The Spatial-verbal Difference in the N-back Task: An ERP Study

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Abstract- The spatial-verbal dichotomy of working memory tasks was investigated using event-related potentials. Using an n-back task with three levels of n (0-, 1-, and 2-back), participants either matched words presented at a fixed screen position (verbal task) or matched the locations of non-word symbols presented at various positions across the screen (spatial task). Therefore, these two conditions were separated without confound of location and stimulus. Factors of match and task loading (Stimulus and N-Back effect) were found significant in P2a, N2 and P3, whereas domain-specific lateralization (Hemisphere×Task interaction, the feature of perception) was found significant in EPC, P2a and N2 but not in P3. These results hint time course of match (before P2a beginning, 200 ms) and perception (before P3 beginning, 300 ms).

Key Words: N-back task, Spatial, Verbal, Working memory, Event-related potentials

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INTRODUCTION

The spatial-verbal dichotomy in working memory (WM) has been emphasized in the classic multi-component model consisting of a visuospatial sketchpad for storing and manipulating visual and spatial information and a phonological loop for the corresponding function on phonemic sound information(1). Many imaging and electrophysiological studies have focused on this spatial-verbal dichotomy(2,3). Early lesion studies suggested that the right hemisphere was associated with spatial information processing(4) and the left hemisphere was involved in verbal information processing(5). Later imaging studies also supported this theory(6-8). An implication of such results was that hemispheric specialization in general information processing might be domain-specific, but this generalized conclusion could not be applied to more specific cortical regions as a matter of course. For example, hemispheric specialization in the prefrontal cortex was considered as domain-specific between spatial and verbal materials(9-12) but as process-specific between maintenance and manipulation(13,14).

The n-back task has been widely used in WM studies(3,15,16) as it is thought to tap into processes involving manipulation as well as maintenance of information in WM(17,18). In the n-back task, a series of stimuli such as letters, words or location markers are shown, and, on each presentation, the participant is asked to report

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whether a particular property of the current item matches the same property of the item n presentations back. With n = 0, each new items are matched against the very first item in the series. With n = 1, a new item is matched against the immediately preceding item, and with n = 2, against the item just before the preceding item, and so on.

Although widely used, the n-back task has not been subjected to a detailed task analysis to clearly identify its process components. For example, the commonly held assumption, that spatial and verbal versions of the task actually tap into spatial and verbal WM processes, was challenged by a task analysis[18]. Using letter identity and position matching n-back tasks, they showed that, irrespective of stimulus and task characteristics, the n-back task always involved both spatial and verbal information processing[19]. This suggestion is also corroborated by neuroimaging studies[3] in which n-back tasks on letter identity and location activated both hemispheres under either task condition.

In a preliminary experiment[20], we studied the n-back task which used the same verbal stimuli in both verbal and spatial task conditions. In the present study, we took into account that cross-domain interference might play a role in verbal vs. spatial task conditions when the stimuli could be encoded for both verbal and spatial characteristics simultaneously[18]. The effects of such cross-domain interference on n-back task performance (or its cortical correlates) have been reported in another preliminary study[21]. In the present study we sought to better isolate the verbal and spatial WM conditions by using word stimuli in the verbal matching conditions and the same non-verbal location marker in the spatial location matching conditions.

We examined the general pattern of event-related potential (ERP) effects associated with the spatial and verbal versions of the task, expecting to replicate earlier findings such as reduced P3 amplitude under higher WM load conditions[22]. A question of particular interest was how the different stimuli in the spatial vs. verbal conditions would alter cortical correlates during an executive task. If the stimuli elicited domain-specific processing, the verbal condition could be expected to show neural activity predominantly in the left hemisphere, whereas the spatial condition should show neural activity predominantly in the right hemisphere[6-8]. As a combination of logical sub-processes: matching, replacement and shift (Fig. 1), does the lateralization during n-back tasks keep constant or vary with anatomical region, time course or domain? This study is aimed to solve this problem with ERPs, which has high temporal resolution. We expect that anatomical, temporal and domain differences exist among different testing conditions.

METHODS

Participants

Thirty paid volunteers (15 female) with age ranging from 18 to 34 (mean 22) years participated in the experiment. According to self-report, all had normal or corrected-to-normal vision, and all except six participants were right-handed.

