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The impact of executive capacity and age on mechanisms underlying multidimensional feature selection

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Abstract

This study examined the role of executive capacity (EC) and aging in multidimensional feature selection. ERPs were recorded from healthy young and old adults of either high or average EC based on neuropsychological testing. Participants completed a color selective attention task in which they responded to target letter-forms in a specified color (attend condition) while ignoring letter-forms in a different color (ignore condition). Two selection negativity (SN) components were computed: the SN_{Color} (attend – ignore), indexing early color selection, and the SN_{Letter} (targets – standards), indexing early letter-form selection. High EC subjects exhibited self-terminating feature selection; the processing of one feature type was reduced if information from the other feature type suggested the stimulus did not contain the task-relevant feature. In contrast, average EC subjects exhaustively selected all features of a stimulus. The self-terminating approach was associated with better task accuracy. Higher EC was also linked to stronger early selection of target letter-forms, but did not modulate the seemingly less demanding task of color selection. Mechanisms utilized for multidimensional feature selection appear to be consistent across the lifespan, although there was age-related slowing of processing speed for early selection of letter features. We conclude that EC is a critical determinant of how multidimensional feature processing is carried out.

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¹See Andersen et al. (2009) and Zhang and Luck (2009) for examples in which non-spatial feature processing was not mediated by spatial attention.

³Our analysis suggested that subjects with high EC exhibited a larger SN_{Letter} under the attend than ignore condition. To determine whether they generated a reliable SN_{Letter} under the ignore condition, one-sample t tests were conducted. These analyses revealed that the size of the SN_{Letter} under the ignore condition was significantly larger than 0 microvolts under both low and high memory loads (all p's < .001). These results have implications for whether subjects with high EC carry out multidimensional feature selection in a serial or parallel manner (see Discussion).

Keywords

Multidimensional Feature Selection; Selective Attention; ERPs; Selection Negativity; Executive Control; Aging

1. Introduction

Visual selective attention reflects the top-down control of information processing based on task demands and has been hypothesized to be principally mediated by the executive control component of working memory (Desimone & Duncan, 1995; Lavie, Hirst, de Fockert, & Viding, 2004; Rutman, Clapp, Chadick, & Gazzaley, 2010). Theoretically, selective attention improves processing efficiency and conserves resources of the capacity-limited decision making system (Awh & Jonides, 2001; de Fockert, Rees, Frith, & Lavie, 2001; Gazzaley, Cooney, McEvoy, Knight, & D'Esposito, 2005; Zanto & Gazzaley, 2009). Individual differences in top-down control mechanisms vary as a function of executive capacity (EC) and age (de Fockert, Ramchurn, van Velzen, Bergstrom, & Bunce, 2009; Riis et al., 2008). There is evidence that individuals with lower EC or with advanced age exhibit suboptimal mechanisms of selective attention (Gazzaley, Cooney, Rissman, & D'Esposito, 2005; Gazzaley & D'Esposito, 2007a; Haring et al., 2013; Vogel, McCollough, & Machizawa, 2005; Zanto, Hennigan, Ostberg, Clapp, & Gazzaley, 2010a). This issue has largely been studied for selective attention to specific spatial and non-spatial features (e.g., location, color, motion). The current study investigates the role of EC and aging in the management of multidimensional feature selection, a topic that has received little attention in the literature.

Several models have been proposed to describe how multiple task-relevant feature dimensions of stimuli are selected for processing. Here, we briefly summarize these models to provide a context for considering whether subjects who vary in EC or age differ in their processing approach. Stimulus feature processing may be either self-terminating or exhaustive (Smid, Jakob, & Heinze, 1997). Self-termination implies that processing of one stimulus feature can influence the extent of processing of another stimulus feature. For example, if evidence accrues from any one feature that the stimulus is not consistent with being a target, processing of other features can be reduced or inhibited (Hawkins, 1969; Zehetleitner, Muller, & Krummenacher, 2008). In contrast, exhaustive processing carries out all stages of feature selection to completion, even if the identification of one feature dimension is completed earlier than the others, and it eliminates the possibility that the stimulus is a target (Deutsch & Deutsch, 1963; Norman, 1968; Zehetleitner et al., 2008). In addition, stimulus processing may be carried out in a serial (Egeth, 1966) or parallel (Hansen & Hillyard, 1983) manner.

Champions of early selection models (Broadbent, 1970; Treisman, 1969) suggested that a serial self-terminating approach allowed for “an economy of processing” by initially filtering based on a fundamental physical stimulus characteristic like color, location, or pitch. Only stimuli containing the appropriate dimension would then be processed further for more complex features, allowing for the identification of targets. Hansen and Hillyard

(1983) offered an alternative economy of processing model based on parallel self-terminating processing. Features are analyzed in parallel, but in a hierarchical or contingent manner. The level of one stimulus dimension influences the depth or extent of processing of other dimensions.

To study multidimensional feature selection, investigators have often utilized event-related potentials (ERPs), since their high temporal resolution makes them the ideal neuroimaging technique for examining operations engaged by early selective attention processes. Many studies have used the posterior selection negativity (SN) component as an index of task-relevant stimulus feature selection. The posterior SN reflects top-down modulation of sensory-perceptual processing in the feature-selection areas of the extrastriate cortex, leading to the enhancement of relevant stimulus dimensions compared to irrelevant ones (Harter & Aine, 1984; Hillyard & Anllo-Vento, 1998; Kopp, Taneling, Moschner, & Wessel, 2007). As one of the first components to demonstrate a difference in activity between attend and ignore conditions, it likely signals early selection and not post-selection processing (Daffner et al., 2012b; Hillyard & Anllo-Vento, 1998; McGinnis & Keil, 2011) (but see Kenemans, Smulders, & Kok, 1995; Zanto, Toy, & Gazzaley, 2010b for an alternative hypothesis). The SN is measured as a difference wave that peaks 200-350 ms post-stimulus presentation (Czigler, 1996; Daffner et al., 2012b; Hillyard & Anllo-Vento, 1998; Keil & Muller, 2010; Martin-Loeches, Hinojosa, & Rubia, 1999). It is computed by performing a subtraction of the ERP response to stimuli lacking a target feature from the response to stimuli with that target feature. Therefore, the amplitude of the SN indexes the difference in the amount of early processing being devoted to the target versus the non-target feature. The latency of the SN reflects the speed of processing to select relevant features.

