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Spontaneous alpha peak frequency predicts working memory performance across the age span

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Abstract

Working memory capacity has been consistently shown to decline with increasing age. Mechanisms underlying this decline are poorly understood. One index that has been found to predict performance on memory tests is alpha peak frequency, the peak of spectral alpha power of the EEG. Activity in the alpha band has been also associated with higher cognitive functions including attention and anticipation and has been shown to slow with age. Few studies, however, have examined whether there might be a relationship between WM decline and alpha peak frequency. The present study specifically investigated this relationship. Digit span was used as the index of WM function. The study made use of 550 normal subjects aged between 11 and 70 years in the Brain Resource International Database. The data were acquired from six laboratories located in the USA (2), Europe (2) and Australia (2). Forward and reverse digit span were found to be lower in older relative to younger age groups. Spontaneous alpha peak frequency slowed with age and more so at anterior than posterior sites. Frontal alpha peak frequency was found to be a significant predictor of reverse digit span, with each 1 Hz increase in frequency associated with a 0.21 increase in reverse digit span score and this was independent of age, indicating a positive relationship between alpha peak frequency and working memory performance.
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1. Introduction

The working memory (WM) system enables the transient storage and manipulation of information needed for effective, moment-to-moment interaction with the environment (e.g. Baddeley, 2000). It includes such functions as distinguishing and evaluating the significance of relevant information in the environment, the production of appropriate responses to such information as well as updating

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and operating upon WM traces reflecting the current state of the environment (see Clark et al., 2000). Numerous studies have found that WM declines with age (e.g. Gilbert and Levee, 1971; Salthouse, 1990; Parkin and Walter, 1991; Yokota et al., 2000; Hartman et al., 2001; Salat et al., 2002) although the mechanisms underlying this decline are not well understood. One index that has been found consistently to predict general memory performance is alpha peak frequency. Alpha peak frequency has been associated with performance on semantic encoding and retrieval tasks and to predict individual differences in general memory performance (e.g. Klimesch, 1999). It is also well established that alpha peak frequency declines with age (e.g. Osaka et al., 1999). The possibility of a specific relationship between alpha peak frequency and WM has not been fully explored, with the few studies that have been reported often limited by small sample sizes or restricted age range.

Age-related decline in WM has been found during verbal WM (Osaka et al., 1999), visuospatial WM (Esposito et al., 1999) and has been shown to become more pronounced with increased memory load (McEvoy et al., 2001). Additionally, it has been suggested that visual WM is more vulnerable to the effects of aging than verbal WM (Jenkins et al., 2000). This decline has been variously attributed to selective prefrontal degeneration (e.g. Daigneault and Braun, 1993), deficient inhibitory processes (Palladio and De Beni, 1999; Grant and Dagenbach, 2000; Hedden and Park, 2001; Persad et al., 2002), deficits in perceptual abilities (Faubert and Bellefuille, 2002) and reduced processing speed (Bryan and Luszcz, 1996).

One index that has been found to be a consistent predictor of higher cognitive capacities is alpha peak frequency, which has been argued to reflect the speed of processing in thalamo-cortical networks (Klimesch, 1997; Steriade et al., 1990). Klimesch et al. (e.g. 1996, 1999) and Klimesch (1997) have extensively explored the effects of individual variability in memory performance and have found a strong relationship between alpha peak frequency and memory performance. The review by Klimesch (1999) concluded that subjects with superior memory performance show an alpha peak frequency that is approximately 1 Hz higher than age-matched controls that perform poorly on memory tasks. Alpha frequency has also been related to other cognitive functions including anticipation (Basar et al., 1997a) and attention (Klimesch, 1997). Kolev et al. (2002) also proposed that alpha band responses might be generally involved in the regulation of frontal function during cognitive activity.

Alpha peak frequency has consistently been shown to slow with age (Mankovskiy and Belonog, 1971; Roubicek, 1977; Li et al., 1996; Osaka et al., 1999). For example, Kropruner et al. (1984) found a linear relationship with age across the 20–70 year band (alpha peak frequency $= 11.95 - 0.53 \times$ age). Although generalized EEG slowing is also found to occur with increasing age, there is some evidence of a specific relationship between alpha peak frequency and memory performance. For example, Klimesch (1997) found that high alpha peak frequency marked better memory performance in Alzheimer's patients, independently of other indices of dementia severity.