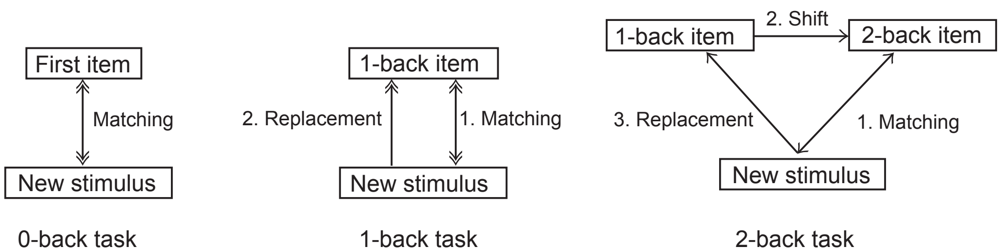

Figure 1. Analysis of sub-processes involved in 0-back, 1-back, and 2-back tasks.

Stimulus and apparatus

Stimulus presentation and data acquisition were managed by C-programs and running under MS-DOS. Behavioral data were saved on the hard disk.

Stimuli in the verbal condition were 20 words with similar frequency and length, whereas stimuli in the spatial condition were strings of $ symbols of matched length. Words were presented in white against background on a 17” computer monitor, at one out of eight circularly arranged positions 4˚ from the screen centre. Words had a height of approximately 0.8˚ visual angle, and their width ranged from 3.2˚ to 6.4˚ (mean: 5˚).

Procedure

Participants were seated in an armchair in front of a computer screen at distance of approximately 60 cm. They were told to keep a comfortable posture, and to avoid eye movements and eye blinks during experimental trials. Participants then completed the first half of the experiment, comprising six blocks of n-back tasks, followed by a break, during which participants were encouraged to leave the experimental room. They then completed the second half of the experiment.

Each half of the experiment consisted of two 0-back blocks, two 1-back blocks, and two 2-back blocks in sequence. In the first half, each pair of blocks was preceded by a corresponding practice block, so as to familiarize participants with the changing task requirements. In the second half, no practice blocks were given. Experimental blocks consisted of 64 trials (32 matching trials and 32 non-matching trials). Each trial began with the presentation of a fixation cross in the centre of a screen for 350 ms, followed by 350 ms of a blank screen. In the verbal task, a stimulus word was then shown for 500 ms at the screen centre. In the spatial task, a string of $ signs was then shown for 500 ms at one of the eight predefined screen location. This was followed by another blank screen for 1500 ms (Fig. 2). In all blocks, identity in verbal tasks and location in spatial tasks of each stimulus were determined pseudo-randomly, to achieve an approximately even distribution of targets for matching and an approximately equal distribution of identities or locations. Practice blocks were constructed in the same way, but contained only 20 trials and provided additional feedback (the words “correct” or “wrong” presented in the centre of the screen) immediately after the participant’s response. Data from practice blocks was not saved.

In the 0-back task, participants indicated whether or not each stimulus matched the first one of the block. For the more demanding levels of the n-back task, participants had to match the current stimulus with the previous stimulus (1-back task) or the stimulus before the previous one (2-back task). Participants pressed a “yes” key for a match (matching stimulus) and a “no” key for a mismatch (non-matching stimulus). Keys were backslash and forward slash keys of a computer keyboard, which had to be pressed with the left (/) and right (\) index finger, respectively. Participants were asked to respond as quickly and accurately as possible, and assignment of keys to “yes” and “no” response was counterbalanced across participants.

Two different versions of the n-back task were employed, and participants were assigned randomly to either of these. In the verbal version, the task-relevant feature of the stimulus words was their identity. In the spatial version, the location of the stimulus on the screen was task-relevant.

Electrophysiological recording and data processing

Using a BioSemi Active-Two amplifier system (Biosemi Company, Nederland), continuous EEG recordings were made with Ag / AgCl electrodes, mounted on a nylon cap, from 32 locations of the international 10-20 system (left: Fp1, AF3, F7, F3, FC1, FC5, T7, C3, CP1, CP5, P7, P3, PO3, O1; midline: FZ, CZ, PZ,OZ; and corresponding right channels). Sampling rate was 256 Hz. EEG signals were off-line filtered using a 0.01 Hz high pass and a 30 Hz low pass filter, and were re-referenced to linked earlobes.