Based on early selection models (Broadbent, 1970; Treisman, 1969), it is not clear whether an SN would be generated to letter-forms. One might expect that discrimination between letter-form features of target and non-target letters would not be observed during early stages of processing, as indexed by the SN. Rather, the differences would emerge in later decision-making stages that might be indexed, for example, by the P3b component. A study by Smid and Heinze (1997) is one of only a few (Smid et al., 1997; Smid, Jakob, & Heinze, 1999) that has examined visual stimulus feature selection in the context of alphanumeric characters, and confirmed the presence of an SN to letter-forms. The investigators sequentially presented letters to subjects in two colors, and asked them to respond to particular letters when presented in one of the colors. They measured the SN component at occipito-temporal sites, and utilized subtractions to index the processing of color, global letter shape, and local letter shape. They found that the color and shape of letters were processed in a parallel self-terminating manner. The Smid and Heinze study (1997) did not address the potential impact of EC, age, or task difficulty, and to our knowledge, no further investigation on letter-forms has been pursued.

In our task, letters were presented sequentially in an attend or ignore color, with particular letters designated as targets. Two levels of difficulty were included in order to determine if task demand modulated indices of feature selection. Subjects were divided in terms of high or average EC, as assessed by neuropsychological testing, and data were collected from both

young and old adults to determine the extent to which there were age-related differences in operations mediating multidimensional feature selection.

To assess the selection of multiple stimulus features, two SN components were computed using two different subtractions. The ERP responses to stimuli under the ignore color condition were subtracted from the ERP responses to stimuli under the attend color condition. The portion of the difference wave within the temporal window of the selection negativity was labeled as the SN_{Color} because it serves as an index of attention to the feature color, and has been measured in many previous studies (Czigler, 1996; Daffner et al., 2012b; Hillyard & Anllo-Vento, 1998; Keil & Muller, 2010; Martin-Loeches et al., 1999). We measured the SN_{Color} in response to target and standard stimuli. To assess the preliminary selection of target letter features, we employed a subtraction of the ERP responses to non-target letters from the ERP responses to target letters. This difference wave was labeled the SN_{Letter} , as it serves as an index of attention to features delineating letter-forms. The SN_{Letter} was measured under both the attend and ignore conditions. A subject had to assess both color and letter-form to correctly identify target stimuli. In summary, there were four difference waves of two main types: an SN_{Color} in response to target or standard stimuli, and an SN_{Letter} under the attend or ignore condition.

The current study's design allowed us to determine whether subjects of varying EC and age performed exhaustive or self-terminating feature selection, and provided indications about the use of serial vs. parallel processing. If subjects exhibited processing that conformed to a serial self-terminating model, the SN_{Letter} would only be present in response to a stimulus in the attend color, but not the ignore color, and have no temporal overlap with the SN_{Color} , as the processing of color features would be completed prior to the start of processing letter features. Moreover, the amplitude of the SN_{Color} would not differ in response to target or non-target letters. If feature selection mechanisms conform to the parallel self-terminating model, the two SNs would overlap temporally, but there would be a reduction in the size of the SN_{Letter} when the stimulus was in the ignore color, and/or a reduction in the size of the SN_{Color} when the stimulus was a non-target letter. One could argue that this processing schema is more efficient than serial self-termination, as it takes advantage of the speed of parallel processing while allowing the two streams of feature selection to influence each other (Hansen & Hillyard, 1983).

In contrast, if subjects carried out the task according to a serial exhaustive model, the size of the SN_{Letter} would be unaffected by whether a stimulus was in the attend or ignore color, and the size of the SN_{Color} would be unaffected by whether the stimulus type was a target or non-target letter. In addition, given the serial nature of the processing, the SN_{Letter} would not temporally overlap with the SN_{Color} . Finally, in the case of the parallel exhaustive model, the size of the SN_{Letter} would not be modulated by the attend vs. ignore color condition, the size of the SN_{Color} would not be modulated by the target vs. standard stimulus type, and the temporal latencies of the two types of SNs would overlap. In summary, the study design is likely to yield clear distinctions between self-terminating and exhaustive processing. However, it may not be able to resolve differences between serial and parallel processing. A serial model would be unambiguously rejected if there were no differences in the peak latency of the two types of SNs (color and letter). However, a parallel model would not be

ruled out if the peak latencies were statistically different, because two components may peak at different times while still having a partially overlapping time course. Table 1 summarizes the predictions each model makes about the ERP results in this study.

Selective attention has been conceptualized as reflecting the activity of executive control functions over sensory input (Gazzaley & D'Esposito, 2007b). Within this framework, executive control is viewed as biasing sensory processing by the enhancement of neural activity in response to task relevant features and/or the suppression of neural activity in response to task irrelevant ones. Lavie and colleagues (2004) have argued that the executive component of working memory allows individuals to actively maintain current processing priorities online that differentiate between relevant targets and irrelevant distractors. In addition, the efficiency of the attentional system influences both the storage and processing of information in working memory (Cowan, 2008). There is ongoing debate over whether individual differences in working memory due to genetic predisposition or aging is mainly a reflection of differences in overall capacity or the failure to inhibit the processing of task-irrelevant information, which clutters and disrupts this capacity-limited system (Cowan, 2008; Cowan, AuBuchon, Gilchrist, Ricker, & Saults, 2011; Rabbitt, 1965; Vogel et al., 2005).

Evidence suggests that individuals with higher executive capacity perform better on tasks requiring selective attention (Desimone & Duncan, 1995; Lavie et al., 2004; Rutman et al., 2010; Vogel et al., 2005). Based on this work and related research (Harter & Aine, 1984; Hillyard & Anllo-Vento, 1998; Kopp et al., 2007), one would expect subjects with high EC to manage the challenges of the current task differently, and presumably more efficiently, than subjects with lower EC. This effect might manifest itself by increased reliance on a parallel, self-terminating approach and faster processing speed in subjects with higher EC. It was also reasonable to expect that limited resources to coordinate top-down control in subjects with average EC, especially in the older age group, might cause them to process stimulus features less efficiently, in a serial, rather than parallel manner. It is plausible that some of the inconsistent findings in the literature on early selection of features may be due to variation across studies of the EC of the subjects investigated.

