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Frontal–parietal synchrony in elderly EEG for visual search

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ABSTRACT

Aging involves selective changes in attentional control. However, its precise effect on visual attention is difficult to discern from behavioural studies alone. In this paper, we employ a recently developed phase-locking measure of synchrony as an indicator of top-down/bottom-up control of attention to assess attentional control in the elderly. Fourteen participants (63–74 years) searched for a target item (coloured, oriented rectangular bar) among a display set of distractors. For the feature search condition, where none of the distractors shared a feature with the target, search time did not increase with display set size (two, or four items). For the conjunctive search condition, where each distractor shared either a colour or orientation feature with the target, search time increased with display size. Phase-locking analysis revealed a significant increase in high gamma-band (36–56 Hz) synchrony indicating greater bottom-up control for feature than conjunctive search. In view of our earlier study on younger (21–32 years) adults (Phillips and Takeda, 2009), these results suggest that older participants are more likely to use bottom-up control of attention, possibly triggered by their greater susceptibility to attentional capture, than younger participants.

1. Introduction

Two types of mechanisms have been proposed for control of visual attention: a bottom-up mechanism driven primarily by perceptual information; and a top-down mechanism driven primarily by contextual information, such as the target of search, stored in memory (Treisman and Gelade, 1980; Duncan and Humphreys, 1992; Wolfe et al., 1989). Each mechanism provides a natural account of two aspects of visual search behaviour that are efficient, and inefficient search, respectively. Efficient search pertains to the well-known effect where search time is virtually independent of display set size (i.e., number of items in the field of search), and typically occurs with homogeneous non-target distractors (feature search). Inefficient search pertains to the often observed effect that search time increases linearly with display size, which usually occurs with heterogeneous distractors and a target that is uniquely defined by a conjunction of items features, such as orientation and spatial frequency (conjunction search).

A recent visual search study on monkeys using embedded electrodes revealed two distinct modes of neural activity associated with feature and conjunctive search (Buschman and Miller, 2007). For feature search, signals distinguishing targets from distractors proceeded from parietal to frontal neurons, but from frontal to parietal for conjunctive search. In addition, greater synchrony between these populations of neurons was observed in a high gamma-band (36–56 Hz) for feature than conjunctive search, but in a low gamma-band (22–34 Hz) for conjunctive than feature search. These results provide corresponding neural evidence for these two modes of attentional control: bottom-up (high gamma-band) and top-down (low gamma-band).

A similar study was performed on humans under the same sorts of conditions using scalp electrodes (Phillips and Takeda, 2009).[1] As with the monkey study, greater synchrony in the same low frequency band was observed in the conjunctive than feature search condition. However, a corresponding increase in synchrony for the feature than the conjunctive search condition in the high gamma-band was not observed. One possible reason for this difference is familiarity with task stimuli: although in both studies the target varied from trial to trial, monkeys received far more training on the task than humans. Top-down control is still useful even under feature search conditions when say there is less certainty about the features of a particular object. Hence, in the human case, there may have been a stronger bias towards top-down driven attention, even in the presence of homogeneous distractors that share no features in common with the target.

Many studies have reported that aging results in selective changes in attentional control (Folk and Lincourt, 1996; Hommel et al., 2004; Plude and Doussard-Roosevelt, 1989; Scialfa et al., 1998). For example, whereas aged participants exhibit efficient feature search just like younger participants, they are significantly poorer than younger

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[1] In this study, feature and conjunctive search were referred to as efficient and inefficient search, respectively.

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participants during inefficient conjunction search (Plude and Doussard-Roosevelt, 1989). Older participants are more sensitive to attentional capture than younger participants when awareness of task irrelevant items is high (Kramer et al., 2000). This difference is particularly acute when only bottom-up information is available (Whiting et al., 2007). These differences suggest that older participants are more likely to rely on a bottom-up than top-down strategy than younger participants. However, the relationship between aging and attentional control is complex. In a response time study, Whiting et al. (2005) found no evidence of age-related deterioration of a top-down component of attentional control during singleton search (i.e., target uniquely identifiable among a display of uni-dimensional items containing homogeneous distractors). Synchrony affords another window into age-related changes in attentional control. Hence, we predict that older participants will show greater synchrony in the high gamma-band for feature than conjunctive search, which was not observed in younger adults. To test this prediction, we repeated our prior study (Phillips and Takeda, 2009) using an older group on the same task.

2. Materials and methods

In the present study, we used the same paradigm as Phillips and Takeda (2009), which was based on Buschman and Miller (2007). Methods reported previously (Phillips and Takeda, 2009), including apparatus and stimuli, conditions, procedures and analysis, are not repeated here. Instead, we detail only those procedures specific to the current study. The main difference is that in this study participants were selected from an older age range (60–80 years).

