Study of behavioural and neural bases of visuo-spatial working memory with an fMRI paradigm based on an n-back task

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The goal of this study was to propose a new functional magnetic resonance imaging (fMRI) paradigm using a language-free adaptation of a 2-back working memory task to avoid cultural and educational bias. We additionally provide an index of the validity of the proposed paradigm and test whether the experimental task discriminates the behavioural performances of healthy participants from those of individuals with working memory deficits. Ten healthy participants and nine patients presenting working memory (WM) deficits due to acquired brain injury (ABI) performed the developed task. To inspect whether the paradigm activates brain areas typically involved in visual working memory (VWM), brain activation of the healthy participants was assessed with fMRIs. To examine the task's capacity to discriminate behavioural data, performances of the healthy participants in the task were compared with those of ABI patients. Data were analysed with GLM-based random effects procedures and *t*-tests. We found an increase of the BOLD signal in the specialized areas of VWM. Concerning behavioural performances, healthy participants showed the predicted pattern of more hits, less omissions and a tendency for fewer false alarms, more self-corrected responses, and faster reaction times, when compared with subjects presenting WM impairments. The results suggest that this task activates brain areas involved in VWM and discriminates behavioural performances of clinical and non-clinical groups. It can thus be used as a research methodology for behavioural and neuroimaging studies of VWM in block-design paradigms.

Working memory (WM) is among the most recently proposed structural models of memory (Baddeley, 1986, 2000, 2003; Baddeley & Hitch, 1974). It refers to storing information in a temporary system that allows monitoring and manipulation of this information in a relevant way to a current task, such as solving a problem. WM also seems to be involved in other cognitive functions, such as reasoning and spatial processing, and has received the theoretical contributions of various authors, such as Cowan (1995), Engle, Kane, and Tuholski (1999), or Ericsson and Delaney (1999), among others (for a revision and comparison of the models, see Miyake & Shah, 1999).

In Baddeley's original multicomponent model (Baddeley & Hitch, 1974), WM is conceptualized as a series of subsystems. The central executive is the most important system. It lacks modal specificity, has limited attentional capacity, and is responsible for processing cognitive tasks. The other two storage systems, the phonological loop and the visuo-spatial sketchpad (frequently called 'slave systems'), are specific to stimuli's different modalities, have limited capacity, depend on the central executive system, and are recruited when needed. The sketchpad can be organized into a visual subsystem and a spatial subsystem. The episodic buffer is the fourth component of Baddeley's model and holds representations that link visual, phonological, spatial information, and information outside the slave systems (Baddeley, 2000). This model is still generating new developments and research (Baddeley, 2003).

To study WM and associated brain areas and brain functioning, various tasks have been designed as paradigms for functional magnetic resonance imaging (fMRI) research. Most employ verbal stimuli (digits, letters, or words), and some use non-verbal stimuli (e.g., spatial locations, colours, abstract objects, faces) (Cabeza & Nyberg, 2000; D'Esposito *et al.*, 1998; Owen, 1997). Although the type of stimulus employed in the tasks depends necessarily on the research question, verbal stimuli have the potential to interfere with the person's performance because they might introduce additional variables, such as those concerning language processing, or educational and cultural factors. Many studies on WM processes use language-dependent n-back WM tasks, possibly generating outcomes that might thus reflect cultural and educational biases. Also, they might invoke language-related processes that can mask the strictly WM-related processes. If language is impaired, as is often the case in brain injury situations (Dahlberg *et al.*, 2006; Dardier *et al.*, 2011), to disentangle the above-mentioned processes and to create specific tasks that elicit WM can become particularly important for both research and clinical purposes. Language-free, visuo-spatial tasks contribute to a better understanding of WM in general and in brain injury situations in particular, especially considering studies suggesting that these patients tend to perform more poorly in verbal than in spatial tasks (Hatfield, Bieliauskas, Begloff, Steinberg, & Kauszler, 2004).