Executive functioning reportedly declines in older adults (De Luca et al., 2003; Dobbs & Rule, 1989; Reuter-Lorenz & Sylvester, 2005; Sander, Lindenberger, & Werkle-Bergner, 2012; Verhaeghen, Steitz, Sliwinski, & Cerella, 2003). Previous research has shown that increased age can impact selective attention by, for example, reducing top-down control over the ability to suppress the processing of task-irrelevant information (de Fockert et al., 2009; Gazzaley & D'Esposito, 2007a; Haring et al., 2013). In accordance with these reports, we expected that aging would influence operations underlying the selection of multiple features and lead to a less optimal approach, especially among older subjects with lower EC. Furthermore, we anticipated age-related slowing of processing speed, as indexed by prolonged peak latencies of the SN. It was less clear what impact task difficulty might have on mechanisms of feature selection. Theoretically, augmented task demands should place a greater burden on the capacity-limited executive control system, hypothesized to mediate selective attention. Competition for limited resources for the coordination of top-down control may lead to reduced efficiency of feature selection, perhaps shifting from a self-

terminating to an exhaustive approach. Because subjects with average EC, especially those in the old age group, may already be operating closer to the limits of their capacity, we expected the impact of increased task difficulty to be more pronounced in these subjects.

In summary, several models describe how feature selection processes may be executed, leading to predictions about the results from the current investigation. The study was designed to determine the impact of EC, age, and task difficulty on mechanisms of feature selection; in particular whether processing is exhaustive or self-terminating. The current study adds to the findings of Smid and Heinze (1997) and expands our understanding of what factors may be important for how task-directed processing of multidimensional stimulus features is carried out.

2. Methods

2.1 Participants

Recruitment of subjects took place through community announcements in the Boston metropolitan area, including the Harvard Cooperative Study on Aging. All subjects underwent informed consent approved by the Partners Human Research Committee and a detailed screening evaluation that included a structured interview to obtain a medical, neurological, and psychiatric history; a formal neurological examination; a neuropsychological test battery; and questionnaires surveying mood, activity, and socioeconomic status.

To be included in this study, participants had to be between the ages of 18 and 32 or 65 and 79, be English-speaking, have 12 years of education, have a Mini Mental State Exam (MMSE) (Folstein, Folstein, & McHugh, 1975) score 26, and an estimated Intelligence Quotient (IQ) on the American Modification of the National Adult Reading Test (AMNART) (Ryan & Paolo, 1992) 100. Subjects were excluded if they had a history of CNS diseases or major psychiatric disorders based on DSM-IV criteria (American Psychiatric Association, 1994), focal abnormalities on neurological examination consistent with a CNS lesion, a history of clinically significant medical or audiological diseases, corrected visual acuity worse than 20/40 (as tested using a Snellen wall chart), a Beck Depression Inventory (Beck & Steer, 1987) score 10 (for Young subjects) or a Geriatric Depression Scale (Yesavage et al., 1983) score 10 (for Old subjects), or were unable to distinguish between the color red and blue. Subjects were paid for their time.

A special effort was made to minimize group differences in cognitive abilities and task performance in order to appropriately interpret age-related changes in neural activity. Otherwise, observed differences between groups could be due not to age, but to other factors (Alperin et al., 2013; Daffner et al., 2011b; Daselaar & Cabeza, 2005; Riis et al., 2008). Because of the strong evidence that selective attention reflects top-down control mechanisms (de Fockert et al., 2001; Gazzaley et al., 2008; Rissman, Gazzaley, & D'Esposito, 2009; Zanto, Rubens, Thangavel, & Gazzaley, 2011), age groups were matched in terms of EC. Although there is no universally accepted operational definition of executive functions, we adopted the position of many investigators who emphasize processes that include working memory, initiation, monitoring, and inhibition, and advocate the use of at

least several neuropsychological tests to assess this complex group of functions (Chan, Shum, Touloupoulou, & Chen, 2008; Delis, Kaplan, & Kramer, 2001; Spreen & Strauss, 1998). We selected tests that had well established norms across a wide range of ages. Tests of EC included: 1) Digit Span Backward subtest of the Wechsler Adult Intelligence Scale-IV (WAIS-IV) (Wechsler, 2008), which measures maintenance and manipulation operations of working memory; 2) Controlled Oral Word Association Test (COWAT) (Ivnik, Malec, Smith, Tangalos, & Petersen, 1996), which indexes initiation, self-generation, and monitoring; 3) WAIS-IV Letter-Number Sequencing, which assesses maintenance, monitoring, and manipulation; 4) WAIS-IV Digit-Symbol Coding, which assesses sustained attention/persistence, cognitive speed, and efficiency; 5) Trail-Making Test Parts A and B (Reitan & Wolfson, 1985), which measures planning/sequencing, set shifting, and inhibition.

Performance across these tests was averaged to create a composite score of EC, which was used to match the age groups. Consistent with suggestions in the literature on aging, the groups were matched according to percentile scores relative to age-appropriate norms rather than raw scores (Daffner et al., 2007; Daffner et al., 2006; Daselaar & Cabeza, 2005; Riis et al., 2008). Our previous work (Daffner et al., 2006; Riis et al., 2008) indicates that age-related changes in information processing, as measured by ERPs, differ between individuals with high and average capacity, suggesting that these groups need to be analyzed separately. Therefore, we split our Young and Old subjects into high and average EC groups. Those subjects designated as high EC had a neuropsychological score in the top third (> 67th percentile) as defined by age-matched norms. Those subjects designated as average EC had a neuropsychological score in the middle third (33rd to 66th percentile), as defined by age-matched norms. Subjects who scored in the bottom third (< 33rd percentile) on neuropsychological tests were not included in this study to help exclude subjects who may be suffering from mild cognitive impairment or very early dementia.