Although many studies have examined the effects of age on WM and on alpha peak frequency, only a few studies have specifically examined the relationship between alpha activity and WM. Further, these studies have been limited in generalizability due to sample size or restricted age range. For example, Stam (2000) and Stam et al. (2002) found that activity in the lower alpha band was associated with successful WM performance, but this could not be generalized either to the full alpha band or across the full age range. Osaka et al. (1999) found that shifts in alpha frequency were sensitive to individual differences in WM but the study was also restricted to a small sample. Similarly, the same relationship was indicated by Li et al. (1996) but this study was restricted to an older age group. This aim of the present research is to investigate whether there is a reliable relationship between alpha peak frequency and WM performance across a wide age range. It was predicted that this relationship would be evident at frontal, temporal and parietal sites, consistent with the effects of working memory load on EEG (Jensen et al., 2002), MEG (Osaka et al., 1999) and on neuroimaging tomography (e.g. Cabeza and Nyberg, 2000; Clark et al., 2000).

2. Materials and methods

2.1. Subjects

The present study makes use of data acquired from the Brain Resource International Database. Six laboratories (New York, Rhode Island, London, Holland, Adelaide and Sydney) participated in the data acquisition in a standardized manner with identical hardware, software, paradigms and experimental procedures. The dataset consisted of 550 normal, non-clinical participants (mean age = 33 years, range 11–70 years, balanced for gender). Exclusion criteria included a personal history of mental illness, physical brain injury, neurological disorder or other serious medical condition and/or a personal history of drug or alcohol addiction. Subjects were also excluded if they had a family history of attention deficit hyperactivity disorder (ADHD), Schizophrenia, bipolar disorder or genetic disorder. The SPHERE questionnaire (Hickie et al., 1998) was used to screen out individuals with a likely anxiety or depressive disorder. All subjects (or their guardians for subjects less than 18 years of age) provided written informed consent to participate in the database.

Subjects were required to refrain from caffeine intake and from smoking for at least 2 h prior to testing.

2.2. Psychophysiology data acquisition

EEG was acquired using an electrode cap (Quikcap) from the following anterior (Fz, F3, F4, F7, F8) and posterior (Pz, P3, P4, T5 and T6) 10–20 sites over frontal, temporal and parietal regions. Scalp sites were referenced offline to the average of A1 and A2 (mastoids). Horizontal eye movements were recorded with electrodes placed 1.5 cm lateral to the outer canthus of each eye. Vertical eye movements were recorded with electrodes placed 3 mm above the middle of the left eyebrow and 1.5 cm below the middle of the left bottom eye-lid. Scalp impedance was kept below 10 kΩ. Data were obtained continuously using a NuAmps system (Neuroscan, USA) with large dynamic range (±132 mV and 22 bit resolution). It was sampled at 500 Hz after low pass filtering with attenuation of 40 dB per decade above 100 Hz. Data were corrected for eye movement offline (Gratton et al., 1983).

The EEG data reported and analysed in the present study were recorded during a 2-min interval in which subjects were asked to rest quietly with their eyes closed. This task was preceded by a 2-min, eyes open EEG paradigm that is not reported in this study.

2.3. Psychological testing

Participants were seated in front of a touchscreen computer (NEC MultiSync LCD 1530V) located within a sound and light attenuated room with an ambient temperature of approximately 24 °C. Task instructions and materials were pre-recorded and delivered in a standardized way using computer 'wav' files presented via headphones and using the visual display of a touchscreen computer. An iterative, human–computer interaction protocol was used to ensure task comprehension and compliance. The test battery involves a total of 12 tasks lasting approximately 50 min. This study examines the results of three of these tasks only: forwards digit span, reverse digit span and the spot the word test. The spot the word test has been reported to provide a robust estimate of verbal intelligence in normal English speakers of 16 years of age or more (Baddeley et al., 1993). Subjects not meeting these criteria were provided with age appropriate means for the purpose of mean IQ estimation for age-groups of interest (see Table 1).

