of covert command following and one behavioural
11 assessment of overt command following in a sample of fourteen patients with severe brain injuries. The
12 primary novel finding of this work is the relationship between an ERP marker of bottom-up attention
13 orienting (the P3a) and command following such that all patients with a P3a response demonstrated
14 positive evidence of command following. Similarly, most patients who did not generate a P3a response
15 also did not demonstrate evidence of command following (see Figure 1 and Supplementary Table 3).

16 Some investigators have reported positive prognostic value in the presence of a P300 following
17 traumatic brain injury²⁵. There have also been reports of correlations between cognitive ERPs and
18 behavioural markers of awareness^{14,24}, as well as the prediction of recovery from the DoC using
19 cognitive ERPs^{47,26}. Crucially, the current study included two neuroimaging-based assessments of covert
20 command following. This step is important given that a recent meta-analysis estimates a 15% rate of
21 covert awareness among patients diagnosed as in a VS²⁷. Previous studies of the P300 in patients with
22 DOC are likely to have included patients capable of covert command following, thus obscuring the
23 relationship reported here. While the feasibility of routine neuroimaging assessments in clinical practice
24 is limited by important health, safety, and financial factors, the findings of this work suggest that these
25 assessments are necessary to elucidate the relationship between a patient's conscious state and their
26 residual sensory and cognitive abilities.

27 It is curious that an ERP marker of unconscious (or preconscious) processing – *i.e.*, the P3a – is
28 closely linked to awareness in this work. Indeed, the P3a can be elicited by unattended stimuli and
29 during REM sleep and deep sedation^{28,48}. We speculate that the correspondence between the P3a and

1 command following stems from the overlap of the neural networks that support attention, and those that
2 are relatively more preserved in conscious patients^{49,50}. Indeed, frontal lobe lesions have been associated
3 with diminished P3a responses to auditory⁵¹ and somatosensory⁵² stimulation. Equally, this association
4 suggests that a P3a response may be less informative for patients with specific frontal lobe injuries.
5 Nevertheless, a P3a can be elicited without the explicit collaboration of the individual – *i.e.*, without
6 following task instructions⁴⁸. This feature is appealing, as it suggests that a passive assessment of
7 attention orienting, which entails lower cognitive demands than active assessments of voluntary top-
8 down attention, may be sufficient to identify patients with covert awareness.

9 The P3b marker of top-down attention in the current EEG task was not detected from any of the
10 patients in this sample, as has been reported previously⁵³. In fact, P3b responses in the current work
11 were detected from only 67% (10/15) of the healthy volunteers. *Post-hoc* analyses of the ERP data
12 indicated that this low sensitivity may be exacerbated by the fewer usable trials in the patient data, as
13 this comparison was sensitive to a reduced signal-to-noise ratio. Additionally, time-variant levels of
14 arousal and fatigue characteristic of the DoC may have led to inconsistent engagement in the counting
15 task needed to generate the top-down ERP effect^{8,19}. In contrast to the fMRI-based selective attention
16 task, the selective attention manipulation in the EEG task may have placed higher cognitive demands on
17 participants due to the longer duration of the EEG task. Participants were required to sustain attention
18 for five minutes in ~22.5-second blocks for both fMRI tasks, whereas the EEG task involved fifteen
19 minutes of attention in ~1-minute blocks. The EEG task was longer to ensure that a high EEG signal-to-
20 noise ratio was achieved, and *post-hoc* analyses confirmed that the top-down ERP effect was sensitive to
21 trial numbers. Unfortunately, increased task duration requires participants to sustain attention for an
22 even longer period, making it unlikely that this manipulation would increase the sensitivity of the task.
23 Some investigators use machine learning to circumvent these issues and address possible spatiotemporal
24 variations in the electrocortical responses of patients with brain injuries⁵⁴. For simplicity of
25 interpretation and consistency with clinical methods, we employed a more traditional approach to
26 comparing scalp voltages. While no false alarms were evident in the current sample, misses occurred
27 with two patients – *i.e.*, patients demonstrated evidence of command following but no evidence of a P3a.
28 As has been discussed elsewhere, signs of awareness in both behavioural and neuroimaging assessments
29 may be missed due to fluctuating arousal¹³. Nevertheless, when a P3a is elicited, the current data suggest
30 the sophisticated cognitive networks that underlie an ability to follow commands are also preserved.

1 The detection of awareness in the DoC is a clinical standard of care. In order to provide
2 sufficient evidence to influence clinical practice, it is essential to compare novel assessments to existing
3 techniques. The current investigation allowed for a comparison of two previously reported
4 neuroimaging-based assessments of covert command following, based on mental imagery^{6,9,10,13,15-17} and
5 selective auditory attention^{29,30}. The results of these assessments converged for nine of the twelve
6 patients with useable data from both paradigms. Two patients demonstrated positive evidence of
7 command following in only the selective auditory attention task, while one patient showed positive
8 evidence of command following only in the mental imagery task. The behavioural profile of the DoC –
9 that is, time-variant fatigue and arousal – always affords the possibility that a patient did not
10 demonstrate positive evidence of covert command following due to lack of voluntary engagement in the
11 task. Likewise, false negatives occur in assessments of healthy volunteers^{11,55}. Nevertheless, the less
12 than perfect correspondence of the two covert fMRI command following tasks may have occurred
13 because the demands of one task were better suited to the patient. For example, some individuals find it
14 difficult to engage in motor imagery⁵⁶, and in some reports, brain-computer interfaces based on selective
15 attention tasks are successfully operated by more users than those based on responses to motor
16 imagery^{57,58}. Accordingly, assessments of covert command following based on selective attention may
17 be better suited to a general population. Overall, however, an optimal evaluation of a patient with a DoC
18 should include multiple assessments to maximise the likelihood of detecting responses that are not
19 evident from overt behaviour¹³. In the absence of unambiguous ground truth, an investigation of the
20 concordance between assessments may be the best way to improve diagnostic and prognostic accuracy.

21 In summary, the brain responses of fourteen patients with severe brain injuries were assessed
22 using an EEG-based somatosensory selective attention task, two fMRI-based assessments of covert
23 command following, and one behavioural instrument. While limited by a relatively small sample of
24 patients, the data tentatively suggest that the detection of a somatosensory bottom-up P3a effect in a
25 patient correlates with an ability to follow commands, as evaluated by multimodal assessments. This
26 provides evidence that a bedside somatosensory oddball procedure can improve diagnostic accuracy in
27 the DoC and more accurately characterise the level of neurocognitive preservation. Overall, this work
28 provides a valuable addition to neuroimaging batteries for the clinical assessment of patients with DoC
29 and convergent, multimodal evidence for the utility of these techniques.

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12 collection and analysis, decision to publish, or preparation of the manuscript.

13 **Author Contributions**

14 R.M.G., D.F.E., L.N., and D.C. contributed to conception and design of the study. R.M.G., D.F.E., L.N.,
15 and D.C. contributed to data collection and analysis. R.M.G., D.C., S.C., and A.M.O. contributed to
16 writing the manuscript.

17 **Potential Conflicts of Interest**

18 Nothing to report.

19

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1 **Figure Captions**

2 **Figure 1. Summary of the relationship between command following and outcomes on the selective** 3 **somatosensory attention task.**

4 The summary depicts the number of patients and healthy volunteers who generated each of the three
5 possible outcomes on the somatosensory selective attention task.

6 VS=vegetative state; MCS=minimally conscious state; EMCS=emergent from a minimally conscious
7 state; LIS=Locked-In Syndrome.