A total of 55 subjects were included in this study. See Table 2 for a summary of subject characteristics. The young group consisted of 26 subjects between ages 19 and 29, 13 of whom had high EC and 13 of whom had average EC. The old group consisted of 29 subjects between ages 65 and 79, 15 of whom had high EC and 14 of whom had average EC. Additionally, one young subject was excluded from participating in the ERP experiment because of neuropsychological test scores below the 33rd percentile. Another 2 Young-High (YH), 2 Young-Average (YA), 3 Old-High (OH), and 2 Old-Average (OA) subjects participated in the experiment but were excluded due to excessively noisy ERP data. Behavioral data was not obtained for 1 Young-High subject due to technical issues.

2.2 Experimental Procedure

The experiment consisted of a color-selective attention task in which subjects were shown a series of letters presented in either the color red or the color blue, and were asked to respond by button press to specific target letters. In the low load task, subjects were required to respond by button press to one specific target letter, either S or N. Under the high load, subjects were required to respond to multiple target letters, which included either K, Q, X, A, and T (set 1), or W, G, Z, E, and V (set 2). Old subjects responded to the first 4 letters of either set; young subjects responded to all 5 letters. Half the subjects were presented one set

of target letters and half the other set, which was counterbalanced. Standard stimuli were any of the remaining letters of the alphabet.

Task demands were made easier for old subjects in order to minimize group differences in performance (Haring et al., 2013). In this way, differences in neural activity were more likely to be due to differences in age and not performance. The number of target letters chosen for each age group was based on pilot data. Letters that were used as targets under one task load were not used as standards under the other task load. Subjects were instructed to pay attention to letters appearing in the designated color while ignoring letters appearing in the other color, and to respond by button press to target letters appearing in the designated color only. Subjects were asked to respond as quickly and as accurately as possible to target letters. No instructions were provided regarding potential strategies for improving task performance. Practice trials preceded each set of experimental trials. The hand used for the target response was counterbalanced across subjects, as was the attended color.

Each task included 800 stimulus trials divided into 8 blocks. Stimuli appeared one at a time within a fixation box that remained on the screen at all times and subtended a visual angle of $\sim 3.5^\circ \times 3.5^\circ$ at the center of a high-resolution computer monitor. Half of the stimuli appeared in the color red and half in the color blue, in randomized order. Target stimuli (7.5% in attend color; 7.5% in ignore color) were designated upper case letters. Standard stimuli (70% overall; 35% in each color) were any non-target upper case letters. Fillers accounted for the remainder of the stimuli presented. Visual stimuli subtended an angle of 2.5° along their longest dimension and were presented for 250 ms. The inter-stimulus interval (ISI) varied randomly between 815-1015 ms (mean ~ 915 ms) (see Figure 1). For analytic purposes, trials were further categorized in terms of whether the stimuli presented were in the attend or the ignore color. The attend condition consisted of all stimuli in the designated color; the ignore condition consisted of all stimuli in the non-designated color.

2.3 ERP Recordings

An ActiveTwo electrode cap (Behavioral Brain Sciences Center, Birmingham, UK) was used to hold to the scalp a full array of 128 Ag-AgCl BioSemi (Amsterdam, The Netherlands) “active” electrodes whose locations were based on a pre-configured montage. Electrodes were arranged in equidistant concentric circles from the 10-20 position Cz. In addition to the 128 electrodes on the scalp, 6 mini bio-potential electrodes were placed over the left and right mastoid, beneath each eye, and next to the outer canthi of the eyes to check for eye blinks as well as vertical and horizontal eye movements. EEG activity was digitized at a sampling rate of 512 Hz.

2.4 Data Analysis

Demographic variables and overall percentile performance on the neuropsychological tests for the four groups (YH, YA, OH, OA) were compared using ANOVAs. We measured mean reaction time (RT) and accuracy rates. A response was considered a hit if it occurred 200-1000 ms after stimulus presentation. Target hits were defined as target stimuli correctly responded to, while false alarms were defined as stimuli incorrectly identified as targets. Accuracy was calculated as percent target hits – percent false alarms.

EEG data were analyzed using ERPLAB (Lopez-Calderon & Luck, 2014; www.erpinfo.org/erplab) and EEGLAB (Delorme & Makeig, 2004; <http://sccn.ucsd.edu/eeglab>) toolboxes that operate within the MATLAB framework. Raw EEG data were resampled to 256 Hz and referenced off-line to the algebraic average of the right and left mastoids. EEG signals were filtered using an IIR filter with a bandwidth of .03-40 Hz (12 dB/octave roll-off). Eye artifacts were removed through an independent component analysis. Individual bad channels were corrected with the EEGLAB interpolation function. EEG epochs for the two stimulus types (standard and target) across two attention conditions (attend and ignore) were averaged separately. The sampling epoch for each trial lasted for 1200 ms, including a 200 ms pre-stimulus period that was used to baseline correct the ERP epochs. Trials were discarded from the analyses if they contained baseline drift or movement artifacts greater than 90 μ V. Only trials with correct responses were included in the analyses.

ROIs across the scalp were designated and labeled Centro-Frontal (CF), Left Anterior Lateral (LAL), Right Anterior Lateral (RAL), Left Anterior Medial (LAM), Right Anterior Medial (RAM), Left Posterior Medial (LPM), Right Posterior Medial (RPM), Left Occipito-Temporal (LOT), Right Occipito-Temporal (ROT), and Centro-Occipital (CO). Each region reflected an averaged cluster of seven electrode sites. The latency of the SN was measured as the local negative peak latency for the target – standard difference wave (SN_{Letter}) and the attend – ignore difference wave (SN_{Color}) between 200 and 400 ms. Consistent with other studies on the SN (Daffner et al., 2012b; Hillyard & Anllo-Vento, 1998; Smid & Heinze, 1997), we measured activity in occipito-temporal regions, focusing on ROIs LOT and ROT. The mean local peak latency of the SN_{Color} and SN_{Letter} were analyzed in two separate ANOVAs with between-subjects factors of age group and EC, and within-subjects factors of load and stimulus type (for the SN_{Color}) or condition (for the SN_{Letter}). Because mean amplitude is not biased by increases in noise (Luck, 2005), mean rather than peak amplitude was measured to handle the differing numbers of trials expected between target and standard stimuli. The amplitude of the SN was derived from the mean amplitude of the 50 ms interval centered at the mean local peak latency for each of the four groups, with peak latency averaged across factors that were not significantly different. The latency values used to determine the measurement windows for calculating the mean SN amplitudes are presented in Table 3.