During each of the digit span tasks, the subject is presented with a series of single digit sequences on the touchscreen. The forward digit span task is completed first, followed by the reverse digit span task. In each task, sequence lengths range from three to nine digits, with sequences presented in ascending order of length with two separate sequences at each length. Each digit in a sequence is presented for 500 ms with a 1 s inter-stimulus interval. Immediately following each sequence, the subject is required to enter the digits on a numeric keypad that is present on the touchscreen. In the

Table 1
Demographic and behavioral data (mean ± S.D.) for each age group

Age Group	11–20	21–30	31–50	51–70
N	140	160	150	100
Years of education	11.69 ± 2.84	13.96 ± 4.33	14.27 ± 3.40	13.01 ± 3.77
Estimated IQ	100.15 ± 6.83	105.54 ± 7.28	108.85 ± 5.93	109.56 ± 6.64
Forward digit span	6.41 ± 1.32	6.71 ± 1.39	6.31 ± 1.29	6.05 ± 1.22
Reverse digit span	5.16 ± 1.51	5.34 ± 1.82	4.39 ± 0.85	4.01 ± 1.69

forward digit span task, the subject is required to enter the digits in the order of presentation. In the reverse digit span task, entry is required in the reverse order of presentation. The score on each test is given by the maximum sequence length completed without error. These tasks take approximately 5 min in total.

2.4. Data analysis

Data were separated into four consecutive age groups, with equal numbers of males and females in each group: 11–20 years ($n = 140$, mean age = 17 years, S.D. = 2.5), 21–30 years ($n = 160$, mean age = 24.6 years, S.D. = 2.8), 31–50 years ($n = 150$, mean age = 40.3 years, S.D. = 6) and 51–70 ($n = 100$, mean age = 58 years, S.D. = 5.7).

Average power spectra were computed and divided into adjacent 4.096 s epochs. Power spectral analysis was performed on each epoch by first applying a Welch window to the data and then performing a fast Fourier transform (FFT) with a block size of 2048 points and a frequency resolution of 0.24 Hz. The resultant power spectra were averaged separately for each electrode. Power was then calculated across the alpha frequency band (8–13 Hz) and square-root transformed in order to approximate the normal distribution required by parametric statistical methods.

Alpha peak frequency (APF) was identified as the maximum value within the defined alpha band, provided its power exceeded the magnitude of the EEG spectra at the point it crossed the lower band limit (8 Hz). A small percentage of APF data (1.9%) that failed to meet this criterion were treated as missing values. In effect, the peak alpha value for these participants fell below 8 Hz, according to the following age distribution: 11–20 (0.9%); 21–30 (0.6%); 31–50 (3.8%); 51–70 (2.3%). In addition, data points that were beyond 1.5 times the inter-quartile range were removed and replaced with age-appropriate means. In particular, there were 17 (3.1%) anterior APF outliers, 24 (4.4%) posterior APF outliers and 6 (1.1%) reverse digit span outliers

3. Results

The group descriptive and behavioral data for participants are presented in Table 1.

Univariate analyses of variance on digit span performance by age group were conducted whilst controlling for sex and years of education. There was a significant effect of age on both forward ($F_{3,545} = 5.32$, $P = 0.001$) and reverse ($F_{3,545} = 23.78$, $P = 0.000$) digit span performance (see Table 1). Bonferroni post-hoc testing revealed in both cases that this difference was due to a significantly lower performance by subjects between 31 and 70 years of age relative to that for subjects between 11 and 30 years of age.