2.1. Participants

Fourteen elderly Japanese (two females, right-handed) were recruited for the experiment, aged 68 ± 3 years (mean ± SD). Self-reports indicated that none of the participants had neurological or psychiatric diseases, or was taking medication that may affect EEG, such as sleeping pills, antidepressants, or tranquilizers. Data for an additional participant were excluded from the analysis, due to a problem obtaining EEG signals. All participants satisfactorily passed visual acuity (near and far), and visual field tests before performing the experiment. Participants were paid for their time.

2.2. Apparatus and stimuli

Participants were screened for visual acuity and field using AS-15 Vision Tester (Kowa Company Ltd) and SBP-3000 Computerized Perimeter (Topcon Corporation) systems, respectively. Stimuli for the main experiment were presented on a standard personal computer. The stimuli were red, green, blue or yellow rectangular bars, at 0°, 45°, 90°, or 135° from horizontal. Electrical signals were recorded using a digital electroencephalograph system (Nihon Kohden Neurofax EEG-1100) with an Ag/AgCl electrode cap.

2.3. Conditions

The experiment used a two (display type: feature, conjunctive search) by two (display size: 2, 4) design. For the feature search condition, none of the distractors shared a feature in common with the target. For the conjunctive condition, each distractor had one feature (either colour, or orientation) in common with the target.

2.4. Procedure

Each trial was divided into four phases, in the following order: (1) fixation (1500 ms), (2) target cue (1000 ms), (3) delay (1000 ms), and (4) search display (2500 ms). Participants identified the location of the target within the search display by pressing a key corresponding to the quadrant containing the target. Participants responded by pressing keys ‘a’ (upper left) and ‘z’ (lower left) with their left hand; and ‘k’ (upper right), and ‘m’ (lower right) with their right hand. Speed and accuracy were stressed. Pressing an incorrect key, or failure to respond within the allotted time was regarded as an error. Trials were blocked by display type. There were 64 trials per block. There were two sessions, separated by about 5 min of rest. Each participants received 768 experiment trials (= 2 sessions × 6 blocks × 64 trials). Response keys and times were recorded.

Electroencephalograms (EEG) were recorded from 19 electrode sites (Fp1, Fp2, F7, F3, Fz, F4, F8, T3, C3, Cz, C4, T4, T5, P3, Pz, P4, T6, O1, and O2) of the International 10–20 system, with AFz as ground. EEG data were subsequently re-referenced offline to the mean of earlobe potentials A1 and A2. Eye movement artifacts were monitored by a vertical electrooculogram (EOG) from electrodes placed above and below the eye, and a horizontal EOG from electrodes placed at the outer left and right canthi. Electrode gel was used to reduce impedance to below 5 kΩ. EEG and EOG were digitized at 1000 Hz, and were band-pass filtered at .032 Hz and 300 Hz. Data were recorded inside an electrically shielded room.

Before doing the experiment, participants were screened for visual acuity and field. They, then, received general instructions regarding the experiment and EEG/EOG procedure. Specific instructions regarding the task, and a short practice session (3–4 min) were provided before doing the main task, which took about 1 h. All procedures were approved by the AIST Safety and Ethics committee, and conducted after receiving informed consent from participants.

2.5. Analysis

For the analysis of behavioural data, two (display type) by two (display size) analyses of variance (ANOVAs) were conducted on response errors and times to infer significant effects. Response time analysis was conducted on error-free trials after removing outliers using the modified recursive method (Selst and Jolicoeur, 1994). An arcsine transform was used for statistical analysis of error rates. For EEG data, trials containing artifacts (identified by visual inspection), or response errors were removed from further analysis (approximately, 6.5% of trials).

For EEG signals, independent component analysis (ICA) was performed to remove eye movement related components, using the RUNICA procedure in the EEGLab software package (Delorme and Makeig, 2004), which is based on the logistic infomax ICA algorithm (Bell and Sejnowski, 1995). Phase-locking values (PLV) were used as measures of synchrony between brain regions (Lachaux et al., 1999; Phillips and Takeda, 2009). Using wavelet decomposition, phases were computed for each frequency from 20 Hz to 60 Hz at intervals of 2 Hz, at 1 ms intervals up to 1000 ms post-stimulus (search display) onset. PLVs were normalized with respect to an interval from 200 ms pre-stimulus to stimulus onset (Phillips and Takeda, 2009). ANOVAs were conducted on low (22–34 Hz) and high (36–56 Hz) gamma-bands (as in our previous study and Buschman and Miller (2007)) and time intervals 200–360 ms and 360–520 ms post-stimulus. These time intervals are 40 ms later than those used in Phillips and Takeda (2009), because PLV latency (i.e., time to rise above baseline) was longer in older than younger participants. As in our previous study, synchrony pertains to electrode pairs P3–F3, Pz–Fz, and P4–F4.