ERP latencies and mean amplitudes for the SN_{Letter} and SN_{Color} were analyzed using ANOVA, with condition (for the SN_{Letter}) or stimulus type (for the SN_{Color}), memory load, and ROI as within-subject variables, and age group and EC as between-subject variables. The Greenhouse-Geisser correction was applied for all ANOVAs with greater than 1 degree of freedom.

3. Results

3.1 Behavior

Accuracy and mean RT data are presented in Table 4. A 2-load (low vs. high) $\times$ 2-age group (young vs. old) $\times$ 2-EC (high vs. average) ANOVA was run on accuracy and mean RT, separately. For accuracy, there were effects of EC, $F(1,50) = 4.32$, $p = .04$, load, $F(1,50) = 62.51$, $p < .001$, and a load $\times$ EC interaction, $F(1,50) = 8.79$, $p = .005$. The EC effect was

such that high subjects were more accurate than average subjects. The effect of load was such that accuracy was higher under low load than high load. The load $\times$ EC interaction was due to an effect of EC under high, $F(1,50) = 7.42$, $p = .009$, but not low, $F(1,50) < .001$, $p = .99$, load.

For mean RT, there were effects of EC, $F(1,50) = 4.14$, $p = .05$, age group, $F(1,50) = 6.79$, $p = .01$, and load, $F(1,50) = 262.55$, $p < .001$. The age group effect was due to young subjects being faster than old subjects. The EC effect was due to high capacity subjects being faster than average capacity subjects. The load effect was due to RTs being shorter under low load than high load.

3.2 ERP Results

Visual inspection of the waveforms (see Figure 2) and one-sample t tests revealed that there was no reliable SN_{Letter} in the right hemisphere (ROI ROT), which is not surprising, given the left hemisphere's specialization for processing language (Friederici, 2011). Therefore, analysis of the SN_{Letter} was limited to the left hemisphere, at ROI LOT, and all comparisons between the SN_{Letter} and SN_{Color} were confined to ROI LOT.²

3.2.1 Mean Amplitude—The following analyses allowed us to test whether stimulus feature processing operated according to an exhaustive or a self-terminating model. To distinguish between these models, the size of the SN_{Letter} under the attend color condition must be compared to the size of the SN_{Letter} under the ignore color condition, and the size of the SN_{Color} in response to target letters must be compared to the size of the SN_{Color} in response to standard letters. As noted in the Introduction, the data would be best explained by the self-terminating model if the SN_{Letter} were reduced in size under the ignore condition, and the SN_{Color} were reduced in size in response to standards. The data would be best explained by an exhaustive model if the size of the SN_{Letter} and SN_{Color} were invariant across condition or stimulus type. Analyzing the size of the SN_{Letter} and SN_{Color} in separate ANOVAs allowed us to directly compare the attend condition to the ignore condition for the SN_{Letter} , and compare targets to standards for the SN_{Color} . Only significant results are reported unless of particular relevance to the goals of the study. See Figure 2 for plots of the SN_{Letter} and SN_{Color} and Figure 3 for plots of the averaged waveforms.

3.2.1.1 SN_{Letter} Mean Amplitude: Figure 4 depicts bar graphs illustrating the difference in the size of the SN_{Letter} between attend and ignore conditions for each of the different groups. A 2-age group (young vs. old) by 2-EC (high vs. average) by 2-condition (attend vs. ignore) by 2-memory load (low vs. high) ANOVA was run. This revealed no effect of age group, $F(1,51) = 1.80$, $p = .19$, an effect of EC, $F(1,51) = 10.52$, $p = .002$, a marginal effect of load, $F(1,51) = 3.16$, $p = .08$, and a condition $\times$ EC interaction, $F(1,51) = 5.67$, $p = .02$. The effect of EC was due to subjects with high EC generating a larger SN_{Letter} than subjects with average EC. The load effect was due to a trend toward the SN_{Letter} being smaller under high load than low load. The interaction of condition and EC was explained by high EC subjects

²Visual inspection of the waveforms suggested that the SN_{Letter} was not reliably generated in the right hemisphere. One-sample t tests were conducted on the SN_{Letter} at ROI ROT. Across subjects, the SN_{Letter} was never reliably different from zero in the right hemisphere (all p 's $> .20$). These results are consistent with the specialization of the left hemisphere for linguistic/word processing.

having a condition effect such that attend was larger than ignore, $F(1,26) = 5.36$, $p = .03$, while average EC subjects had no effect of condition, $F(1,25) = 1.16$, $p = .29$. In summary, subjects with high EC had a larger SN_{Letter} under attend than ignore, while subjects with average EC had no difference between the attend and ignore conditions in the size of their SN_{Letter} .³