Further analysis was conducted using EEGLAB 4.43[23] under MATLAB 6.1 environment. EEGs were averaged off-line for epochs of 900 ms, starting 100 ms prior to stimulus onset, and ending 800 ms afterwards. Trials containing saccadic eye movement or eye blinks (indicated by amplitudes beyond 3 SD in single channel

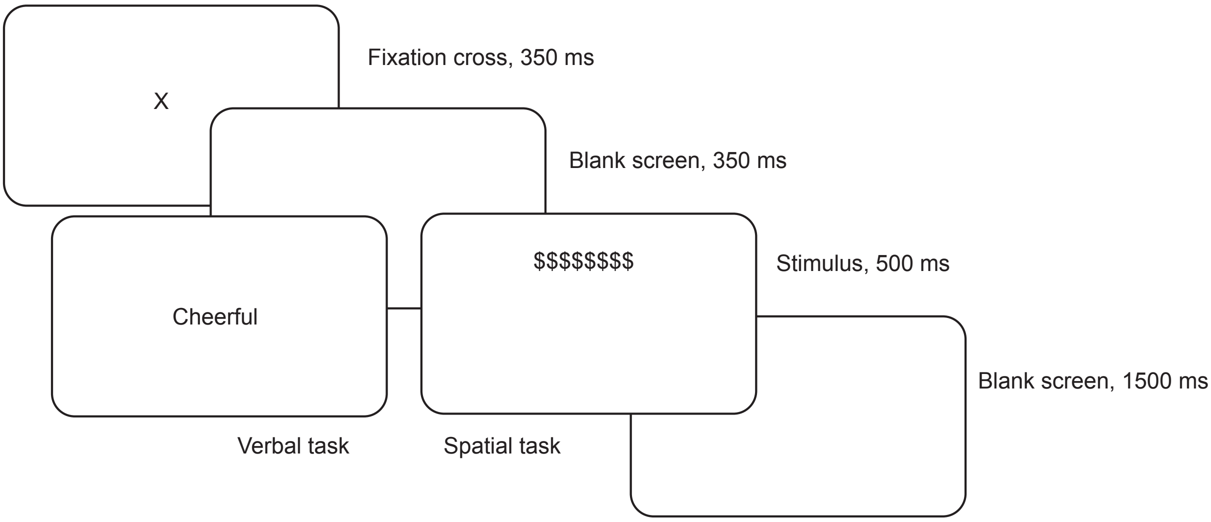

Figure 2. Experimental trial.

and 1.5 SD in all channels), and trials where participants gave an incorrect response, were excluded from analysis. EEG on correct-response trials was averaged for each condition separately, relative to a 100-ms pre-stimulus baseline. Thus for each participant, six ERP waveforms were constructed one match ERP and one non-match ERP from each of the 0-back, 1-back, 2-back task.

Behavioral data

All the behavioral data including response time (RT) and error rate were analyzed by mixed analysis of variance (ANOVA). The between-subject factor for behavioral data in the ANOVA was Task (spatial / verbal). The within-subject factors were Stimulus (non-match/ match) and N-Back (0 / 1 / 2).

ANOVA of general ERPs

Four latency windows were selected for analysis: early-posterior complex, 150-250 ms in posterior areas (non-midline: P3, P4, P7, P8, O1, O2, PO3, PO4; midline: Pz, and Oz), further referred to as early posterior complex (EPC); 200-300 ms in anterior areas (non-midline: FP1, FP2, AF3, AF4, F7, F8, FC1, FC2, FC5, and FC6; midline: Fz and Cz), further referred to as P2a; a negative-going shift at 300-400 ms in anterior areas (non-midline: FC5/6, F7/8, FC1/2, AF3/4, FP1/2; midline: Fz, Cz), further referred to as N2; and 300-500 ms in central-posterior areas (non-midline: FC1, FC5, C3, T7, CP1, CP5, P3, P7, O1, PO3, and corresponding contralateral channels; midline: Cz, Pz, and Oz), further referred to as P3. ERP component amplitudes, which were defined as mean amplitudes within certain time window, were analyzed separately using a repeated-measure ANOVA with the between-subject factor Task (verbal, spatial), and with the within-subject factors Stimulus (non-match, match) and N-Back (0, 1, 2), and the factor Hemisphere (left, right) for non-midline channels only.