Alpha peak frequency for each age group is presented in Fig. 1. Mixed factorial analysis of variance examined the effect of age group, topographic region (anterior, posterior) and site on alpha frequency whilst controlling for sex. Age group was treated as a between subjects factor and both topographic region and site as within subjects factors. Analysis showed a significant decrease in alpha peak frequency with age ($F_{3,417} = 5.2$, $P = 0.002$) (see Table 2 and Fig. 2). There was also a significant interaction between age and topographic region ($F_{3,418} = 4.55$, $P = 0.004$). Simple effects analysis revealed that the decrease in peak alpha frequency with age was stronger at anterior

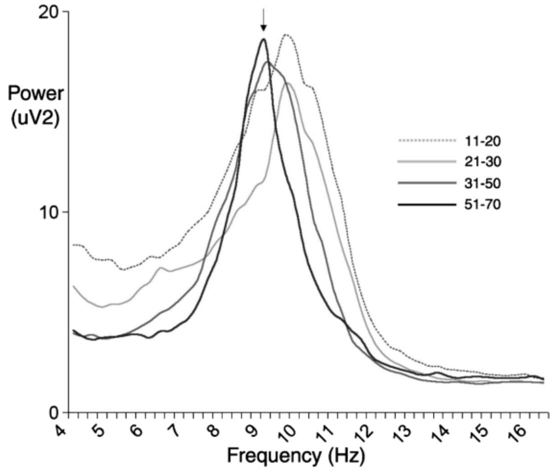

Fig. 1. The anterior (Fz) EEG power spectra from 4 to 16 Hz during the eyes closed paradigm. The figure demonstrates a lower peak alpha frequency in the 51–70 year age group (see arrow) relative to other age groups. Age groups are represented in different shades of grey-scale lines.

($F_{3,417}=7.19$, $P=0.000$) than posterior ($F_{3,417}=2.91$, $P=0.034$) regions.

A stepwise linear regression model was used to test whether alpha peak frequency was a direct predictor of memory performance across the entire sample (age range 11–70 years). As the effect of age was the strongest on the reverse digit span task, the reverse digit span scores were selected as the memory performance dependent variable. Co-linearity between anterior and posterior alpha peak frequency meant that it was necessary to be selective about which region was put into the initial model. The anterior alpha peak frequency was selected on the basis that it had produced the most significant results in the earlier analysis of variance. Age, sex and years of education, which were also thought to be likely predictors of reverse digit

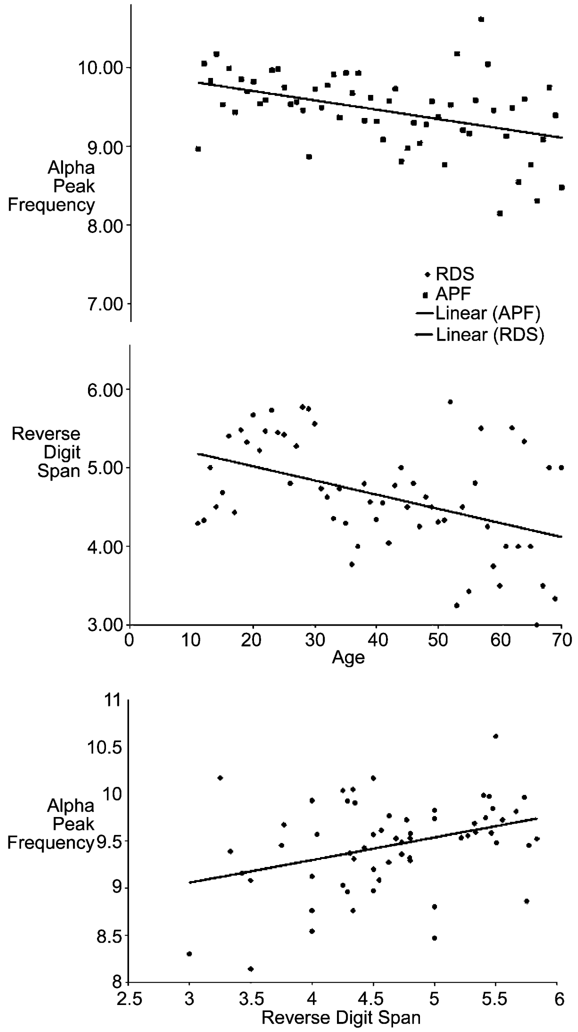

Fig. 2. Scatter plots of alpha peak frequency by age, reverse digit span by age and alpha peak frequency by reverse digit span. Age is in 1 year increments.