8 **Figure 2. Steady-state evoked responses to the repetitive vibrotactile stimulation.**

9 Power spectra (top panels) and averaged EEG responses (bottom panels) calculated over a period of 1-
10 second. Analyses were conducted using the data recorded from site Pz only; each waveform (bottom
11 panels) is depicted with ± 1 standard error of the mean.

12 EEG=electroencephalography; **= $p < 0.01$; ***= $p < .001$; VS=vegetative state; MCS=minimally
13 conscious state; EMCS=emergent from a minimally conscious state; LIS=Locked-In Syndrome.

14 **Figure 3. Bottom-up attention event-related potentials to the standard and deviant vibrotactile** 15 **stimulation.**

16 Spatiotemporal clusters were calculated across all twelve electrodes and are depicted with ± 1 standard
17 error of the mean in colour-matched shading. The electrodes included in the significant spatiotemporal
18 cluster are enclosed with a black line on each topographic plot. The temporal boundaries and the
19 probability value of each cluster are indicated with shading and inset text. (A) depicts the grand-
20 averaged ERP effect for the healthy volunteers, (B) depicts the single-subject ERP effects for the healthy
21 volunteers ($p < 9.9E-03$ in all cases), and (C) depicts the single-subject ERP effects for the patients with
22 statistically significant results.

23 VS=vegetative state; MCS=minimally conscious state; EMCS=emergent from a minimally conscious
24 state; LIS=Locked-In Syndrome.

25 **Figure 4. Top-down attention event-related potentials to the target and non-target vibrotactile** 26 **stimulation for the healthy volunteers.**

1 Spatiotemporal clusters were calculated across all twelve electrodes with each waveform depicted with
2 ± 1 standard error of the mean. The electrodes included in the significant spatiotemporal cluster are
3 enclosed with a black outline on each topographic plot. The temporal boundaries and the probability
4 value of each cluster are indicated with shading and inset text. The grand-averaged result ($n=15$) is
5 depicted in (A). For the single subject results (B), only results from participants with statistically
6 significant clusters are shown.

7 **Figure 5. Replication data from the four patients with whom follow-up investigations were**
8 **conducted.**

9 Data are depicted for the initial and follow up tests of Patients VS4, MCS3, EMCS1, and VS6, as
10 labelled. For the steady-state evoked potentials, power spectra (top left panels within each cell) and
11 averaged EEG data (bottom left panels within each cell) were calculated over a period of 1-second.
12 Analyses were conducted using the data recorded from site Pz only; each waveform is depicted with ± 1
13 standard error of the mean. For the bottom-up attention ERP effects (right panels within each cell),
14 spatiotemporal clusters were calculated across all twelve electrodes and are depicted with ± 1 standard
15 error of the mean. The electrodes included in the significant spatiotemporal cluster are enclosed with a
16 black line on each topographic plot. The temporal boundaries and the probability value of each cluster
17 are indicated with shading and inset text. For Patient VS6 only, two separate fMRI assessments were
18 conducted at each testing session. For the fMRI mental imagery paradigm, significant task-related fMRI
19 activation is depicted (Imagery>Rest), and results are thresholded at an uncorrected $p<.001$. For the
20 fMRI selective auditory attention task, only activation clusters within the attention network
21 (Count>Relax) that survived the familywise error correction threshold of $p<.05$ at the whole-brain level
22 are displayed. The fMRI results are rendered on the patient's T1 anatomical MRI image, and scales
23 depicting the t -value statistical maps are inset.

24 $*=p<0.05$; $**=p<0.01$; $***=p<.001$; n.s.=not statistically significant; VS=vegetative state;
25 MCS=minimally conscious state; EMCS=emergent from a minimally conscious state.

SOMATOSENSATION IN DISORDERS OF CONSCIOUSNESS

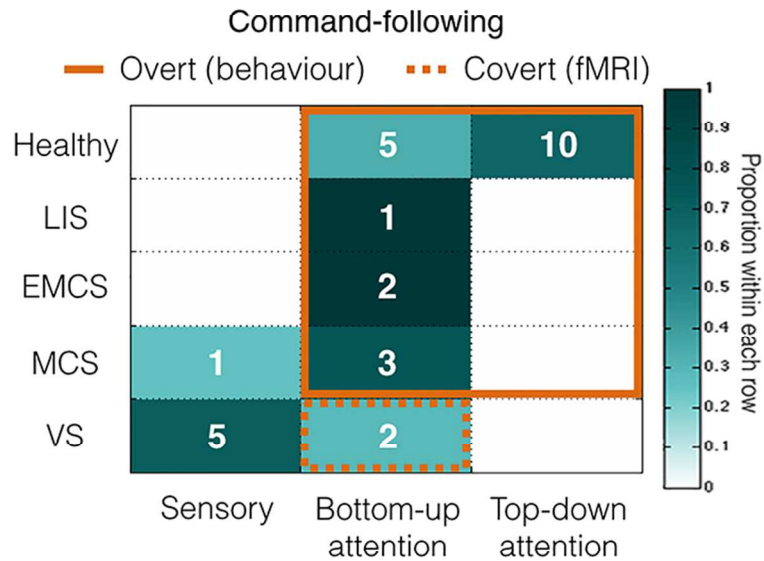
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Table 1. Number of trials available for the analyses of the EEG data from the somatosensory selective attention paradigm following artefact rejection.

	Stimulus Type^a			
	<i>M (MIN-MAX)</i>			
	Upper Back	Target Wrist	Non-Target Wrist	Trials Rejected (%)
Patients (<i>n</i> =14)	2614 (1591-3246)	313 (188-384)	311 (180-388)	35 (20-59)
Controls (<i>n</i> =15)	2890 (2718-5026)	345 (327-363)	345 (321-359)	25 (20-32)

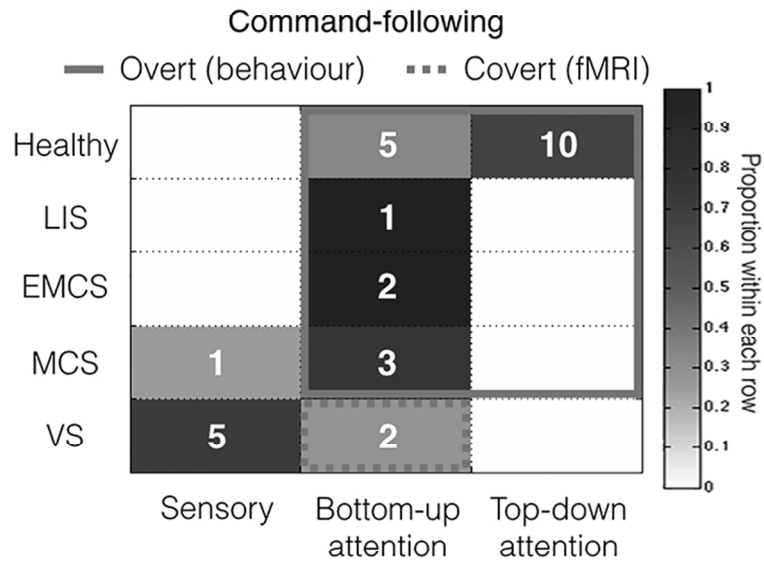
Notes. M=mean; MIN=minimum; MAX=maximum.

^aA 2x3 Chi-square goodness of fit test indicated that the minimum number of trials in each of the three stimulus types did not significantly differ between the controls and patients, $\chi^2(2)=0.21, p=0.9$.



Summary of the relationship between command following and outcomes on the selective somatosensory attention task.