RESULTS

Behavioral data

Fig. 3 presents RT and error rate.

RT in the spatial task was larger than in verbal task, as evidenced by a significant Task effect, $F(1, 28) = 8.40$, $p = .007$. RT to matching stimuli was larger than to non-matching ones, as evidenced by a significant Stimulus effect, $F(1, 28) = 147.32$, $p < .001$. RT differences between matching and non-matching stimuli were larger in spatial tasks than in verbal tasks, as evidenced by a significant Stimulus $\times$ Task interaction, $F(1, 28) =$

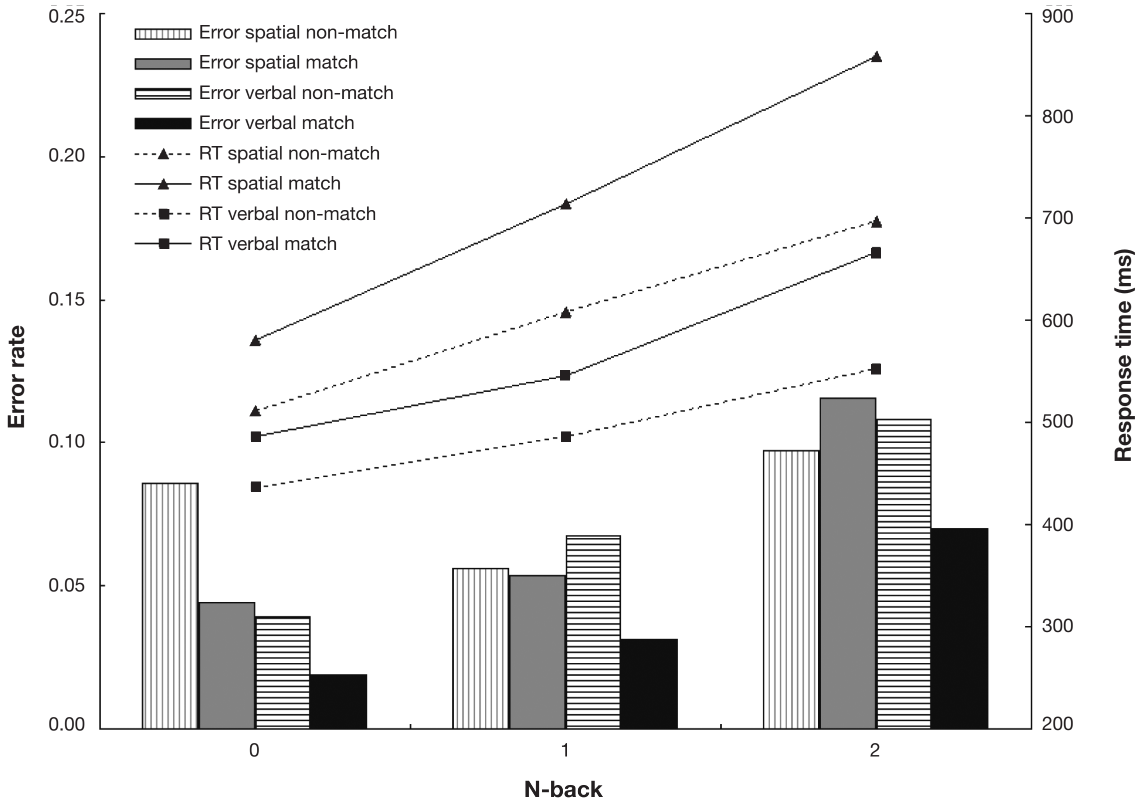

Figure 3. Response time (lines) and error rate (bars) in 0-, 1-, and 2-back conditions, separately for spatial and verbal tasks, and separately for match trials and non-match trials.