Table 2
Means and standard deviations of alpha peak frequency across age groups at anterior and posterior sites

Age in years	11–20	21–30	31–50	51–70
Anterior sites	9.77 ± 0.76	9.65 ± 0.83	9.48 ± 0.74	9.31 ± 0.85
Posterior sites	9.81 ± 0.74	9.89 ± 0.84	9.66 ± 0.70	9.54 ± 0.81

The values for anterior sites represent averages across sites F7, F3, Fz, F4 and F8. The values for posterior sites represent averages across T5, P3, Pz, P4 and T6.

span performance, were also included in the initial model. The resultant model showed that age and frontal alpha peak frequency were the only significant predictors of performance on the reverse digit span task. Years of education and sex were excluded as they did not meet the pre-defined 0.05 alpha rate. This model explained 10.2% of the variance ($R^2=0.102$) in the reverse digit span scores ($R=0.32$, $P=0.000$).

The age coefficient ($B=-0.028$, Beta $=-0.28$, $t=-6.06$, $P=0.000$) showed that each additional year of age was estimated to result in a 0.02 digit decrease in reverse digit span, when alpha peak frequency was held constant. The alpha peak frequency coefficient ($B=0.21$, Beta $=0.11$, $t=2.35$, $P=0.019$) estimated that each additional 1 Hz of alpha peak frequency was associated with a 0.21 digit increase in reverse digit span, when age was held constant. Scatterplots illustrating these relationships across 1 year age bands are shown in Fig. 2.

4. Discussion

This study replicated previous findings of change in both WM ability and alpha peak frequency with increasing age. The slowing of alpha peak frequency was more prominent frontally. Declining memory performance was most evident on the more demanding reverse digit span task relative to the forward digit span task. Notably, reverse digit span not only requires the short-term retention of information WM, as does forward digit span, but also requires the manipulation and operation upon such information. In addition, the relationship between WM and alpha peak frequency was also found to be independent of age. This suggests that alpha peak frequency directly reflects the activity of the related cognitive processes. Further, the relationship between alpha peak frequency and memory performance extended across the full 11–70 age range investigated, extending earlier findings apparent for a 50+ age group (Li et al., 1996).

Consistent with earlier research (e.g. Kropruner et al., 1984; Klimesch, 1999), this study found that alpha peak frequency slowed across the adult age range. The physiological cause of such slowing is unclear. It has been suggested that slowed alpha peak frequency reflects speed of processing in thalamo-cortical networks (Steriade et al., 1990), but it has also been proposed that this effect may be related to differential power changes across the alpha band (e.g. Klimesch, 1999). For example, it is proposed that the alpha band is comprised of several functionally distinct sub-components (e.g. Neidermeyer, 1997), in which both tonic (e.g. age-related, Kolev et al., 2002) and phasic (e.g. task-related, Klimesch, 1997) changes occur independently. Two of these sub-components have been implicated in higher cognitive function: the upper band, which has been linked to semantic memory performance and the lower alpha band, suggested to reflect attentional processes (Klimesch, 1997, 1999). A relative reduction in upper band power or increase in lower band power would result in a shift in peak frequency that was not related to speed of processing. Previous research has found evidence of slow and fast alpha networks being differentially affected by age (e.g. Kolev et al., 2002).

The present study also found that the effect of age on alpha peak frequency was most evident over anterior relative to posterior scalp regions. One explanation for this differential effect might be specific neural degeneration, which tends to preferentially target the frontal regions (see Greenwood, 2000), and that has been linked to EEG slowing (Klimesch, 1999). Another explanation might be a topographic reorganization of alpha patterns with age (e.g. Basar et al., 1997a; Yordanova et al., 1998; Kolev et al., 2002). Research has consistently shown a general decrease in spectral alpha power with age together with a posterior to anterior shift in topographic distribution (Neidermeyer, 1997; McEvoy et al., 2001). Interestingly, Klimesch (1996) found that slowed alpha frequency in age-matched poor memory performers was most prominent frontally.