Table 1
Mean response error rates and times (ms) for each display type-size condition.

	Feat-2	Feat-4	Conj-2	Conj-4
Error rate	.029	.012	.049	.058
Response time	715	694	837	960

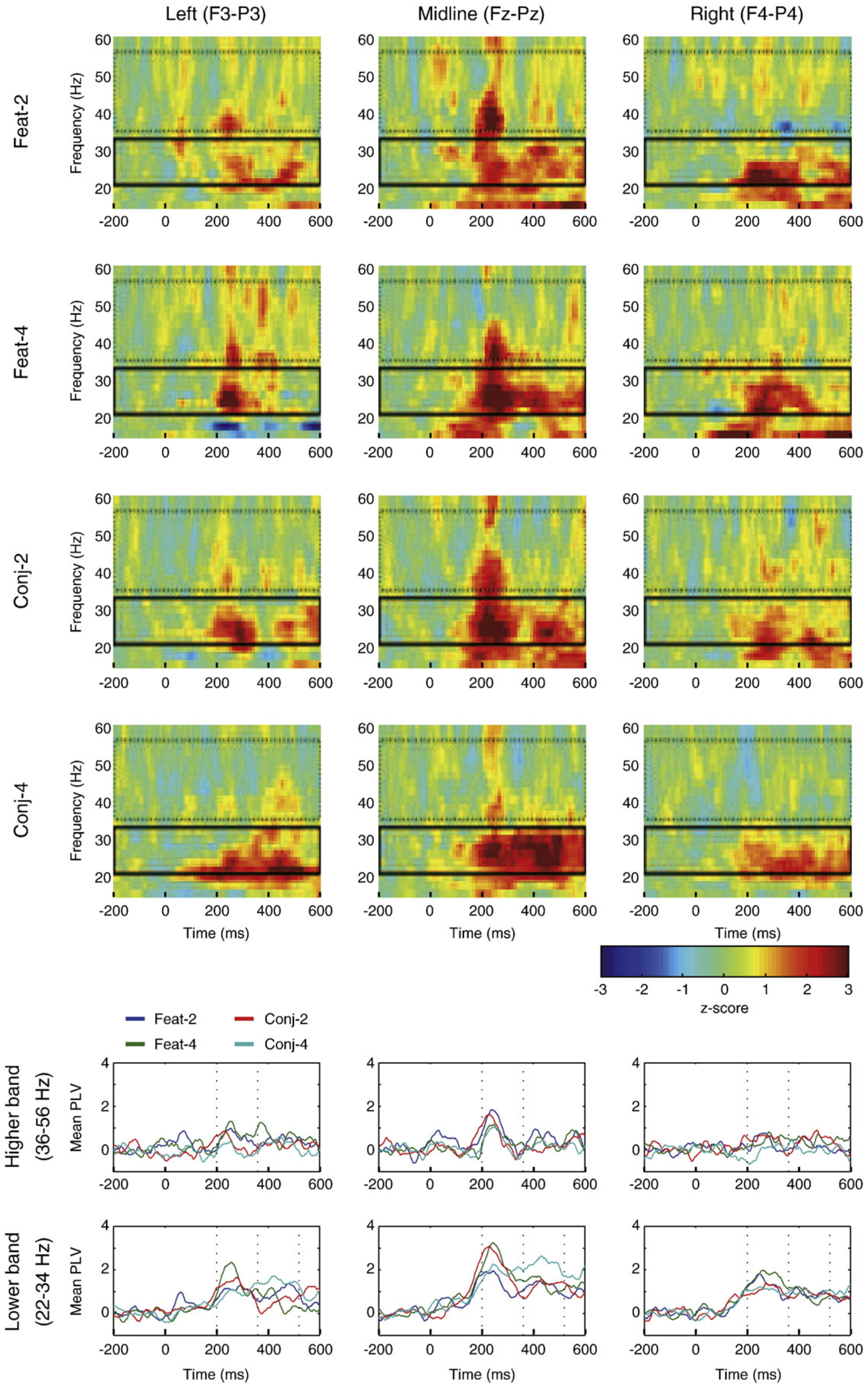

Fig. 1. Time-frequency plots of PLV significance (z-score) relative to baseline (top panel). Solid boundary indicates low gamma-band (22–34 Hz) and dotted boundary indicates high gamma-band (36–56 Hz). Graphs (lower panel) indicate mean PLVs for the associated frequency bands. Left, middle and right columns indicate P3–F3, Pz–Fz, and P4–F4 electrode pairs, respectively.

Table 2
Mean PLVs at each region for each display type-size condition.