6.15, $p = .019$. RT increased with increasing memory loads, as evidenced by a significant N-Back effect, $F(2, 56) = 44.85$, $p < .001$. RT differences between matching and non-matching stimuli were largest in 2-back tasks than in 0- and 1- back tasks, as evidenced by a significant Stimulus × N-Back interaction, $F(2, 56) = 30.82$, $p < .001$. Other main effects or interactions were non-significant in RT, all $F < 2.23$, all $p > .133$.

Error rate increased as a function of memory load, as evidenced by a significant N-Back effect, $F(2, 56) = 14.46$, $p < .001$. Other main effects or interactions were non-significant in error rate, all $F < 3.80$, all $p > .060$.

Electrophysiological data

Fig. 4 presents grand mean ERP waveforms collapsing the n-back factor in 28 channels.

Omnibus ANOVA for original ERPs

Table shows F and p values from the omnibus ANOVA. Fig. 5 demonstrates mean amplitudes in each ERP component.

The stimulus effect was significant in P2a, N2 and P3 latency windows, but non-significant in the EPC component. Amplitudes in these latency windows were more positive-going for matching stimuli than for non-matching ones. The Stimulus × Task interaction was significant in N2 and P3. The amplitude differences in these latency windows between matching and non-matching stimuli were larger in verbal tasks than in spatial ones.

The N-Back factor was significant in P2a and N2 latency windows in both midline and non-midline channels, and non-midline P3 latency window. In general, amplitudes increased with increasing load. Increases in

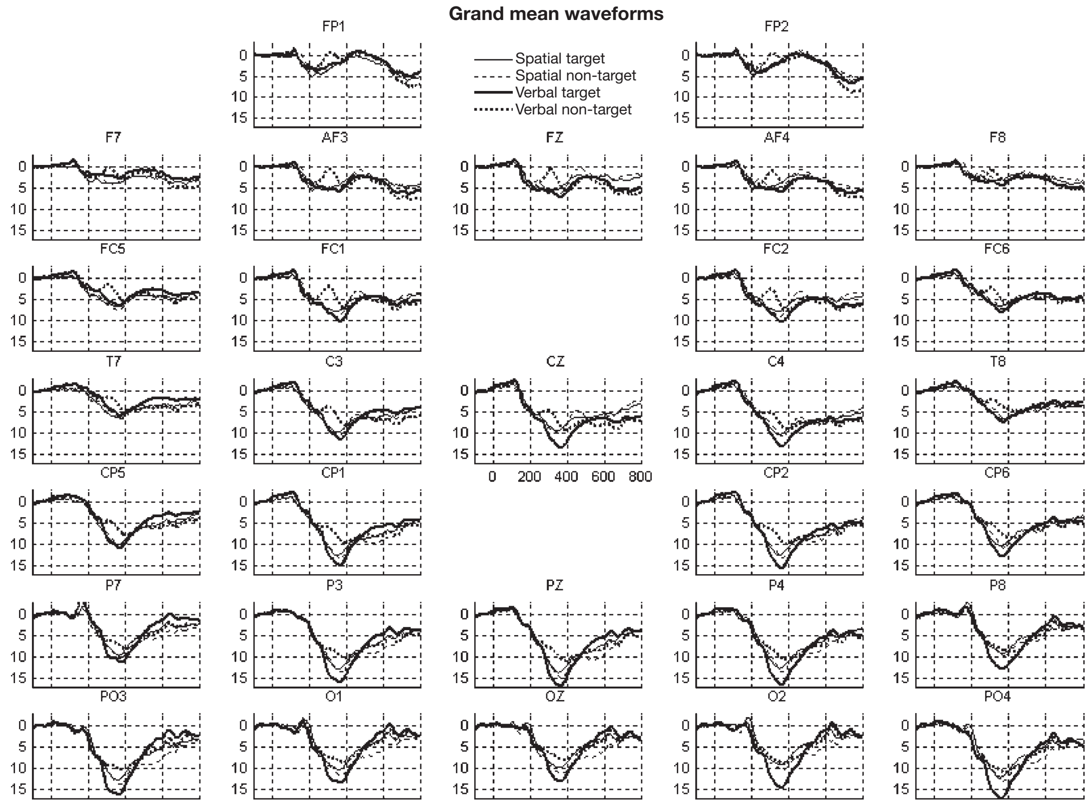

Figure 4. Grand mean ERP waveforms, collapsed across the n-back factor, elicited during spatial (thin lines) and verbal (thick lines) tasks. Solid lines indicate ERPs elicited by matching items. Dashed lines indicate ERPs elicited by non-matching items.