3.2.1.2 SN_{Color} Mean Amplitude: A 2-age group (young vs. old) by 2-EC (high vs. average) by 2-stimulus type (targets vs. standards) by 2-load (low vs. high) by 2-hemisphere (LOT vs. ROT) ANOVA was run. There was no effect of age group, $F(1,51) = 1.65$, $p = .21$, EC, $F(1,51) = 0.97$, $p = .33$, or stimulus type, $F(1,51) = 0.24$, $p = .63$. There was an effect of memory load, $F(1,51) = 7.38$, $p = .009$, and of hemisphere, $F(1,51) = 9.09$, $p = .004$. There was a 2-way interaction between load and age group, $F(1,51) = 9.95$, $p = .003$, and a 3-way interaction between EC, stimulus type, and hemisphere, $F(1,51) = 7.63$, $p = .008$. The memory load effect was due to the SN_{Color} being larger under high memory load. The load $\times$ age group interaction was due to the SN_{Color} being larger under high, rather than low, memory load for young subjects, $F(1,24) = 12.58$, $p = .002$, with no difference between loads for old subjects, $F(1,27) = .14$, $p = .71$. The hemisphere effect was present because the SN_{Color} was larger at ROI LOT than ROT. Follow-up analyses to understand the interaction between EC, stimulus type, and hemisphere revealed that subjects with high EC demonstrated an interaction between hemisphere and stimulus type, $F(1,26) = 11.56$, $p = .002$, whereas subjects with average EC did not ($p = .54$). For high EC subjects, there was a robust hemisphere effect, $F(1,26) = 2.98$, $p = .009$, due to the amplitude of the SN_{Color} being much larger at LOT than ROT. The hemisphere effect was modified by stimulus type such that the magnitude was greater for target, $F(1,51) = 7.78$, $p = .007$, than standard, $F(1,51) = 6.28$, $p = .015$, stimuli. In contrast, average EC subjects did not exhibit reliable differences in the size of the SN_{Color} between left and right hemisphere regions ($p = .18$), a finding that was not modified by stimulus type (no hemisphere $\times$ stimulus type interaction). The most noteworthy findings here are that for subjects with high EC, color selection, as indexed by the SN_{Color} , was strongly modulated by the processing of letter characteristics, with size of the response being larger to targets than standards, and in the left hemisphere compared to the right hemisphere, a pattern that was not observed in subjects with average EC. See Figure 4 for bar graphs illustrating the difference in the size of the SN_{Color} between attend and ignore conditions at ROI LOT.

3.2.1.3 Re-analyzing With High And Low Accuracy Groups: In order to understand whether self-terminating versus exhaustive feature selection differentially impacted accuracy on the task, subjects were divided into high and low performance groups based on median accuracy collapsed across load and age/EC groups. ANOVAs on the size of the SN_{Letter} and SN_{Color} were re-run using the high or low accuracy group as a between-subjects

⁴We also investigated whether feature selection processes impacted mean RT. Subjects were divided into fast and slow groups based on the median value of the RT collapsed across, age, load, and EC. ANOVAs on the size of the SN_{Letter} and SN_{Color} were re-run using the fast or slow RT group as a between-subjects variable in place of high or average EC. Of interest was whether effects of condition or stimulus type would be modulated by RT group. For the SN_{Letter} , there was no interaction of condition and RT group, $F(1,50) = 1.21$, $p = .28$. Similarly, for the SN_{Color} , there was no interaction of stimulus type and RT group, $F(1,50) = .02$, $p = .90$. In summary, the particular method by which features were selected for processing did not appear to impact on the speed of a subject's reaction.

variable in place of high or average EC. Of particular interest was whether effects of condition or stimulus type were impacted by accuracy group. For the SN_{Letter} , there was an accuracy group $\times$ condition interaction, $F(1,50) = 4.16$, $p < .05$. This was due to a trend toward an effect of condition for the high accuracy group, $F(1,27) = 3.73$, $p = .06$, such that the size of the SN_{Letter} was larger under attend than ignore, while there was no effect of condition for the low accuracy group, $F(1,23) = .90$, $p = .35$. For the SN_{Color} , there was an accuracy group $\times$ stimulus type interaction, $F(1,50) = 4.69$, $p = .04$, due to a trend toward an effect of stimulus type for the high accuracy group, $F(1,27) = 3.24$, $p = .08$, such that the SN_{Color} was larger to targets than standards, with no effect of stimulus type for the low accuracy group, $F(1,23) = 1.76$, $p = .20$. These results are suggestive that subjects who utilize a self-terminating as opposed to an exhaustive strategy (i.e., reduced processing of standards or of stimuli in the ignore color) achieve higher accuracy on the task. A similar procedure reanalyzing the data using RT (shorter vs. longer) yielded no significant findings.

4

3.2.2 Peak Latency—The main interest in the following analyses was to investigate differences in peak latency between the SN_{Color} and the SN_{Letter} by comparing the latencies of the two difference waves directly to each other. The absence of latency differences between the two types of SNs would rule out a serial processing model. We also sought to determine if there were age-associated changes in the peak latency of the difference waves. Because the SN_{Color} includes a stimulus type level (standards vs. targets), whereas the SN_{Letter} includes a condition level (attend vs. ignore), it was not possible to directly compare the two difference waves in one ANOVA with all levels. Therefore, four ANOVAs, 2-difference wave (Letter vs. Color) $\times$ 2-load (low vs. high) $\times$ 2-age group (young vs. old) $\times$ 2-EC (high vs. average), were run to compare each of the four possible combinations of the two difference waves (SN_{Letter} under attend vs. SN_{Color} to targets, SN_{Letter} under attend vs. SN_{Color} to standards, SN_{Letter} under ignore vs. SN_{Color} to targets, and SN_{Letter} under ignore vs. SN_{Color} to standards). In this way, we were able to assess whether there were reliable latency differences between the SN_{Color} and SN_{Letter} . Only main effects of, or interactions with, the difference wave level (SN_{Letter} vs. SN_{Color}) are reported here, as these are pertinent to the goals of the analyses. See Table 5 for a summary of all main effects and interactions.

When comparing the SN_{Letter} under the attend condition to the SN_{Color} to standards, there was a difference wave $\times$ age group interaction, $F(1,51) = 9.70$, $p = .003$. This was explained by the SN_{Letter} peaking later than the SN_{Color} for old subjects, $F(1,27) = 10.38$, $p = .003$, but not young subjects, $F(1,24) = 1.53$, $p = .23$. This interaction could also be explained by an age group effect on the peak latency of the SN_{Letter} under attend, $F(1,51) = 18.26$, $p < .001$, such that old subjects peaked later than young subjects, but not for the peak latency of the SN_{Color} to standards, $F(1,51) = .09$, $p = .77$.