The functional explanation for the relationship found in this study between alpha peak frequency and WM is not clear. Notably, though, alpha frequency has been found to be associated with functions such as attention and semantic memory (Klimesch, 1999) and anticipation (Basar et al., 1997b). These functions, like WM, are all frontally regulated (Luria, 1973; Fuster, 1989; Cabeza and Nyberg, 1997). Thus, the relationship between WM and alpha peak frequency may be associated with frontal lobe capacities. Conversely, it has been found that parietal rather than frontal alpha is associated with short-term memory span (e.g. Jensen et al., 2002).

An alternative explanation is that the relationship between alpha peak frequency and WM is due to the role of alpha producing networks in modulating attentional control. As has been discussed, previous research has indicated a role for the lower alpha band in attentional processing (e.g. Klimesch, 1999). Research has also suggested that desynchronization in the lower, but not upper alpha band reflects aspects of WM function (Gevins et al., 1997; Osaka et al., 1999; Stam, 2000; Stam et al., 2002) and that greater lower alpha desynchronization predicts WM performance (Osaka et al., 1999). Previous research has found attentional variations to be a significant predictor of WM performance. The relationship between WM and alpha activity may therefore be due to specific changes in the lower band that have been observed with age (e.g. Klimesch, 1999; Kolev et al., 2002), rather than non-specific frontal degeneration.

It is important to note that the present study used measures of peak alpha obtained from spontaneous (passive) EEG rather than from active EEG obtained during digit span performance. Nevertheless, previous work has demonstrated a significant, albeit smaller, relationship between memory function and baseline alpha measures obtained non-simultaneously (Klimesch, 1997). The present study accords with this outcome, however, the effect might have been shown to be larger with more related measures. Clearly, it would be of interest to assess the relationship with more directly related measures.

At the same time, it is worth noting that the use of spontaneous rather than active EEG reflects a state in which working memory activity is not experimentally controlled. According to one point of view (Steriade et al., 1990), the putative relationship between alpha peak frequency and working memory operations might be regarded to reflect trait rather than state. As such, although alpha power might be expected to vary as a function of cognitive activity, alpha peak frequency itself could be expected to be invariant. However, Klimesch (1999) has argued that alpha peak frequency also varies as a function of cognitive activity. On this interpretation, alpha peak frequency during active, experimentally induced EEG would also vary as a function of phasic attentional or working memory demands. But, this was unlikely to have been the case in the present study, since level of cognitive activity was not manipulated during EEG measurement. Indeed, if the Klimesch (1999) position is correct, then the use of a resting EEG index of alpha peak frequency avoids the potential confound under this model of phasic effects on the peak frequency measure, and provides perhaps a more robust predictor of working memory performance. Nevertheless, this study now indicates a clear need to evaluate whether a differential relationship exists for active relative to passive EEG with working memory function.

There were several limitations to this study. First, Klimesch (1996, 1997, 1999) has proposed the use of subject-adjusted alpha frequency bands in order to explore more accurately the relationship between alpha peak frequency and memory processes. This proposal is related to the fact that there is significant variability across individuals in both the precise range of the alpha band as well as peak alpha frequency. A failure to accommodate such variability would necessarily obscure the relationship between alpha and memory performance. However, the use of a large sample size, as in the present study, appears to have overcome this potential difficulty to some extent, though it is recognized that only a small proportion of the variance was accounted for. Additionally, no distinction was made in the present study between lower and upper alpha band measures. Earlier work indicates that this is an important distinction and future work examining the relationship between WM and alpha frequency should take the distinction into account.

Previous work has noted that a small percentage of adults exhibit an alpha peak frequency below the traditional 8 Hz boundary (Klimesch et al., 1993). This was also found to be the case in 1.9% of participants in the present study. Notably, however, the majority of these low alpha peak outliers fell within the older age ranges, consistent with the results of this study. This suggests that future work investigating alpha peak frequency should not rigidly delimit the search range for this component.

In conclusion, this research found a relationship between alpha peak frequency and WM independent of age, consistent with previous research examining the relationship between the alpha rhythm and other memory abilities. The exact nature of this relationship, however, remains to be fully elucidated. In addition, it still needs to be resolved whether the specific relationship between alpha peak frequency and WM is mediated by factors such as speed of information processing, non-specific frontal decline and/or attentional capacity.

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