The summary depicts the number of patients and healthy volunteers who generated each of the three possible outcomes on the somatosensory selective attention task.
 VS=vegetative state; MCS=minimally conscious state; EMCS=emergent from a minimally conscious state;
 LIS=Locked-In Syndrome.
 80x60mm (300 x 300 DPI)



(Black and white version of Figure 1 for print)
80x60mm (300 x 300 DPI)

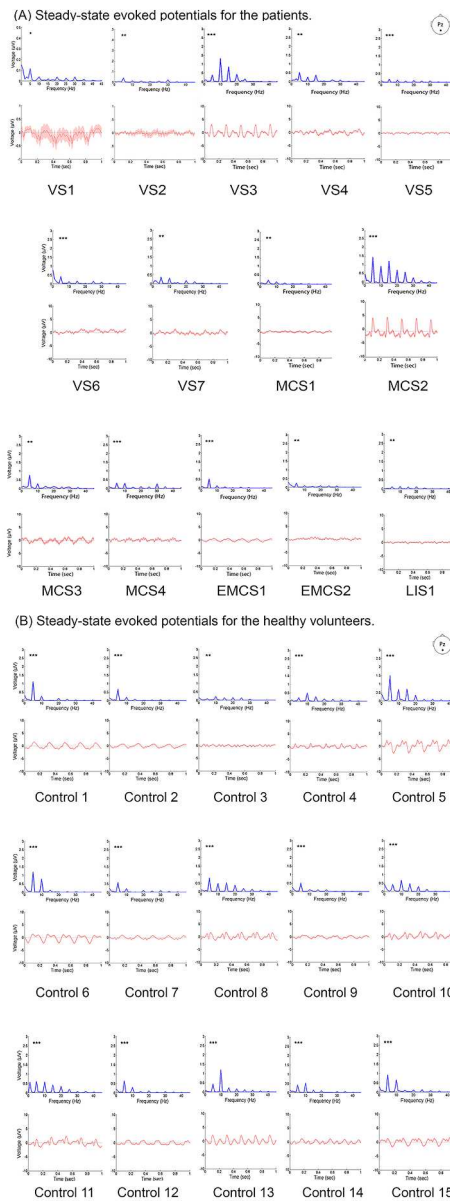
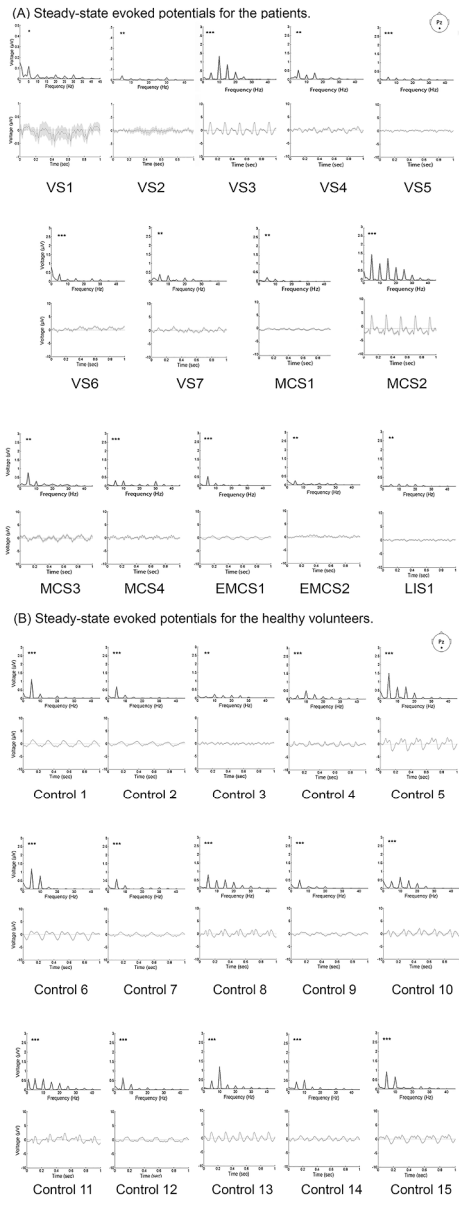


Figure 2. Steady-state evoked responses to the repetitive vibrotactile stimulation.

Power spectra (top panels) and averaged EEG responses (bottom panels) calculated over a period of 1-second. Analyses were conducted using the data recorded from site Pz only; each waveform (bottom panels) is depicted with ± 1 standard error of the mean.

EEG=electroencephalography; **= $p < 0.01$; ***= $p < .001$; VS=vegetative state; MCS=minimally conscious state; EMCS=emergent from a minimally conscious state; LIS=Locked-In Syndrome.

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(Black and white version of Figure 2 for print)
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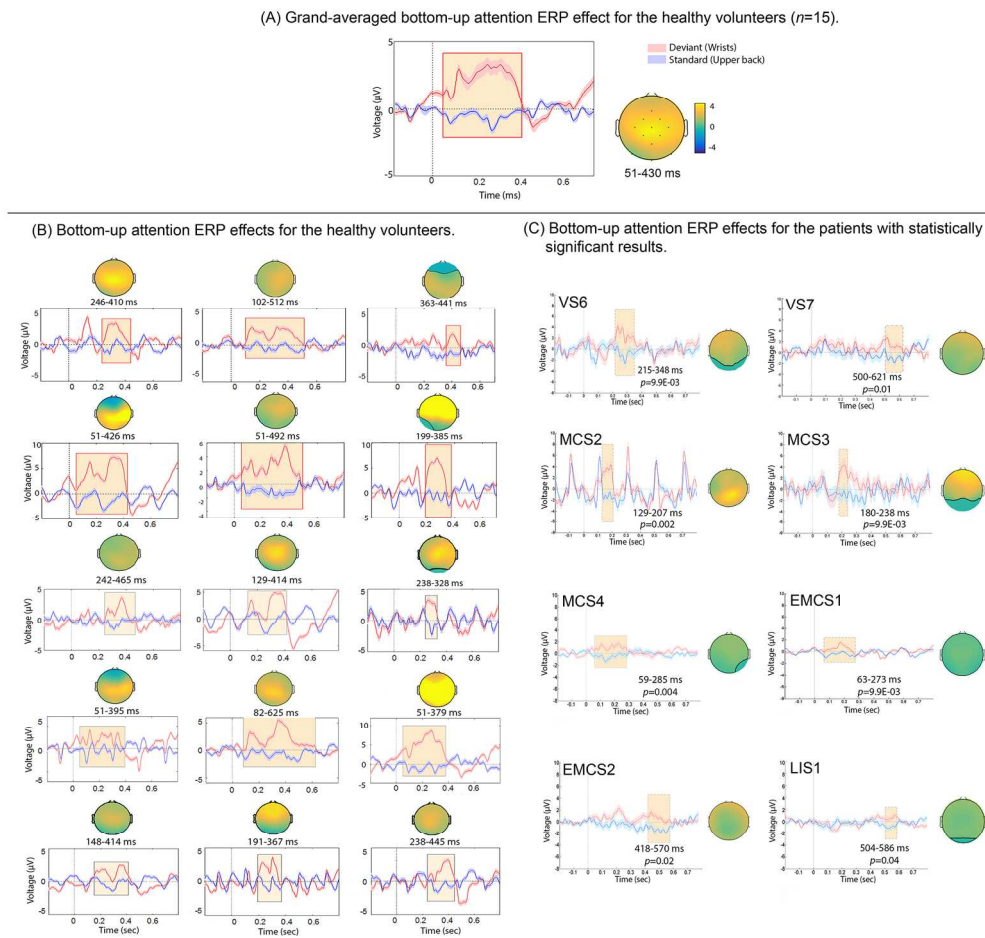
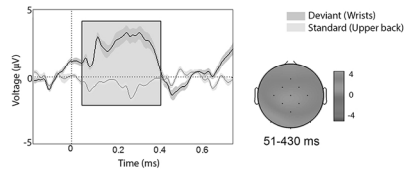