Most tasks employed in the study of visuo-spatial working memory (VWM) have been derived from the procedure of Luck and Vogel (1997). In a more recent work, Baddeley and colleagues (Baddeley, Hitch, & Allen, 2009) developed a visuo-spatial n-back task that consists of a 3×3 grid with each cell measuring 4×4 cm. The grid is presented on a screen. On each trial, a 1 cm diameter black circle appears in one of the nine possible locations in the grid and remains there until a response is attempted or the trial times out. The next trial follows immediately, with the circle appearing in one of the other eight (randomly chosen) locations. In the 2-back condition of this experiment, the instruction is for participants to respond to the location the circle occupied two trials before. Results showed that the 2-back task was highly demanding regarding executive functioning. This n-back visuospatial grid task has been employed in various other studies (see Owen, McMillan, Laird, & Bullmore, 2005; for a revision), and Kane, Conway, Miura, and Colflesh (2007) indicate that an n-back task presents face validity as a WM task.

Neuroimaging studies indicate that performance of the n-back visuospatial grid task depends on both the frontal regions associated with executive control and the more cortical regions associated with storing information (Owen *et al.*, 2005; Smith & Jonides, 1999). This study supports Baddeley's (2000) proposed existence of a multimodal episodic buffer that operates under central executive control. In a different study on the neuroanatomical substrates of VWM, Carlson *et al.* (1998) employed a visuo-spatial n-back task with two memory-load conditions (0-back, 1-back, 2-back) and found that a network of distributed brain areas in the dorsal visual pathway was activated when the memory load increased. Specifically, a bilateral activation of the medial frontal gyrus (MFG), superior frontal sulcus and adjacent areas (SFS/SFG), and intraparietal sulcus (IPS) was observed in most participants. They also reported an activation of the medial superior frontal gyrus, precentral gyrus, superior and inferior parietal lobuli, occipital visual association areas, anterior and posterior cingulate areas, and insula (Carlson *et al.*, 1998). Other studies reported domain specificity in VWM activation, with activation of the superior frontal sulcus [Brodmann's areas (BAs) 6/8] and portions of the inferior frontal gyrus (BAs 44, 45, 47). However, other lateral PFC regions, such as the medial frontal gyrus (BAs 9, 46, 9/46), might not show domain specificity (D'Esposito, 2008). Regarding the contribution of the parietal lobe (for a review, see Berryhill, Chein, & Olson, 2011; Berryhill & Olson, 2008a,b), its superior portion (SPL; BAs 5 and 7) is recognized to be involved in VWM (Olson & Berryhill, 2009; Wager & Smith, 2003).

The neuroanatomical correlates of VWM are well established not only as a result of neuroimaging studies, but also as a result of research of brain-damaged patients, animal studies, and electrophysiological measures (Shah & Miyake, 1999). For example, the medial temporal lobe is thought to play a role in VWM (Olson & Ezzyat, 2008), because when lesions of this brain region occur, VWM is also impaired (Olson, Moore, Stark, & Chatterjee, 2006).

Despite the popularity of the n-back visuospatial grid task in the study of WM, it is important to adapt this task, particularly when it is intended to be used in populations such as those with acquired brain injury (ABI). For example, challenges associated with fMRIs include the need for proper selection of specific tasks, or of cognitive operations related to them, and the need to consider dimensions such as the difficulty that patients have in understanding the instructions related to the tasks (Sunaert & Yousry, 2001). The use of the same material to study different cognitive functions contributes to improve participants' understanding of instructions, because they are already familiarized with the (same) stimulus material in the following tasks. This problem of understanding instructions is not only crucial for the application of fMRIs, but is also topical when patients have cognitive deficits such as those resulting from ABI (e.g., attention, memory, or executive deficits). The task we propose addresses this issue and can thus potentially be used to evaluate the effects of a rehabilitation programme on ABI patients, both in terms of behavioural performances in the task before and after the programme, and in terms of possible neuroanatomical changes (e.g., in the dispersion of brain activation).