amplitude from 0- to 1-back tasks were smaller than those from 1- to 2-back tasks in anterior latency windows (the midline P2a). Conversely, amplitude increases from 0- to 1-back tasks were larger than those from 1- to 2-back tasks in posterior latency windows (the non-midline P3). The N-Back × Task interaction was significant only in the midline P3, where difference amplitudes between verbal and spatial instructions decreased abruptly in 2-back tasks. The N-Back × Stimulus interaction was significant in both lateral and midline N2 latency windows, where difference amplitudes between match and non-match conditions increased abruptly in 2-back tasks. The N-Back × Stimulus × Task interaction was significant in N2 and P3 latency windows. Under spatial instructions, difference amplitudes between match and non-match conditions were largest in 1-back tasks, whereas difference amplitudes increased from 0- to 2-back tasks under verbal instructions. The N-Back × Task interaction was non-significant in all the latency windows.

The analyses below involving the Hemisphere factor only cover the non-midline channels. The Hemisphere effect and Hemisphere × Stimulus interaction were non-significant in all the four latency windows. The Hemisphere × Task interaction was significant in all the latency windows except P3. In spatial tasks, amplitudes were higher in the left hemisphere than in the right one, whereas in verbal tasks, amplitudes were higher in the right hemisphere than in the left one. The Hemisphere × N-Back interaction was non-significant in all the latency windows.