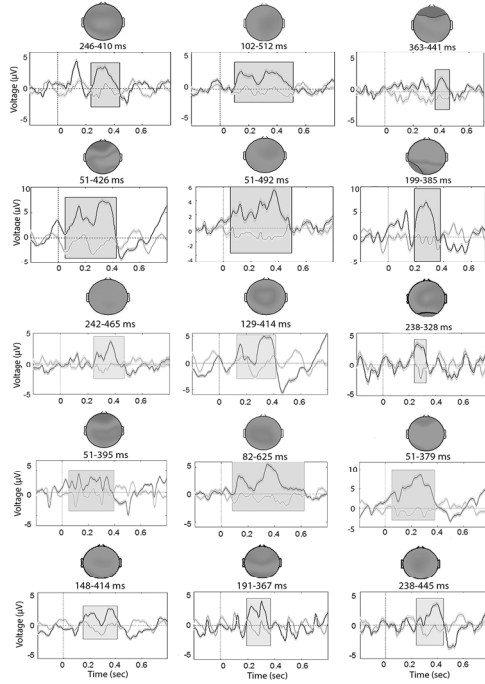
Figure 3. Bottom-up attention event-related potentials to the standard and deviant vibrotactile stimulation. Spatiotemporal clusters were calculated across all twelve electrodes and are depicted with ± 1 standard error of the mean in colour-matched shading. The electrodes included in the significant spatiotemporal cluster are enclosed with a black line on each topographic plot. The temporal boundaries and the probability value of each cluster are indicated with shading and inset text. (A) depicts the grand-averaged ERP effect for the healthy volunteers, (B) depicts the single-subject ERP effects for the healthy volunteers ($p < 9.9E-03$ in all cases), and (C) depicts the single-subject ERP effects for the patients with statistically significant results. VS=vegetative state; MCS=minimally conscious state; EMCS=emergent from a minimally conscious state; LIS=Locked-In Syndrome.

170x160mm (300 x 300 DPI)

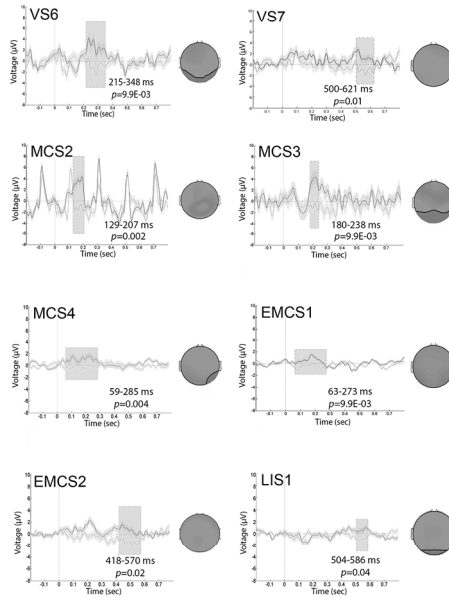
(A) Grand-averaged bottom-up attention ERP effect for the healthy volunteers ($n=15$).



(B) Bottom-up attention ERP effects for the healthy volunteers.

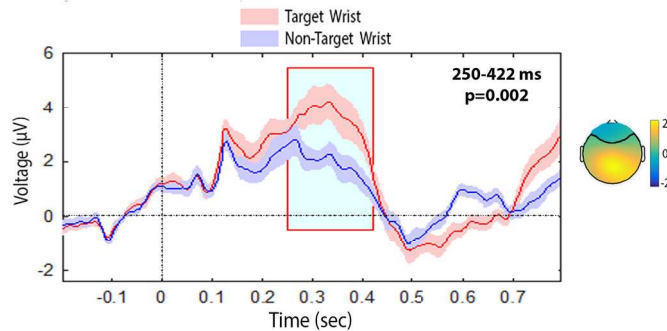


(C) Bottom-up attention ERP effects for the patients with statistically significant results.



(Black and white version of Figure 3 for print)
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(A) Grand-averaged top-down attention ERP effect for the healthy volunteers ($n=15$).

(B) Top-down attention ERP effects for the healthy volunteers with statistically significant results.

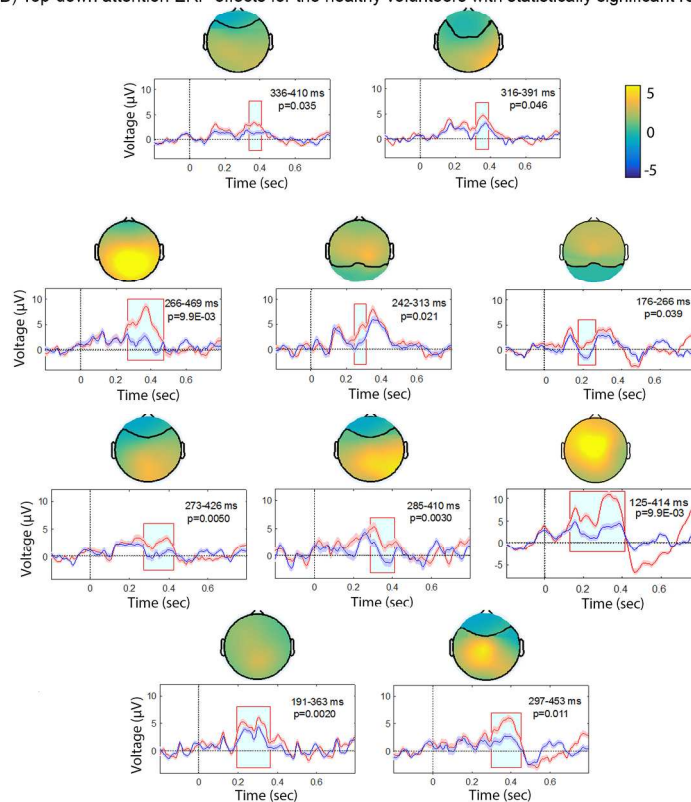
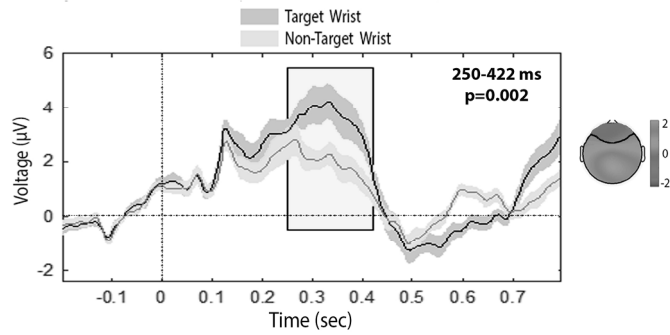


Figure 4. Top-down attention event-related potentials to the target and non-target vibrotactile stimulation for the healthy volunteers.