In this study, we build on previous research to propose a VWM task specifically designed for fMRI research and taking into account the difficulties of people with ABI. Specifically, we provide non-verbal material that (1) minimizes educational and cultural biases, (2) can be used to study diverse cognitive functions (e.g., selective attention and sustained attention, in addition to VWM) in terms of both behavioural performances in the task and neuroanatomical substrates activated while performing the task, and (3) can be used in experimental tasks for neuroimaging studies.

The goals of this work are as follows: (1) to propose an n-back task as an fMRI paradigm designed to be administered to patients with brain lesions, such as ABI, (2) to provide an index of the validity of the proposed paradigm, and (3) to test whether the experimental task discriminates the behavioural performances of healthy participants from those of individuals with VWM deficits.

This paradigm uses a language-free adaptation of a 2-back VWM task that is based on Baddeley *et al.*'s (2009) proposal and represents a refinement of visuo-spatial WM tasks previously applied to the study of VWM and its neural substrates (e.g., Owen *et al.*, 1998). To examine the validity of the proposed paradigm, this study tests the hypothesis, based on the literature, that the paradigm produces an increase in the blood oxygenation level-dependent (BOLD) signal in specialized areas related with VWM. It also assesses the task's capacity to discriminate between healthy individuals and brain-injured patients regarding their capacity to perform the task (e.g., their number of errors). The hypothesis is that healthy subjects present distinctively superior behavioural performances in the task than a group of people with ABI presenting WM deficits. Confirmation of the hypotheses that (a) the neurobiological correlates of this task are equivalent to those found in the literature on the neuroanatomical bases of VWM, and (b) behavioural performance in the task is significantly inferior in the ABI group, provides an index of the validity of this experimental task for the study and evaluation of VWM processes and of its capacity to discriminate between healthy participants and individuals with WM deficits.

Method

Participants

To examine the value of the proposed task as an experimental paradigm directed at VWM, 10 healthy participants were recruited from the local community. All were registered as caregivers of former patients in local rehabilitation institutions' databases. To be included in the study, participants needed to be right-handed. Pathologies of the central nervous system, psychiatric disorders, trauma, visual acuity deficits, motor disabilities that could interfere with performances, and contraindication for MRI were exclusion criteria. Six participants were male and four were female. Their mean age was 27.10 years old (*SD* = 2.89, *range* = 21–30), and their mean education level was 11.40 years (*SD* = 2.27). These sample characteristics are depicted in Table 1.

To assess the capacity of the proposed task to discriminate behavioural performances of healthy individuals from those of clinical groups, a new sample of participants with ABI was selected. In addition to working memory deficits, these new participants needed to be right-handed and have normal or corrected-to-normal vision and absence of motor disabilities that could interfere with their performances to be included in the study. All 11 ABI patients who were starting their treatment in a rehabilitation institution were invited to the study, and nine accepted to participate. Their neuropsychological assessment included the Token Test (McNeil & Prescott, 1978), the d2 Test of Attention (Brickenkamp & Zillmer, 1998), the Mini-Mental State Score (Teasdale & Jennett, 1974), different subtests of the Wechsler Memory Scale III (WMS-III; Wechsler, 2008), such as digit span and reverse digit span, and Behavioural Assessment of the Dysexecutive Syndrome (BADS, Wilson, Alderman, Burgess, Emslie, & Evans, 1996). The group results

Table 1. Sample characteristics

Characteristics	Healthy group (n = 10)		ABI group (n = 9)	
	M	*SD*	*M*	*SD*
Years of education	11.40	2.27	9.67	3.97
Years of age at assessment	27.10	2.89	29.67	4.80
Years of age at injury			26.11	4.68
Months since the injury			38.22	18.55
	n	%	*n*	%
Gender				
Male	6	60.00	7	77.80
Female	4	40.00	2	22.20
Injury aetiology and location				
Stroke			5	55.50
Diffuse injury location, including the right middle cerebral artery				
TBI			4	44.40
Diffuse injury location, including frontal, temporal, parietal, and lateral brain areas				
Injury severity at admission (GOSE)				
Severe			7	77.80
Moderate			2	22.20

Note. ABI = acquired brain injury; TBI = traumatic brain injury; GOSE = Glasgow Outcome Scale Extended.