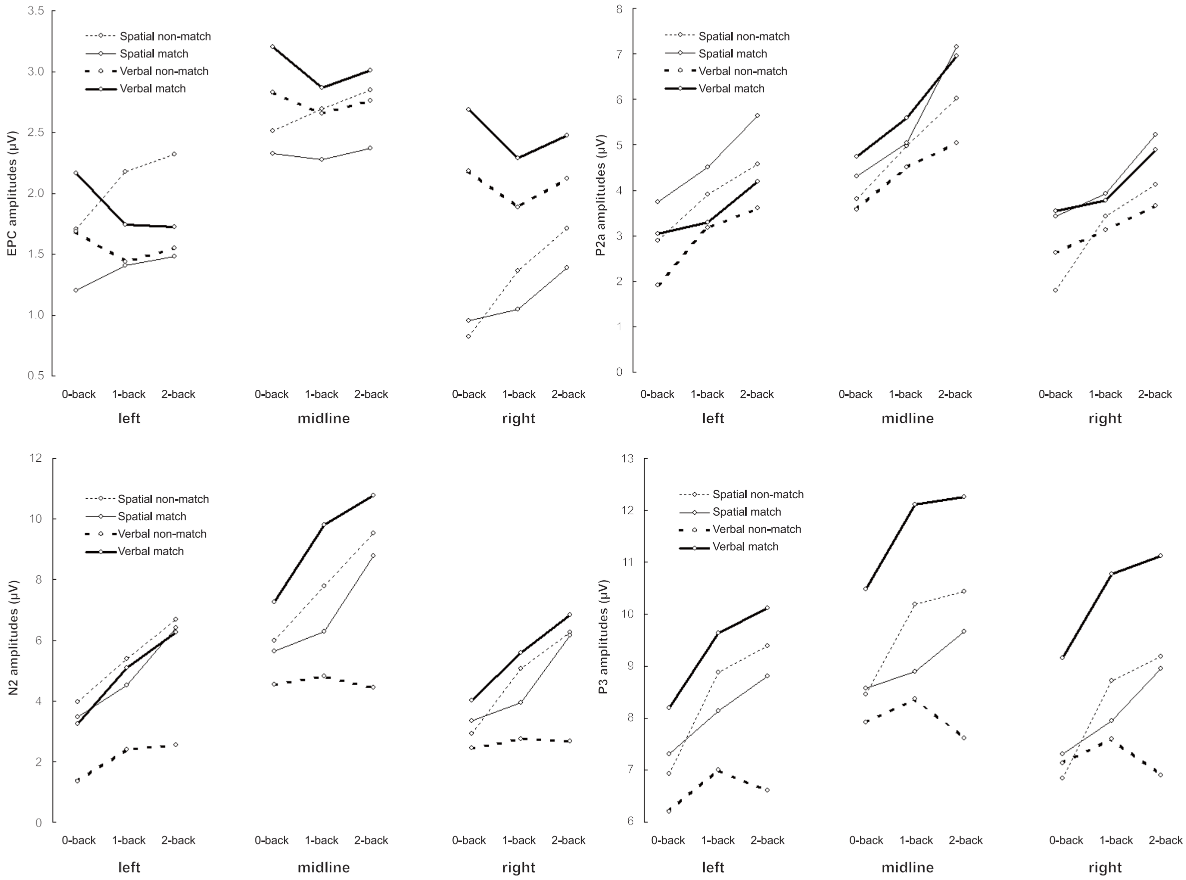

Figure 5. Mean amplitudes in EPC (150-200 ms), P2a (200-300 ms), N2 (300-400 ms), P3 (300-500 ms) latency windows elicited during for spatial (thin lines) and verbal (thick lines) tasks. Solid lines indicate ERPs elicited by matching items. Dashed lines indicate ERPs elicited by non-matching items.

DISCUSSION

The present experiment investigated the electrophysiological correlates of verbal and spatial WM in the n-back task with varying information processing load. In the following, we discuss the overall ERP effects of task instruction and memory load.

The original response of n-back tasks reflects matching because memorization is logically immobilized and executed in the background. The average RT (595 ms) suggests the latest limit of matching sub-process. Response time should be longer than actual activity in the brain because of the additional time for motor plan, peripheral nerve conduction and muscle reaction. One hundred and fifty ms have been reported as the interval between the onset of a hand-specific motor preparation in the primary motor cortex to the execution of the corresponding key-press[24]. Thus, matching sub-process was reasonably ended before 445 ms (595-150 ms) in average, which fell in the ranges of four latency windows in this study.

Within RT ranges, EPC amplitudes (in the similar time window as N1 and P1) were loading-constant (stable effects with N in the n-back task), but loading effects (changing effects with N in the n-back task) were found in other latency windows. Because loading-constant perception was before loading-changing manipulation in the task *per se*, these results suggested that EPC might stand

Table. *Omnibus ANOVA for original ERPs*

Effects	dF	EPC *F*	EPC *p*	P2a *F*	P2a *p*	N2 *F*	N2 *p*	P3 *F*	P3 *p*
Non-midline									
Hemisphere	(1,28)	0.01	.909	0.19	.664	0.05	.824	2.53	.123
Hemisphere × Task	(1,28)	5.09	.032	6.96*	.013	4.22*	.049	3.78*	.062
N-Back	(2,56)	0.22	.782	8.47	.002	9.48*	.001	4.24*	.027*
N-Back × Task	(2,56)	0.93	.391	0.33	.651	0.67	.488	0.43	.614
Stimulus	(1,28)	0.03	.868	8.80	.006	16.05*	<.001	20.52*	<.001*
Stimulus × Task	(1,28)	4.07	.053	0.10	.755	28.58	<.001	28.57*	<.001*
Hemisphere × N-Back	(2,56)	1.28	.284	0.38	.668	0.47	.605	0.31	.698
Hemisphere × N-Back × Task	(2,56)	0.05	.923	1.66	.201	1.90	.165	0.57	.538
Hemisphere × Stimulus	(1,28)	3.32	.079	3.30	.080	0.64	.432	1.64	.211
Hemisphere × Stimulus × Task	(1,28)	1.53	.227	0.06	.815	0.17	.683	0.41	.528
N-Back × Stimulus	(2,56)	0.51	.594	2.56	.089	4.62	.015	1.80*	.178
N-Back × Stimulus × Task	(2,56)	0.06	.935	<0.01	.996	5.30	.008	7.50*	.002*
Hemisphere × N-Back × Stimulus	(2,56)	0.06	.932	0.19	.819	1.10	.338	1.95	.155
Hemisphere × N-Back × Stimulus × Task	(2,56)	0.28	.751	8.44	.001	5.41*	.008	0.91*	.404
Midline									
N-Back	(2,56)	0.08	.916	13.77	<.001	7.88*	.002	2.08*	.142
N-Back × Task	(2,56)	0.16	.845	0.42	.612	1.27	.287	0.29	.720
Stimulus	(1,28)	0.03	.857	6.28	.018	29.42*	<.001	18.82*	<.001*
Stimulus × Task	(1,28)	1.94	.175	1.12	.299	61.79	<.001	38.70*	<.001*
N-Back × Stimulus	(2,56)	0.18	.827	2.97	.065	5.25	.009	1.37*	.262
N-Back × Stimulus × Task	(2,56)	0.02	.974	0.10	.885	9.16	<.001	6.32*	.005*