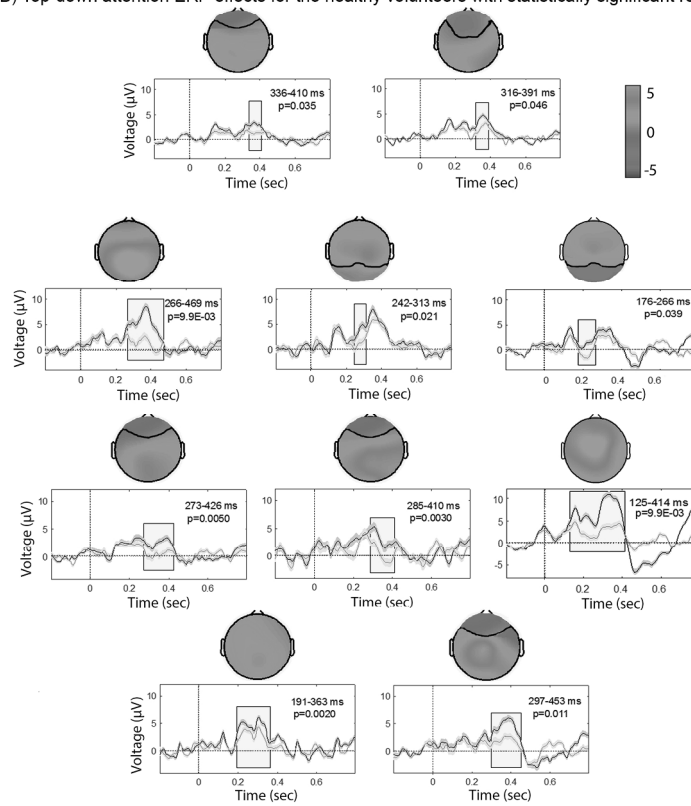
Spatiotemporal clusters were calculated across all twelve electrodes with each waveform depicted with ± 1 standard error of the mean. The electrodes included in the significant spatiotemporal cluster are enclosed with a black outline on each topographic plot. The temporal boundaries and the probability value of each cluster are indicated with shading and inset text. The grand-averaged result ($n=15$) is depicted in (A). For the single subject results (B), only results from participants with statistically significant clusters are shown.

170x262mm (300 x 300 DPI)

(A) Grand-averaged top-down attention ERP effect for the healthy volunteers ($n=15$).



(B) Top-down attention ERP effects for the healthy volunteers with statistically significant results.



(Black and white version of Figure 4 for print)
170x262mm (300 x 300 DPI)

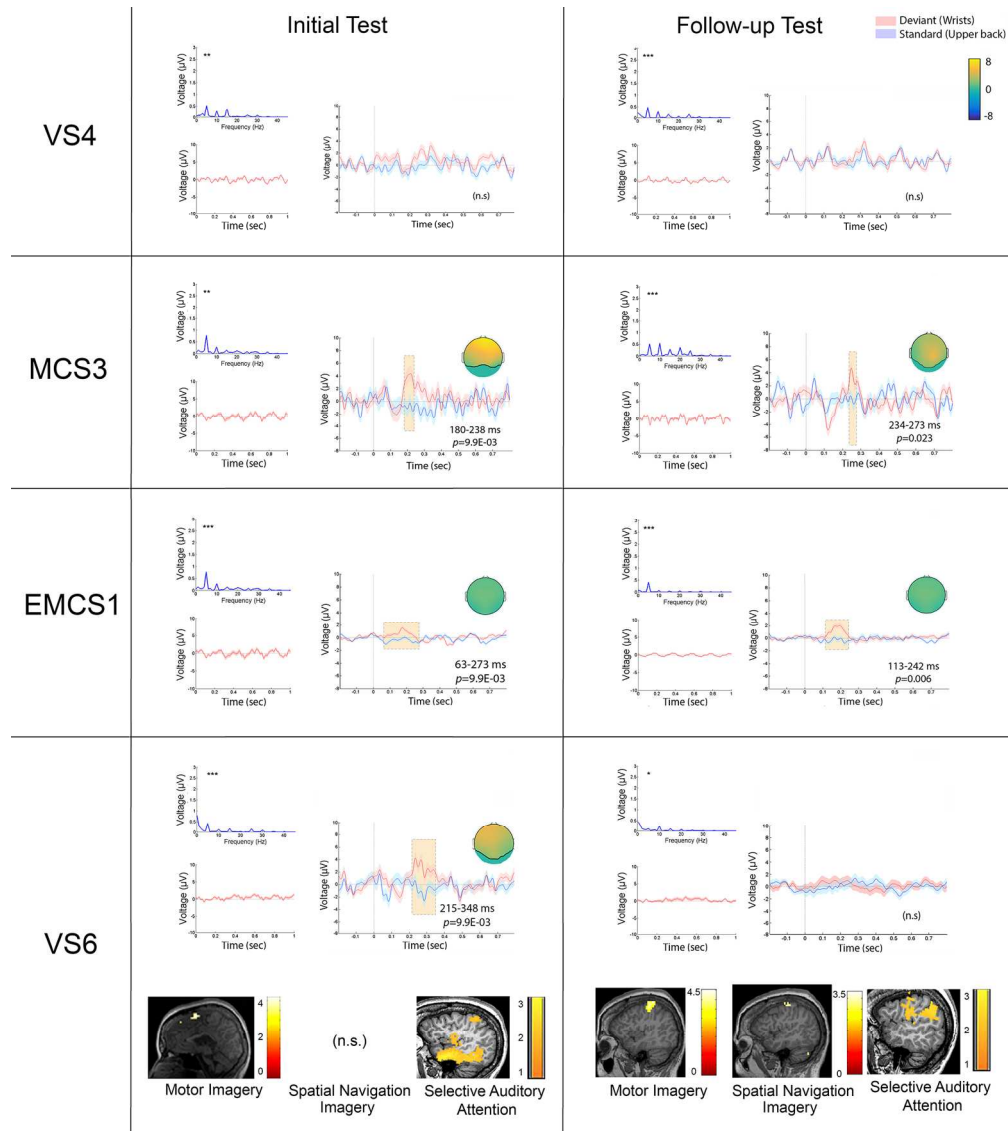


Figure 5. Replication data from the four patients with whom follow-up investigations were conducted. Data are depicted for the initial and follow up tests of Patients VS4, MCS3, EMCS1, and VS6, as labelled. For the steady-state evoked potentials, power spectra (top left panels within each cell) and averaged EEG data (bottom left panels within each cell) were calculated over a period of 1-second. Analyses were conducted using the data recorded from site Pz only; each waveform is depicted with ± 1 standard error of the mean.