fell within the mean in all cognitive functions except WM (1 *SD* from the test means). The aetiology of participants' ABI was stroke (five cases) and traumatic brain injury (four patients). The injury location was diffuse for stroke patients (and included the right middle cerebral artery), as well as for the traumatic brain injury (TBI) patients (including frontal, temporal, parietal, and lateral brain areas). Most patients presented a severe brain lesion ($n = 7$) which interrupted schooling for one participant who was attending college. Mean age at the time of the injury was 26.11 years old ($SD = 4.68$), and mean time since the injury was 38.22 months ($SD = 18.55$). Seven of these patients were male and two were female. Their mean age was 29.67 years old ($SD = 4.80$, $range = 23–37$), and their mean education level was 9.67 years ($SD = 3.97$). Table 1 presents these sample characteristics.

Participants who accepted to take part in this study gave their written informed consent before starting. The study was approved by the local ethics committee and complies with the Declaration of Helsinki.

Design and procedures

The experiment with the 2-back VWM task was organized according to a block-design paradigm during which participants watched the 36 stimuli in the task (Figure 1) repeated in four blocks. Each cycle consisted of a resting period of 15,000 ms immediately followed by an activation block in which the 36 stimuli were presented one at a time (650 ms of exposure time) with an interstimuli interval of 2350 ms (corresponding to 3000 ms per

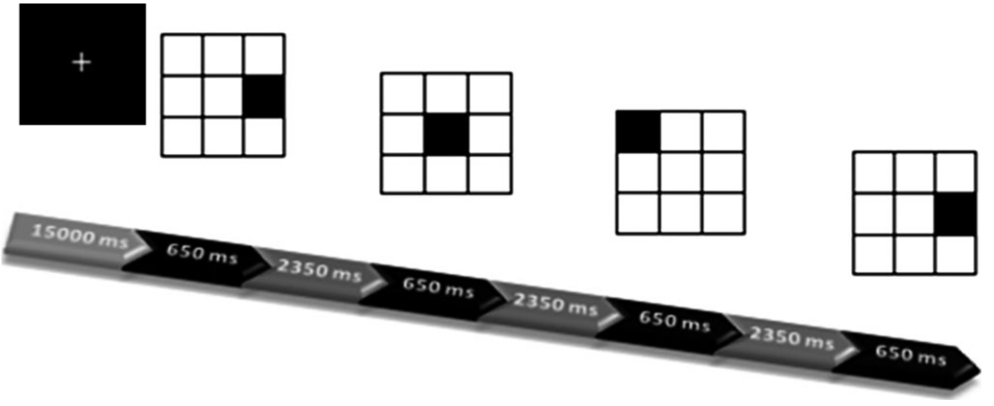

Figure 1. Visuo-spatial Working Memory Task. Sequence of resting period, exposure time, and interstimuli interval.

trial). Stimuli were presented in a pseudorandom order to avoid more than three consecutive trials of the same type. Participants were instructed to pay attention to a sequence of visual stimuli and press a pre-defined button, as fast as possible, each time the black square was the same as two trials earlier. During the resting periods, participants were told to rest while paying attention to a fixation point. Participants could respond only during the exhibition of each stimulus.

For the neuroimaging study, the experiment was organized in a single session of fMRI scanning. The activation blocks were synchronized with the fMRI scans. The MR scanning was carried out with a 3T (MAGNETON Trio Tim 3T, Siemens, Munich, Germany) scanner located at the Portuguese Brain Imaging Network (BIN). It was equipped for echo-planar imaging (EPI), used in data acquisition. The timing of the stimulus presentation was synchronized with the magnet trigger pulses. The study protocol consisted of the acquisition of a T1-6t high-resolution volumetric sequence (RT = 2,300 ms, ET = 2.98 ms, IT = 900 ms, 160 slices were obtained in a matrix of 256 mm with a voxel size of $1 \times 1 \times 1$ mm), followed by the acquisition of whole-brain functional data, using a 2D EPI sequence (RT = 2,500 ms, ET = 37 ms, obtained in a 104×104 matrix with a voxel size of $2.5 \times 2.5 \times 3$ mm).