When comparing the SN_{Letter} under attend to the SN_{Color} to targets, there was a main effect of difference wave, $F(1,51) = 6.20$, $p = .02$, and interactions between difference wave and EC, $F(1,51) = 6.34$, $p = .02$, and difference wave and load, $F(1,51) = 6.63$, $p = .01$. The effect of difference wave was such that the SN_{Letter} was later than the SN_{Color} . However, this effect was strongly influenced by EC. The SN_{Letter} was later than the SN_{Color} for subjects with high EC, $F(1,26) = 11.27$, $p = .002$, but not subjects with average EC, $F(1,25)$

$<.001$, $p = .98$. The difference wave $\times$ load interaction was due to the SN_{Letter} being later than the SN_{Color} under high memory load, $F(1,51) = 8.36$, $p = .006$, but not low memory load, $F(1,51) = .22$, $p = .64$.

When comparing the SN_{Letter} under ignore to the SN_{Color} to standards, there was an effect of difference wave, $F(1,51) = 5.92$, $p = .02$, a difference wave $\times$ age group interaction, $F(1,51) = 10.72$, $p = .002$, and a difference wave $\times$ load $\times$ EC interaction, $F(1,51) = 4.76$, $p = .03$. The effect of difference wave was such that the SN_{Letter} was later than the SN_{Color} . This was modulated by age group such that the SN_{Letter} was later than the SN_{Color} for old subjects, $F(1,27) = 16.21$, $p < .001$, but not young subjects, $F(1,24) = .36$, $p = .55$. The interaction between difference wave and age group can also be explained by the effect of age group on the peak latency of the SN_{Letter} under ignore, $F(1,51) = 11.68$, $p = .001$, such that old subjects peaked later than young subjects, but no effect of age group on the peak latency of the SN_{Color} to standards, $F(1,51) = .09$, $p = .77$, was shown. The difference wave $\times$ load $\times$ EC interaction was due to a difference wave $\times$ EC interaction under high memory load only, $F(1,51) = 5.34$, $p = .03$, with the SN_{Letter} being later than the SN_{Color} for subjects with high EC, $F(1,26) = 7.49$, $p = .01$, but not average EC, $F(1,25) = .45$, $p = .51$. Finally, in comparing the SN_{Letter} under ignore to the SN_{Color} to targets, an effect of difference wave was revealed, $F(1,51) = 7.55$, $p = .008$, such that the SN_{Letter} was later than the SN_{Color} .

In summary, the high EC group reliably generated an SN_{Letter} that peaked later than their SN_{Color} . The average EC group was less consistent. In some cases, the two components did not have different peak latencies, and in other cases the SN_{Letter} was later than the SN_{Color} . The SN_{Letter} peaked later for old than young subjects under both the attend and ignore conditions. There were no age-related differences in the peak latency of the SN_{Color} .

4. Discussion

This study focused on one circumscribed but important aspect of target identification: multidimensional feature selection. There are several theories about how multiple task-relevant stimulus features may be selected for processing in order to identify targets. While self-terminating models posit that stimulus processing may cease after one feature dimension has been found not to match the target properties, exhaustive processing models suggest all feature dimensions may be fully processed regardless of the target-matching status of any individual feature (Smid et al., 1997; Zehetleitner et al., 2008). In addition, serial processing models suggest that feature dimensions are assessed one after the other (Dick & Dick, 1969; Egeth, 1966; Sternberg, 1969), while parallel models counter that different feature dimensions are processed simultaneously (Hansen & Hillyard, 1983). It was unclear whether age and varying EC would impact on the way stimulus features are selected for processing.

We found that EC was an important determinant for how stimulus features were processed. Only high EC subjects exhibited processing in accordance with self-termination, reducing the appropriation of resources to one feature dimension if another feature was target-negative. This was evidenced by high EC subjects generating a smaller SN_{Letter} under the ignore condition than the attend condition, and a smaller SN_{Color} to standards than targets.

Average EC subjects exhibited no difference in the size of the SN_{Letter} between conditions, or the size of the SN_{Color} between stimulus types, in accordance with an exhaustive processing model. Thus, the EC of subjects strongly influenced whether multidimensional feature selection conformed to self-terminating or exhaustive processing models. Results from previous studies, (Desimone & Duncan, 1995; Gazzaley & D'Esposito, 2007b; Lavie et al., 2004; Rutman et al., 2010; Vogel et al., 2005) would suggest that the impact of EC is mediated by differences in top-down control over early selection processes. It is unclear whether EC also influences conscious strategies utilized by subjects to improve task performance. Future studies should explore this idea further, possibly through the use of structured post-experiment interviews.

We also found that in response to letters presented in color, high EC subjects generated an asymmetric SN_{Color} (left > right), whereas average EC subjects did not exhibit a lateralized response. These results provide additional evidence that in contrast to average EC subjects, those with high EC utilize letter feature processing, mediated by the left hemisphere, to modify color processing in a manner that conforms to a self-terminating feature selection model. These results also may have implications for theories of cognitive aging that emphasize an age-associated reduction in asymmetric neural activity (Cabeza, 2002). Our study raises the possibility that observed age-related declines in neural asymmetry may be due, in part, to samples of older adults who have lower EC. However, much more research is needed to test this conjecture.

To distinguish between serial and parallel processing, the peak latencies of the SN_{Letter} and SN_{Color} were compared. A failure to find significant differences in the peak latencies of the two components would exclude serial processing models. However, if the SN_{Letter} and SN_{Color} peaked at different times, it would not preclude the possibility of temporal overlap between the processing indexed by the two components. For the high EC subjects, the SN_{Letter} consistently peaked later than the SN_{Color} . As noted, this result cannot clearly distinguish between serial and parallel processing. However, because these subjects generated an ERP pattern consistent with a self-terminating processing model, there was an alternative way to distinguish between serial and parallel self-terminating models. In the serial self-terminating case, one would expect no SN_{Letter} to be generated when the stimulus was presented in the ignore color. Visual inspection of the waveforms (Figure 2a) as well as the results of one-sample t tests, as summarized in footnote 3, show that both young and old subjects with high EC generated a reliable SN_{Letter} under the ignore condition (although smaller than that observed under the attend condition). Taken together, the data for subjects with high EC are most consistent with a parallel self-terminating model.