Task: verbal vs. spatial task; Stimulus: matching vs. non-matching stimulus; Hemisphere: left vs. right hemisphere; N-Back: 0-back vs. 1-back vs. 2-back task; M, L: midline vs. lateral electrode sites. Significant effects ($p < .05$) are marked with star. ERP: event-related potential; EPC: early posterior complex.

for the perception whereas other ERP components might stand for manipulation. The significant P2a match effects were only found in verbal tasks, and suggested due to subtraction by negative-going N2. The N2 peaks were only seen in verbal non-match stimuli and significant "non-match" effects were seen. In contrast, P3 match effects were seen only in verbal tasks. Interestingly, no significant match effects were found in spatial tasks. The expected domain-specific lateralization was found in EPC, P2a and N2 time windows, but not in P3. Similar results were also seen in the experiment using item-recognition task[2]. Because P3 was suggested as manipulation (matching) whereas EPC was suggested as perception, a speculation might be that the general lateralization could only be applied in perception rather than execution.

The amplitude difference between verbal and spatial tasks, accompanying with the results that spatial tasks require more response time, suggested that verbal tasks elicited stronger and faster response than spatial tasks. This result was constant with the finding that difference amplitudes between verbal and spatial instructions decreased abruptly in 2-back tasks. Put them together, it suggested that our brain resource was limited. Verbal tasks utilized more resources than spatial tasks, and the performance was better. This conclusion was supported by a previous study using n-back task analysis[18]. When the resource was shared by the difficult 2-back task, the performance of verbal tasks was therefore lower and close to spatial tasks.

'Loading-constant' is the character of matching subtask whereas 'loading-effects' is the character of memory processing[25]. Therefore, loading-constant character hints that memory processing does not exist in EPC but it is possible that matching sub-process existes in EPC. By setting frequency of match and non-match stimuli equal, P3 effects in verbal tasks only were suggested from matching[22] rather than from infrequency. This result was also consistent with ERP experiments which surveyed spatial and verbal WM by item-recognition tasks[2]. The presence of domain-specific lateralization contrasts with the assumption that WM is a unitary system[26] and appears to be more in line with traditional theory of domain-specific lateralization even when stimuli are held constant[3]. Furthermore, amplitudes in the spatial task were found to be higher in the left hemisphere and in the verbal task higher in the right hemisphere. Although different from general concepts, these results are congruent with the previous survey using item-recognition tasks[2]. Therefore, the lateralization in executive tasks like in the n-back or item-recognition tasks should be different from that in the static perception. A speculation is that right frontal lobe processes verbal tasks but left frontal lobe processes spatial tasks. This inference is different from the conclusion of a study using functional magnetic resonance image[10,12] and positron emission tomography[10], which suggests that verbalization exists in the left frontal lobe and imaging exists in the right frontal lobe. However, it is doubtful that verbalization and imaging have same effects as verbal and spatial perception. Therefore, further experiments are needed for this question.

To sum up, EPC, P2a and N2 were influenced by domain-specific information but P3 was not. In contrast, P2a, N2 and P3 were influenced by match and loading factors but EPC was not. In other words, the domain-specific attribute took effects before P3 whereas the match-specific attribute was given before P2a. Because match-specific attribute (match/non-match) must be given via matching sub-process and domain-specific attribute (spatial/verbal) caused lateralization only during perception, this provides hints, although somewhat speculative, that matching exists before 200 ms and the perception ends before 300 ms. This result supports the conclusion of evoked-potential researches[2,22], that a simple WM task is made of many different sub-processes, and these sub-processes are different among the types of information to be remembered.

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