For the assessment of behavioural performances in the task, the same stimulation protocol and procedures presented above were followed. Response accuracy of all participants (number of hits and number of errors, including omissions, false alarms, and self-corrected responses) and reaction times during the task were automatically recorded in SuperLab 4.5 (2011, Cedrus Co., San Pedro, CA, USA).

Stimuli and instruments

The stimuli in the proposed task consisted of nine different nine-square matrices with one of the squares painted in black (36 stimuli). Stimuli were presented using a high-resolution rear projection system (Avotec Silent Vision 6011, Way Stuart, Finland) with responses recorded via a fibre-optic response pad (Lumina Response Pad for fMRI, model LU400-Pair, Cedrus). The stimulation protocol was prepared in SuperLab 4.5 (2011, Cedrus, California), and a laptop computer running the same software was used to control stimuli presentation and to record the responses.

Sociodemographic data (age, education and sex) and information on right handedness were obtained directly from the participants. In addition, hospital discharge medical reports from the time when patients' brain injury occurred were consulted for clinical information (e.g., lesions' aetiology, location, and level of motor impairment). Lesion severity was determined according to the criteria of the Glasgow Coma Scale (Teasdale & Jennett, 1974) or through clinical consensus of three rehabilitation team members when that information was lacking. The Glasgow Outcome Scale Extended (GOSE; Wilson, Pettigrew, & Teasdale, 1998) was also applied at patient admission.

Data analysis

For the neuroimaging study, data pre-processing was performed using the BrainVoyager QX 2.3 software (2011, Brain Innovation, Maastricht, The Netherlands). Pre-processing of functional data included slice time correction, 3D motion correction, spatial smoothing, and temporal filtering. Functional and anatomical scans of the data were co-registered and normalized to Talairach space. Brain activation during the resting blocks was subtracted from brain activation during the 2-back blocks. A GLM-based random effects analysis was run on the data. A whole-brain analysis was performed with activation maps (thresholded at p-value <.001), and activation areas with less than 300 voxels were excluded. The data were corrected for multiple comparisons with false discovery rate (FDR) calculations. For reading easiness, results on the activated areas in the whole brain are reported in terms of Brodmann's areas (BAs).

For the study of behavioural performances in the task, participants' response accuracy and reaction times while performing the task were analysed. Comparisons between the group of healthy participants and the group of ABI patients regarding behavioural data were conducted with t-tests. Statistical analyses were performed in PASW Statistics version 18.0 (Predictive Analytics Software, SPSS Inc., Chicago, IL USA).

Results

Analyses of the sociodemographic data showed that the ABI group and the healthy group were equivalent regarding age, education, and sex. No statistically significant differences were found between the two groups for these variables. There was also intragroup homogeneity, namely regarding age and education. The small sample size prevented intragroup analyses by sex.

Capacity of the proposed 2-back task to activate WM-related brain areas (Imaging data)

The whole-brain analysis showed that task-related BOLD activations of the healthy participants during the VWM task were statistically significant ($p < .001$) for several BAs, namely the superior frontal sulcus, BA 6, the dorsolateral prefrontal cortex (BAs 9/46), and the bilateral ventrolateral prefrontal cortex (BA 47, inferior frontal gyrus, pars orbitalis). The inferior frontal gyrus (BAs 44/45) and the premotor cortex (bilateral BA 6) were also activated in this study. The same occurred for bilateral BA 4 (activation of the precentral gyrus in the primary motor cortex). BAs 6/47/19 were also activated, as well as the inferior parietal lobe (BAs 7/19/39) and the intraparietal sulcus (BA 7). Visual association areas were activated as well, including the lingual and fusiform gyri (BAs 17/18). All statistically significant results are presented in Table 2 and depicted in Figure 2.