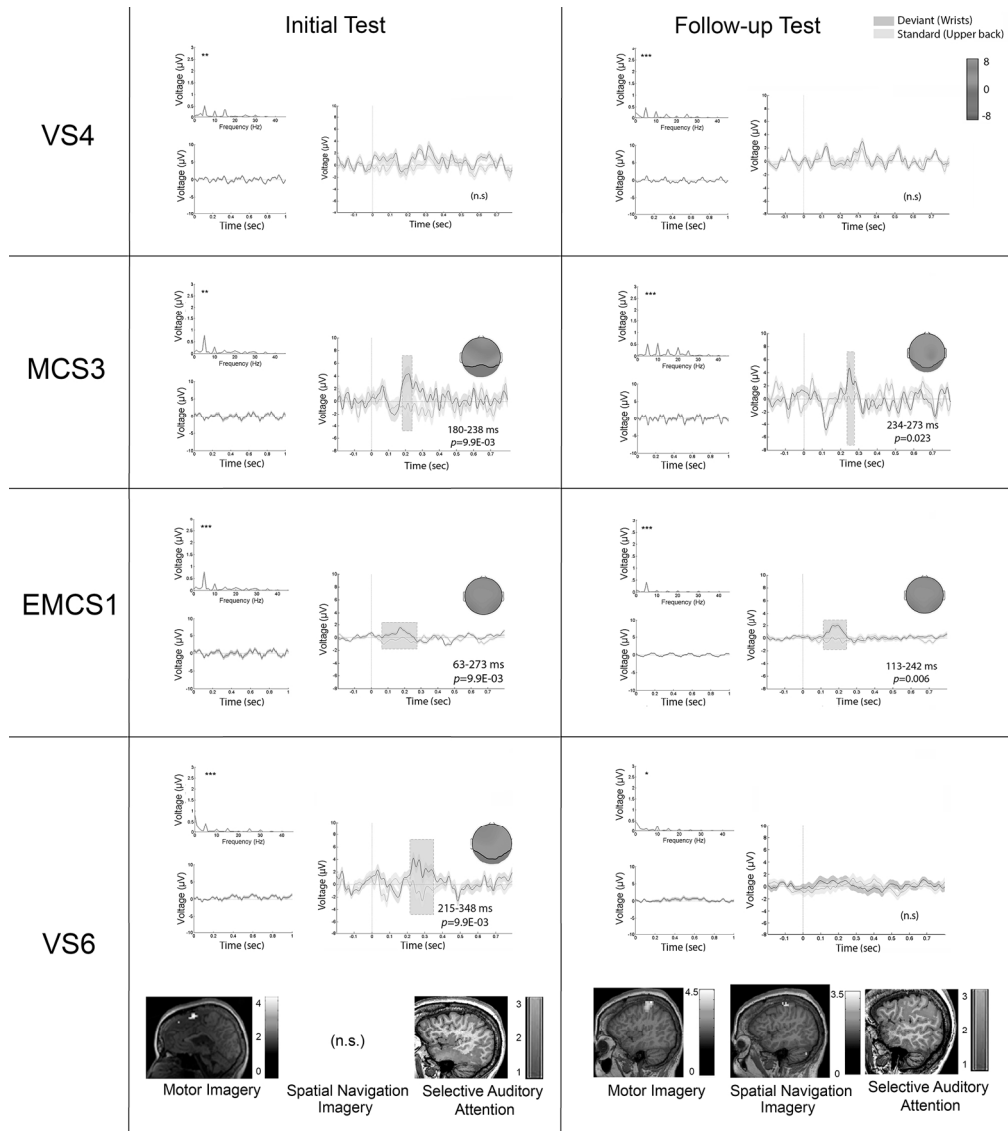
For the bottom-up attention ERP effects (right panels within each cell), spatiotemporal clusters were calculated across all twelve electrodes and are depicted with ± 1 standard error of the mean. The electrodes included in the significant spatiotemporal cluster are enclosed with a black line on each topographic plot. The temporal boundaries and the probability value of each cluster are indicated with shading and inset text.

For Patient VS6 only, two separate fMRI assessments were conducted at each testing session. For the fMRI mental imagery paradigm, significant task-related fMRI activation is depicted (Imagery>Rest), and results are thresholded at an uncorrected $p < .001$. For the fMRI selective auditory attention task, only activation clusters within the attention network (Count>Relax) that survived the familywise error correction threshold of $p < .05$ at the whole-brain level are displayed. The fMRI results are rendered on the patient's T1 anatomical MRI image, and scales depicting the t-value statistical maps are inset.

*= $p < 0.05$; **= $p < 0.01$; ***= $p < 0.001$; n.s.=not statistically significant; VS=vegetative state;

MCS=minimally conscious state; EMCS=emergent from a minimally conscious state.
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Supplementary Table 1. Summary of the patients recruited for this investigation, including their age, *post ictus* interval, and behaviour as measured by the Coma Recovery Scale-Revised.

All behavioural data reported here correspond with the patient’s abilities at the time when they generated the highest total score on the Coma Recovery Scale-Revised; these assessments occurred prior to the patient’s participation in the current investigation in some cases.

Patient	Diagnosis	Age (years)	Sex	Aetiology	Post ictus (years)	Sensory Responses		Attention Responses			Command Following Responses		
						Reflexive Behaviour (CRS-R)	Somatosensory Evoked Potential	Behavioural Arousal (CRS-R)	Non-reflexive Behaviour (CRS-R)	Somatosensory Attention Orienting (P3a)	Behaviour (CRS-R)	Mental Imagery (BOLD)	Selective Auditory Attention (BOLD)
VS1	VS	19	M	Non-traumatic brain injury secondary to Commodo Cordis	4.0	Auditory startle Localization to sound Visual startle Abnormal posturing Flexion withdrawal Oral reflexive movement	Present	Eye opening without stimulation	Absent	Absent	Absent	Absent	Absent
VS2	VS	51	F	Massive myocardial infarction	0.9	Auditory startle Abnormal posturing Oral reflexive movement	Present	Eye opening with stimulation	Absent	Absent	Absent	Absent	Absent
VS3	VS	57 (fMRI) 58 (EEG)	M	Non-traumatic brain injury secondary to cardiac arrest	3.1 (fMRI) 4.1 (EEG)	Auditory startle Abnormal posturing Flexion withdrawal Oral reflexive movement	Present	Eye opening without stimulation	Absent	Absent	Absent	Absent	Absent
VS4	VS	42	F	Non-traumatic brain injury secondary to	4.3	Auditory startle Localization to	Present	Eye opening without	Absent	Absent	Absent	Absent	Absent

				cardiac arrest		sound		stimulation					
						Visual startle							
						Abnormal posturing							
						Flexion withdrawal							
						Oral reflexive movement							
VS5	VS	52	F	Hypoxic ischemic encephalopathy, severe generalized atrophy/cardiac arrest	6.5	Auditory startle							
						Abnormal posturing							
						Flexion withdrawal	Present	Eye opening with stimulation	Absent	Absent	Absent	Absent	Absent
						Oral reflexive movement							
VS6	VS/MCS*	44 (Test 1) 46 (Test 2)	F	Traumatic brain injury secondary to motor vehicle accident	20.4 (Test 1) 22.2 (Test 2)	Auditory startle							
						Abnormal posturing							
						Flexion withdrawal	Present	Eye opening without stimulation	Absent	Present (Test 1) Absent (Test 2)	Absent	Present	Present
						Oral reflexive movement							
VS7	VS/MCS*	23 (fMRI) 26 (EEG)	M	Traumatic brain injury secondary to motor vehicle accident	6.0 (fMRI) 9.5 (EEG)	Auditory startle							
						Visual startle							
						Abnormal posturing	Present	Eye opening without stimulation	Absent	Present	Absent	Present	(fMRI data could not be analysed due to excessive motion)
						Flexion withdrawal							
						Oral reflexive movement							
MCS1 ^a	MCS-	40	M	Traumatic brain injury secondary to motor vehicle accident	3.1	Auditory startle							
						Visual startle							
						Abnormal posturing	Present	Eye opening with stimulation	Visual fixation and pursuit	Absent	Absent	Absent	Present
						Oral reflexive movement							
MCS2	MCS+	35	M	Non-traumatic brain injury secondary to cardiac arrest	16.9	Auditory startle							
						Localization to sound	Present	Eye opening without stimulation	Visual pursuit	Present	Object localisation	Reproducible movement to command	Absent
						Visual startle and fixation ^b							Present
						Abnormal posturing							