	Feat-2	Feat-4	Conj-2	Conj-4
Higher (200–360 ms)	.57	.60	.43	.10
Lower (200–360 ms)	1.22	1.83	1.48	1.32
Lower (360–520 ms)	1.05	.91	.88	1.57

3. Results

3.1. Behaviour

An ANOVA indicated significant main effects of Type, $F(1, 13) = 35$, $p < .0001$, and Size, $F(1, 13) = 6.18$, $p = .03$, on response errors; and a significant interaction, $F(1, 13) = 5.76$, $p < .05$. *Post hoc* analysis (Newman–Keuls) revealed significant differences between all pairs of means ($p < .02$), except between Conj-2 and Conj-4. An ANOVA also indicated significant main effects of Type, $F(1, 13) = 80$, $p < .00001$, and Size, $F(1, 13) = 72$, $p < .00001$, on response times; and a significant interaction, $F(1, 13) = 64$, $p < .00001$. All pairwise means were significantly different ($p < .0005$). Mean error rates and response times are shown in Table 1.

3.2. Phase-locking

One-sample *t*-tests for each type-size condition at each time-frequency point revealed significant increases (red regions) in frontal–parietal synchrony approximately 200 ms after stimulus onset relative to the pre-stimulus baseline in all four conditions, with the effects most prominent for the midline pair (Fig. 1). In all conditions, for the lower frequency band, the mean PLVs rose above baseline in both the earlier and later time intervals. For the higher frequency band, mean PLVs rose above baseline only in the earlier time interval. Accordingly, three-way (type × size × site) ANOVAs were conducted for the earlier and later time intervals in the lower frequency band and the earlier time interval only for the higher frequency band. For the higher frequency band during the earlier time interval, there was a significant main effect of type on PLV, $F(1, 13) = 5.13$, $p < .05$, where there was greater synchrony in the feature than conjunctive search condition. For the lower frequency band during the earlier interval, there was a significant main effect of site, $F(2, 26) = 7.99$, $p < .002$. *Post hoc* analysis indicated that the mean PLV for the midline pair was significantly greater than for the left or right pairs, $p < .005$. There was also a significant type by size interaction, $F(1, 13) = 6.97$, $p < .03$. Only the difference between Feat-4 and Feat-2 means was significant, $p < .05$, where there was greater synchrony in the Feat-4 condition. For the lower frequency band during the later interval, there was a significant main effect of site, $F(2, 26) = 4.99$, $p < .02$, where the mean PLV for the midline pair was significantly greater than for the left or right pairs, $p < .03$. There was also a significant type by size interaction, $F(1, 13) = 6.45$, $p < .03$. Only the mean for Conj-4 was significantly greater than the means for the other three conditions, $p < .05$. There were no other significant effects. Mean PLVs are shown in Table 2.

4. Discussion

The PLV results confirm our prediction that older participants show significantly greater synchrony for feature than conjunctive search in the high gamma-band. We also observed a significant increase in synchrony in the lower frequency band for conjunctive than feature search. This effect was only observed in the later time band and only for the Conj-4 condition, where the mean PLV was significantly greater than for the other conditions. In our earlier study, with younger participants, we also observed a significant increase in synchrony for an earlier time period (160–320 ms) in the same lower frequency band. Top-down control may be less effective in older participants, and only engaged in the more difficult search conditions. We note, however, that the design of the task—specifically, the small display sizes and target location objective, which potentially introduces the need to compute an additional (object-location) conjunction—may have resulted in an underestimation of the effect of conjunctive search on phase-locking in contrast to feature search. For example, with greater display sizes participants may tag items already visited (Takeda and Yagi, 2000). This increased use of working memory may drive additional top-down control of attention, reflected in greater phase-locking in the lower gamma-band.

Although we observed significantly greater PLVs in the high gamma-band for feature than conjunctive search, no corresponding effect was revealed in our previous study on younger adults (Phillips and Takeda, 2009). This difference suggests a greater bias towards bottom-up driven attention in older participants, which is most likely due to increased susceptibility to attentional capture. As mentioned in the Introduction, older adults may be more susceptible to attentional capture than younger adults (Kramer et al., 2000). Attentional capture triggers bottom-up control of attention, which is expressed as increased high gamma-band synchrony. However, attentional capture alone is generally not sufficient in the more difficult Conj-4 condition, where all items share a feature with the target. The failure of bottom-up control to identify the target in this case, may in turn trigger top-down control, hence the increase in low gamma-band synchrony during the later interval for Conj-4 search.

Although the response time data indicated feature and conjunction search effects for the older group, there was no significant interaction between age and search type when the data were pooled with the data from the younger group. The older group was consistently slower than the younger group in all conditions, but these differences did not change between feature and conjunctive search. Others have pointed out (see Whiting et al., 2005) that search is likely to involve an interaction between bottom-up and top-down control. So, response time data may not be ideally suited for revealing selective deficits in our study if on the one hand older participants are more likely to initiate search with fast bottom-up control, but terminate it with slower top-down processes relative to younger participants.

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