Table 2. Brain areas activated during the visuo-spatial working memory task after a whole-brain analysis of healthy participants. Brodmann's areas (BAs) are presented for reading easiness

BA	*x M (SD)*	*y M (SD)*	*z M (SD)*	No. of Voxels	Average *t*	Average *p*
BA4L	−36.00 (8.00)	−7.67 (3.00)	50.22 (5.30)	1,241	11.700.088	0.006
BA6L	−31.31 (18.93)	4.48 (7.53)	37.22 (10.21)	3,545	7.733.869	0.013
BA7L	−28.21 (11.91)	−58.12 (10.82)	42.99 (4.54)	4,316	9.238.437	0.009
BA9L	−40.30 (2.34)	22.56 (4.37)	34.62 (3.80)	925	7.909.834	0.012
BA17L	−14.11 (8.46)	−90.17 (5.91)	1.01 (8.15)	1,002	5.632.151	0.043
BA18L	−22.85 (10.51)	−79.81 (4.269)	4.44 (15.98)	573	9.167.931	0.009
BA39L	−49.05 (3.29)	−49.83 (2.94)	35.44 (4.90)	576	7.501.182	0.015
BA44L	−40.39 (4.52)	13.37 (9.05)	27.26 (6.56)	853	7.111.234	0.019
BA45L	−33.04 (2.32)	20.21 (3.54)	8.48 (2.99)	344	6.620.371	0.025
BA47L	−31.86 (2.93)	19.78 (2.98)	5.01 (2.65)	376	5.937.047	0.035
BA4R	22.80 (7.78)	−6.33 (4.50)	51.30 (2.77)	1,179	8.086.189	0.012
BA6R	27.16 (17.97)	9.03 (7.57)	40.41 (8.37)	3,032	10.483.876	0.004
BA7R	25.43 (13.02)	−58.05 (12.14)	44.69 (5.58)	3,583	10.565.937	0.004
BA9R	37.78 (3.73)	30.38 (7.11)	36.38 (3.46)	706	6.527.842	0.024
BA17R	12.70 (11.79)	−86.99 (4.43)	0.98 (8.88)	818	6.257.608	0.028
BA18R	30.95 (5.39)	−77.75 (2.83)	15.66 (10.22)	907	6.659.940	0.025
BA19R	30.44 (7.22)	−63.81 (7.94)	33.45 (15.37)	3,309	8.018.610	0.012
BA44R	40.50 (5.37)	18.66 (10.17)	30.54 (5.76)	1,295	6.689.806	0.025
BA46R	31.85 (3.04)	51.42 (3.89)	19.63 (4.34)	477	5.502.589	0.045
BA47R	30.42 (2.51)	21.58 (2.81)	3.53 (3.83)	555	5.561.234	0.043

Note. Corrected *p*-value for multiple comparisons with false discovery rate (FDR).

Capacity of the proposed 2-back task to discriminate behavioural performances (Behavioural data)

Descriptive statistics for behavioural performances of the healthy group and the ABI group on the VWM task are presented in Table 3.

The *t*-test reveals a group effect for hits and for errors. The ABI group shows significantly fewer hits, $t(28) = -4.62$, $p < .001$, $d = -1.80$, more errors in the form of omissions, $t(28) = 3.90$, $p = .001$, $d = 1.47$, and of false alarms, $t(20) = 3.19$, $p < .005$, $d = 1.02$, and fewer self-corrected responses, $t(28) = -2.85$, $p = .008$, $d = -1.09$, than the healthy group. The ABI group also displays larger reaction times than the healthy group, $t(28) = 2.07$, $p = .048$, $d = .80$. The standard deviations of each of these results are similar for the two groups except regarding false alarms, which register greater variability in the ABI than in the healthy group ($SD = 7.39$ and $SD = .97$, respectively).