						Flexion withdrawal Oral reflexive movement Vocalization/Oral movement				
MCS3	MCS+	47	F	Non-traumatic brain injury from near-drowning	19.8	Auditory startle Localization to sound Visual startle and fixation ^b Abnormal posturing Present Flexion withdrawal Oral reflexive movement Vocalization/Oral movement	Eye opening without stimulation	Visual pursuit Present	Reproducible movement to command Present Present	
MCS4	MCS-	25	F	Traumatic brain injury secondary to motor vehicle accident	5.7	Auditory startle Localization to sound Visual startle Present Abnormal posturing Oral reflexive movement	Eye opening without stimulation	Visual fixation and pursuit Present	Absent Present Present	
EMCS1	EMCS	49	F	Traumatic brain injury secondary to motor vehicle accident	12.3	Auditory startle Localization to sound Visual startle Abnormal posturing Present Flexion withdrawal Localization to noxious stimulation Oral reflexive movement Vocalization/Oral movement	Consistent behaviour following verbal or gestural prompts	Visual fixation and pursuit Present	Object localisation and recognition Object manipulation Automatic motor response Functional object use Present Absent Reproducible and consistent movement to command Functional and accurate communication	

EMCS2	EMCS	32	M	Traumatic brain injury secondary to motor vehicle accident	4.1	<p>Auditory startle</p> <p>Localization to sound</p> <p>Visual startle</p> <p>Abnormal posturing</p> <p>Flexion withdrawal</p> <p>Localization to noxious stimulation</p> <p>Oral reflexive movement</p> <p>Vocalization/Oral movement</p>	Present	Consistent behaviour following verbal or gestural prompts	Visual fixation and pursuit	Present	<p>Object localisation and recognition</p> <p>Object manipulation</p> <p>Automatic motor response</p> <p>Functional object use</p> <p>Reproducible and consistent movement to command</p> <p>Intelligible verbalization</p> <p>Functional and accurate communication</p>	(fMRI data could not be acquired because the patient moved excessively during the scan)
LIS1	LIS	55	M	Brainstem infarct related to vertebral artery thrombosis	1.5	<p>Auditory startle</p> <p>Localization to sound</p> <p>Visual startle</p> <p>Abnormal posturing</p> <p>Flexion withdrawal</p> <p>Oral reflexive movement</p> <p>Vocalization/Oral movement</p>	Present	Consistent behaviour following verbal or gestural prompts	Visual fixation and pursuit	Present	<p>Object localisation and recognition</p> <p>Reproducible and consistent movement to command</p> <p>Functional and accurate communication</p>	Present Present

CRS-R=Coma Recovery Scale-Revised; EEG=electroencephalography; fMRI=functional magnetic resonance imaging; VS=vegetative state; MCS=minimally conscious state; MCS*=non-behavioural minimally conscious state; EMCS=emergent from a minimally conscious state; LIS=Locked-In Syndrome.

Notes. ^aPatient MCS1 scored in the VS range immediately prior to his participation in the EEG assessment. However, he scored in the MCS- range in another assessment with the Coma Recovery Scale-Revised several hours prior to his participation in the EEG assessment and has thus been classified as in a MCS-.

^bSustained visual fixation does not necessarily reflect higher order cortical brain function in patients with DoC and non-traumatic aetiology⁵⁹.

Supplementary Table 2. Coma Recovery Scale-Revised scores for each patient immediately prior to their assessment with electroencephalography and functional magnetic resonance imaging for this investigation.

Patient	CRS-R Sub-scores at EEG assessment								CRS-R Sub-scores at fMRI assessment								Time between fMRI assessments	Time between EEG and fMRI assessments	Time between EEG replication sessions
	Session	Auditory Function	Visual Function	Motor Function	Oromotor/Verbal Function	Communication	Arousal	Total Score	Session	Auditory Function	Visual Function	Motor Function	Oromotor/Verbal Function	Communication	Arousal	Total Score			
VS1	1	1-Auditory startle	0-None	2-Flexion withdrawal	1-Oral reflexive movement	0-None	1-Eye opening with stimulation	5	1 (Selective Attention)	1-Auditory startle	1-Visual startle	0-None	1-Oral reflexive movement	0-None	2-Eye opening without stimulation	5	2 days	2 days	N/A
									2 (Imagery)	1-Auditory startle	0-None	2-Flexion withdrawal	1-Oral reflexive movement	0-None	1-Eye opening with stimulation	5			
VS2	1	1-Auditory startle	0-None	1-Abnormal posturing	1-Oral reflexive movement	0-None	1-Eye opening with stimulation	4	1 (Selective Attention)	1-Auditory startle	0-None	1-Abnormal posturing	1-Oral reflexive movement	0-None	1-Eye opening with stimulation	4	1 day	2 days	N/A
									2 (Imagery)	1-Auditory startle	1-Visual startle	0-None	1-Oral reflexive movement	0-None	1-Eye opening with stimulation	4			
VS3	1	1-Auditory startle	0-None	2-Flexion withdrawal	1-Oral reflexive movement	0-None	2-Eye opening without stimulation	6	1 (Both paradigms)	1-Auditory startle	1-Visual startle	2-Flexion withdrawal	1-Oral reflexive movement	0-None	1-Eye opening with stimulation	6	<1 hour (Same scan)	1 year	N/A
VS4	1 (Initial)	2-Localization to sound	1-Visual startle	2-Flexion withdrawal	1-Oral reflexive movement	0-None	2-Eye opening without stimulation	8	<i>(fMRI assessments conducted only at EEG Session 2)</i>								N/A	3.5 months	3.5 months
	2 (Replication)	1-Auditory startle	0-None	2-Flexion withdrawal	1-Oral reflexive movement	0-None	2-Eye opening without stimulation	6	1 (Imagery)	1-Auditory startle	1-Visual startle	2-Flexion withdrawal	1-Oral reflexive movement	0-None	2-Eye opening without stimulation	7	1 day	1 day	
									2 (Selective Attention)	1-Auditory startle	0-None	2-Flexion withdrawal	1-Oral reflexive movement	0-None	1-Eye opening with stimulation	5		2 days	
VS5	1	1-Auditory startle	0-None	1-Abnormal posturing	1-Oral reflexive movement	0-None	1-Eye opening with stimulation	4	1 (Selective Attention)	1-Auditory startle	0-None	2-Flexion withdrawal	1-Oral reflexive movement	0-None	1-Eye opening with stimulation	5	1 day	1 day	N/A
									2 (Imagery)	1-Auditory startle	0-None	2-Flexion withdrawal	1-Oral reflexive movement	0-None	2-Eye opening without stimulation	6			
VS6	1 (Initial)	1-Auditory startle	0-None	2-Flexion withdrawal	1-Oral reflexive movement	0-None	1-Eye opening with stimulation	5	1 (Both paradigms)	0-None	1-Visual startle	0-None	0-None	0-None	2-Eye opening without stimulation	3	<1 hour (Same scan)	1 day	22 months