Discussion

The analysis of the capacity of our proposed 2-back task to elicit WM shows that, as expected, brain regions associated with specialized areas for VWM displayed higher activation during the activation period than during the resting condition (namely, the superior frontal sulcus, BA 6). We also observed the activation of the dorsolateral prefrontal cortex (DLPC, BAs 9/46), considered to be the locus of the active manipulation of information, and the bilateral ventrolateral prefrontal cortex (BA 47, inferior frontal gyrus, pars orbitalis), considered to be involved in maintaining the information

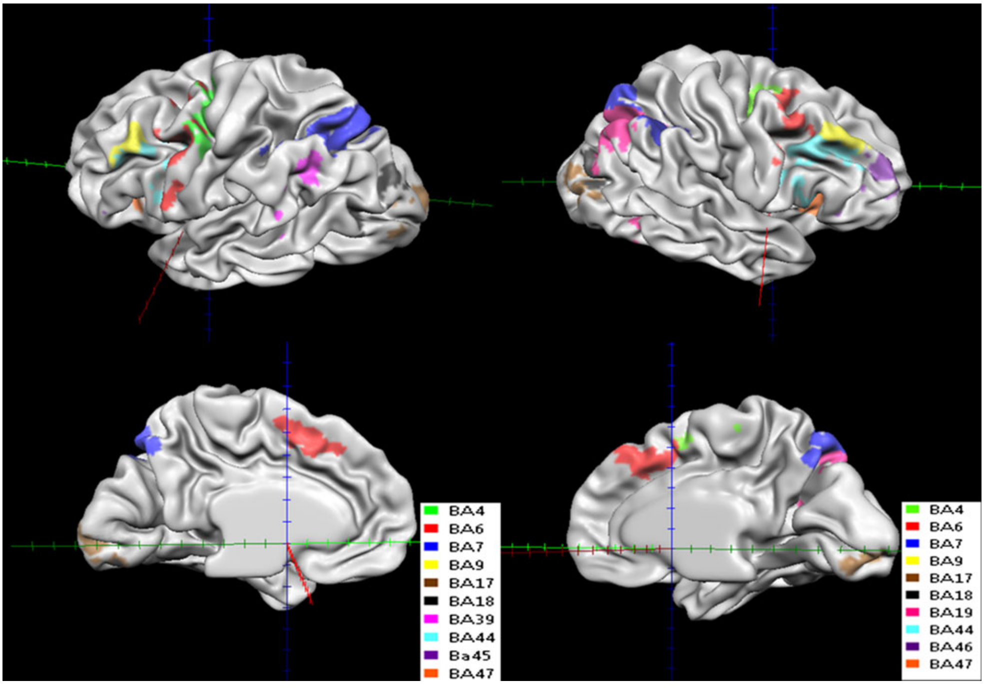

Figure 2. Activation in the brain's left hemisphere (left in the picture) and right hemisphere (right in the picture) after whole-brain analyses of healthy participants. Surface colouring represents the different Brodmann's Areas (BAs). The picture shows brain lateral views (top) and medial views (bottom).

Table 3. Behavioural performances of the healthy group and the acquired brain injury (ABI) group on the visuo-spatial working memory task

Behavioural performance	Healthy group *M* (*SD*)	ABI group *M* (*SD*)	Mean difference	95% CI
Hits	123.50 (10.19)	104.90 (10.48)	−18.60**	[−26.84, −10.36]
Errors				
Omissions	16.90 (10.62)	31.35 (9.04)	14.45**	[6.85, 22.05]
False alarms	0.60 (0.97)	5.95 (7.39)	5.35*	[1.85, 8.85]
Self-corrected responses	3.00 (1.15)	1.80 (1.06)	−1.20*	[−2.06, −0.34]
Reaction times	441.74 (50.32)	482.68 (51.56)	40.94*	[0.35, 81.53]

*$p < .05$; **$p \leq .001$.

(D'Esposito *et al.*, 1998). The inferior frontal gyrus (BAs 44/45) and the premotor cortex (bilateral BA 6) were also activated in this study. Both have been reported in the literature as associated with performance of visuospatial n-back tasks (see, e.g., Carlson *et al.*, 1998). The observed bilateral activations of BA 4 (the precentral gyrus in the primary motor cortex) are not surprising given that performance of the VWM task requires individuals' motor responses. Similar activations were reported in other studies (Metzak *et al.*, 2012; Ventre-Dominey *et al.*, 2005).

The right inferior parietal cortex (BA 40) that Baddeley (2003) considers to be the brain area that corresponds to the visuo-spatial sketchpad and the inferred area of the storage constituent of the loop was not sufficiently activated in our task. However, some studies reporting the activation of BA 40 also report the activation of the right BAs 6/47/19, and these same areas were activated in our study (Baddeley, 2003; Smith, Jonides, & Koeppe, 1996). Consistent with the findings of Rämä *et al.* (2001), the inferior parietal lobe (BAs 7/19/39) and the intraparietal sulcus (BA 7, but not BA 40) were activated, as well as visual association areas, including the lingual and fusiform gyri (BA 17/18). Finally, and as previously reported in the literature, we found evidence for the fact that several bilateral anterior and posterior regions of the cortex are involved in this task, indicating that a distributed neural system is implicated in WM (Cabeza & Nyberg, 2000; Cicerone, 2002).

The analysis of the capacity of the proposed 2-back task to discriminate clinical and non-clinical groups' behavioural performances shows that the healthy group displayed the predicted pattern of more hits, less omissions and a tendency for fewer false alarms, more self-corrected responses, and faster reaction times than participants with WM impairments due to ABI. These difficulties in behavioural accuracy and the decrease in processing speed are common consequences of brain injury (although the ABI group registered great variability regarding false alarms) and have been extensively shown in the literature (Johansson & Tornmalm, 2012).

This task can now be extended to neuroimaging studies of brain-injured populations. Its stimulus material has already been used in the study of other cognitive functions (e.g., sustained and selective attention) and can thus be consistently the same across tasks, regardless of the cognitive functions under evaluation (e.g., sustained attention, selective attention, or VWM). This is the feature that distinguishes this proposed task from other language-free tasks reported in the literature. It simplifies the understanding of instructions because subjects are already familiar with the stimulus material from task to task. Simplifying cognitive tasks (instructions, materials, demands, and response mechanisms) is particularly important for ABI patients, especially when researchers and practitioners use fMRIs.

A potential limitation of this study is its sample's size. Yet, this small number of participants still yielded significant results with large effect sizes. The activation results in this study were obtained using the typical baseline condition in neuroimaging studies in the literature, that is, a resting condition with a fixation point. Future research could also include a different condition for comparison. A possibility would be a scenario similar to the 2-back condition, with the same number and type of stimuli and the same number of button presses, but with different instructions (i.e., requiring no WM). As the stimulus material employed in this study is already the same which has been used in the study of sustained and selective attention also with ABI patients, the sustained and selective attention task could be applied as the baseline condition in future research. Such condition would also simplify the process of instructing participants, who encounter the same material across different tasks. This baseline condition would represent an addition to the lack of finger movement and visual stimulation inherent to the typical resting condition, which can constitute a limitation, possibly influencing results. Specifically, it is possible that differences in brain activation would be smaller if the baseline condition was derived from a task involving visual and motor activity. Behavioural differences between the clinical and non-clinical groups might also decrease, especially if they are partly due to particular motor or visual difficulties of the ABI group, although visual acuity deficits and motor disabilities that might interfere with performances were exclusion criteria of participants in both groups.

Conclusion

In this work, we propose a non-verbal WM task to be used as an experimental paradigm in studies on VWM. This task minimizes the influence of cultural and educational biases involved in verbal tasks. These are aspects that can mask the recruited neural areas in experimental research and are particularly important in the study of populations presenting deficits in those areas.

Our results indicate that the proposed task is suitable for neuroimaging research on VWM in block-design paradigms. It also discriminates between healthy and clinical groups' behavioural performances.

This paradigm for fMRI studies has application in basic research, as well as in studies about the effects of neurocognitive rehabilitation programmes on VWM, and the current study contributes initial normative data for comparison. It is a tool that can be used to assess not only behavioural changes but also concurrent alterations in brain functioning resulting from rehabilitation programmes. Our findings provide support for the possibility of combining neuroimage and behavioural strategies to study VWM. Future studies using this task can now inspect brain functioning in various groups and in different pathologies.

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