	2 (Replication)	1-Auditory startle	0-None	2-Flexion withdrawal	1-Oral reflexive movement	0-None	2-Eye opening without stimulation	6	1 (Both paradigms)	0-None	0-None	0-None	0-None	0-None	2-Eye opening without stimulation	2	<1 hour (Same scan)	2 days	
VS7	1	1-Auditory startle	0-None	1-Abnormal posturing	1-Oral reflexive movement	0-None	2-Eye opening without stimulation	5	1 (Imagery)	1-Auditory startle	1-Visual startle	2-Flexion withdrawal	1-Oral reflexive movement	0-None	2-Eye opening without stimulation	7	2 days	3.5 years	N/A
									2 (Selective Attention)	1-Auditory startle	0-None	2-Flexion withdrawal	1-Oral reflexive movement	0-None	2-Eye opening without stimulation	6			
MCS1 ^a	1	1-Auditory startle	1-Visual startle	1-Abnormal posturing	1-Oral reflexive movement	0-None	1-Eye opening with stimulation	5	1 (Both paradigms)	1-Auditory startle	3-Visual pursuit	1-Abnormal posturing	1-Oral reflexive movement	0-None	1-Eye opening with stimulation	7	<1 hour (Same scan)	2 days	N/A
MCS2	1	1-Auditory startle	3-Visual pursuit	2-Flexion withdrawal	1-Oral reflexive movement	0-None	1-Eye opening with stimulation	8	1 (Both paradigms)	1-Auditory startle	3-Visual pursuit	4-Object manipulation	1-Oral reflexive movement	0-None	1-Eye opening with stimulation	10	<1 hour (Same scan)	1 day	N/A
MCS3	1 (Initial)	3- Reproducible movement to command	3-Visual pursuit	2-Flexion withdrawal	1-Oral reflexive movement	0-None	2-Eye opening without stimulation	11	1 (Imagery)	2- Localization to sound	3-Visual pursuit	2-Flexion withdrawal	1-Oral reflexive movement	0-None	2-Eye opening without stimulation	10	1 day	7.5 months	2.5 months
									2 (Selective Attention)	1-Auditory startle	3-Visual pursuit	2-Flexion withdrawal	1-Oral reflexive movement	0-None	1-Eye opening with stimulation	8			
	2 (Replication)	3- Reproducible movement to command	3-Visual pursuit	2-Flexion withdrawal	2-Vocalization/ Oral movement	0-None	2-Eye opening without stimulation	12	(fMRI assessments conducted once 7.5 months prior to EEG Session 1)							N/A	10 months		
MCS4	1	1-Auditory startle	3-Visual pursuit	1-Abnormal posturing	1-Oral reflexive movement	0-None	2-Eye opening without stimulation	8	1 (Imagery)	1-Auditory startle	3-Visual pursuit	1-Abnormal posturing	1-Oral reflexive movement	0-None	2-Eye opening without stimulation	8	1 day	2 days	N/A
									2 (Selective Attention)	2- Localization to sound	3-Visual pursuit	1-Abnormal posturing	1-Oral reflexive movement	0-None	2-Eye opening without stimulation	9			
EMCS1 ^b	1 (Initial)	4-Consistent movement to command	5-Object recognition	6- Functional object use	2-Vocalization/ Oral movement	2-Functional: Accurate	3- Attention	22	1 (Imagery)	4- Consistent movement to command	5-Object recognition	6-Functional object use	2-Vocalization/ Oral movement	2-Functional: Accurate	3- Attention	22	2 days	1.5 months	2 months
									2 (Selective Attention)	4- Consistent movement to command	4-Object localization	4-Object manipulation	1-Oral reflexive movement	1-Non-Functional: Intentional	1-Eye opening with stimulation	15			
	2 (Replication)	4-Consistent movement to command	5-Object recognition	6- Functional object use	2- Vocalization/Oral movement	2-Functional: Accurate	3- Attention	22	(fMRI assessments conducted once 1.5 months prior to EEG Session 1)							N/A	3.5 months		
EMCS2	1	4-Consistent movement to command	5-Object recognition	6- Functional object use	3-Intelligible Verbalization	2-Functional: Accurate	3- Attention	23	1 (Imagery)	4- Consistent movement to command	5-Object recognition	5-Automatic motor response	0-None	2-Functional: Accurate	3- Attention	19	1 day	2 days	N/A

								2 (Selective Attention)	4- Consistent movement to command	5-Object recognition	5-Automatic motor response	3-Intelligible Verbalization	2-Functional: Accurate	3- Attention	22		1 day		
LIS1	1	4-Consistent movement to command	5-Object recognition	0-None	1-Oral reflexive movement	2-Functional: Accurate	3- Attention	15	1 (Both paradigms)	4- Consistent movement to command	5-Object recognition	0-None	1-Oral reflexive movement	2-Functional: Accurate	3- Attention	15	<1 hour (Same scan)	1 day	N/A

CRS-R=Coma Recovery Scale-Revised; EEG=electroencephalography; fMRI=functional magnetic resonance imaging; VS=vegetative state; MCS=minimally conscious state; EMCS=emergent from a minimally conscious state; LIS=Locked-In Syndrome.

Notes. ^aPatient MCS1 scored in the VS range immediately prior to his participation in the EEG assessment. However, he scored in the MCS- range in another assessment with the Coma Recovery Scale-Revised several hours prior to his participation in the EEG assessment and has thus been classified as in a MCS-.

^bPatient EMCS2 was not assessed with the CRS-R at her replication session. However, she was able to communicate using an arm movement.

















Supplementary Table 3. Patient outcomes on the behavioural, neuroimaging-based, and electroencephalography-based assessments.

Only positive results are depicted for the EEG- and fMRI-based assessments. For the fMRI mental imagery paradigm, significant task-related fMRI activation is labeled by region (Imagery>Rest), and results are thresholded at an uncorrected $p<.001$. For the fMRI selective auditory attention task, only activation clusters within the attention network (Count>Relax) that survived the familywise error correction threshold of $p<.05$ at the whole-brain level are displayed. All fMRI results are rendered on each patient's T1 anatomical MRI image, and scales depicting the t -value statistical maps are inset.

EEG=electroencephalography; fMRI=functional magnetic resonance imaging; SMA=supplementary motor area; OPJ=occipito-parietal junction; TOPJ=temporo-occipito-parietal junction; PHC=parahippocampal cortex; IFG=inferior frontal gyrus; VS=vegetative state; MCS=minimally conscious state; EMCS=emergent from a minimally conscious state; LIS=Locked-In Syndrome; **= $p<0.01$; ***= $p<.001$ (** and *** apply to power spectra only, as marked).

Note. ^aPatient MCS1 scored in the VS range immediately prior to his participation in the EEG assessment. However, this patient scored in the MCS *Minus* range in another CRS assessment several hours prior to his participation in this EEG investigation. For this reason, this patient has been classified as in a MCS *Minus*.

Patient	Diagnosis	Somatosensory Selective Attention	Mental Imagery (Commands)	Auditory Selective Attention (Commands)
VS1	Vegetative state	 Sensory Only	Negative	Negative
VS2	Vegetative state	 Sensory Only	Negative	Negative
VS3	Vegetative state	 Sensory Only	Negative	Negative
VS4	Vegetative state	 Sensory Only	Negative	Negative
VS5	Vegetative state	 Sensory Only	Negative	Negative
VS6	Negative state/ Non-behavioural minimally conscious state	 Sensory and Attention	Positive (motor imagery)	Positive
VS7	Negative state/ Non-behavioural minimally conscious state	 Sensory and Attention	Positive (spatial navigation)	Unable to use data
MCS1*	Minimally conscious state minus	 Sensory Only	Negative	Positive
MCS2	Minimally conscious state plus	 Sensory and Attention	Negative	Positive
MCS3	Minimally conscious state plus	 Sensory and Attention	Positive (spatial navigation)	Positive
MCS4	Minimally conscious state minus	 Sensory and Attention	Positive (spatial navigation)	Positive
EMCS1	Emergent from a minimally conscious state	 Sensory and Attention	Positive (spatial navigation)	Negative
EMCS2	Emergent from a minimally conscious state	 Sensory and Attention	Unable to use data	Unable to use data
LS1	Locked-In Syndrome	 Sensory and Attention	Positive (spatial navigation)	Positive

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