In contrast, the amplitudes of the SN_{Letter} and SN_{Color} generated by the average EC group were more consistent with an exhaustive processing model. In this case, the most appropriate way to distinguish between serial exhaustive and parallel exhaustive processing is to examine the SN latency data. The SN peak latency results for the average EC group were not uniform. When comparing the SN_{Letter} under the attend condition to the SN_{Color} to either stimulus type, the components did not peak at different times. In addition, under the high memory load task, the SN_{Letter} under ignore did not peak at a different time than the SN_{Color} to standard stimuli. These results are consistent with parallel processing models and

exclude the possibility of serial processing. However, the SN_{Letter} under ignore peaked later than the SN_{Color} to target stimuli under both memory loads and the SN_{Color} to standard stimuli under low memory load. These results do not allow one to draw definitive inferences about whether there is temporal overlap between processing the features of color and letter-form. We conclude that under certain circumstances the average EC group performs parallel exhaustive feature selection, but not necessarily in a consistent manner.

Self-terminating feature selection was associated with higher accuracy, as suggested by the ANOVAs that included a variable indexing high vs. low accuracy. Why self-terminating selection did not also decrease RT is unclear. Nonetheless, this method of feature selection appears to be more effective than exhaustive processing and facilitates a reduction of stimulus feature processing if one feature dimension has yielded results that are inconsistent with a target stimulus. Of note, high EC was linked not only with a parallel self-terminating approach to multi-feature selection, but also with stronger early selection of target letter-forms themselves, as indexed by a larger SN_{Letter} . In contrast, EC did not modulate the seemingly less challenging task of color selection, as indexed by the SN_{Color} , consistent with prior work that focused on young adult subjects (Daffner et al., 2012a). We suspect that executive control operations affecting the size of the SN may be recruited to manage more demanding aspects of feature selection. Future studies that systematically vary task demands are needed to explore the experimental factors that are likely to more fully engage executive control operations in the service of feature selection.

We did not find that the load effect was modulated by EC as we had predicted. It is possible that the high load version of the task was not sufficiently difficult to elicit differences between subjects with high and average EC. However, task load did have differential effects on letter and color processing. As task difficulty increased, there was enhanced engagement of color selection mechanisms, as measured by a larger SN_{Color} , and somewhat diminished execution of early selection of target letter features, as indexed by a marginal decline in the size of the SN_{Letter} . These findings may suggest an increased reliance on color processing to support correct response selection, perhaps related to the increase in the size of the set of target letters, making it more difficult to discriminate between targets and standard stimuli. This situation may lead to increased reliance on the easier task of color discrimination in order to more quickly eliminate stimuli as potential targets. We also found that increasing load resulted in longer RTs, which may reflect the impact of task demands on processing stages that include not only early selection, but also post-selection decision making and response execution (Tollner, Rangelov, & Muller, 2012; Wiegand, Finke, Muller, & Tollner, 2013). It is important to note that task difficulty was augmented by adding more target letters for the subject to remember. This expanded the number of letter-form features that a subject had to hold in mind, but not the number of colors. Increasing task difficulty along a particular feature dimension (in this case, letter-forms) may partially deplete selection resources operating on that dimension, leading to a reduction in the size of the applicable SN component. Future research should manipulate task difficulty along the dimension of color to determine its impact on multidimensional feature selection.

Contrary to expectation, the study's main result (that EC plays a major role in mediating multidimensional feature selection) was not modulated by age. Thus, within the high and

average executive control groups, young and old subjects exhibited very similar patterns of letter and color processing, as measured by the SN components. These findings suggest that the level of efficiency with which individuals coordinate feature selection remains relatively stable over the lifespan. A longitudinal study would be the most appropriate way to confirm this hypothesis. Results from our study underscore the importance of explicitly measuring EC in investigations of changes associated with cognitive aging, which is not often done (Castel, Farb, & Craik, 2007; Czigler, 1996; de Fockert et al., 2009; Hommel, Kray, & Lindenberger, 2011; Kenemans et al., 1995). This information would allow researchers to address questions about the extent to which differences between groups are due to variations in EC rather than age alone.

There are other reports in the aging literature suggesting that if investigators account for individual differences in functions like working memory, there is a reduction in age-related differences in the pattern of neural activity (Daffner et al., 2011a; Schneider-Garces et al., 2010). At certain levels of task demand, there is a greater similarity between high capacity old and young subjects than between high and low capacity old subjects. However, even theories of cognitive aging that emphasize the explanatory power of accounting for individual differences in processing capacity (e.g., Reuter-Lorenz & Cappell, 2008), suggest that high capacity old adults are less efficient than their high capacity younger counterparts. Thus, as task load increases, old subjects are likely to deplete their cognitive resources for efficiently managing feature selection at a lower level of demand than young subjects. We suspect that our high load task was not difficult enough to test this hypothesis; future studies would benefit from augmenting task demands to explore whether high EC subjects will shift from parallel self-terminating feature selection to a less efficient exhaustive or serial approach. We would expect that the level of task demand at which a shift in feature selection may occur would be lower for old subjects with high EC than for young subjects with high EC.

Our prediction about age-related slowing of feature selection was validated for the SN_{Letter}. Although altered processing speed did not appear to change the critical mechanisms underlying early feature selection, such slowing may have downstream effects by causing the delivery of suboptimal information for later stages of processing. In a previous paper (Alperin et al., 2013), older individuals who were slow to initiate early selection appeared to be less successful at executing late selection/decision making.

There are a number of potential challenges to our interpretation of the data. One concern involves the possible impact of the difference between the target stimuli included in the analyses and all other stimuli on the ERP results. Target stimuli differ from the other stimulus types by eliciting a process involving target identification and response execution. Research on the SN component has a long history of comparing stimuli with differential response demands (Hansen & Hillyard, 1983; McGinnis & Keil, 2011; Smid & Heinze, 1997; Woods & Alain, 2001). However, it remains an open question whether the differences in the SN between high and average EC subjects observed in the current study were driven by processing related to target identification or motor output, and not feature selection. There are several reasons we believe this interpretation is unlikely. First, the occipito-temporal regions at which the SN components were measured are not areas known to reflect

the programming of motor output (Grill-Spector & Malach, 2004). More importantly, studies have compared the ERP response to stimuli that contain two out of three target features to stimuli that include a third (target-relevant) feature indicating a behavioral response needs to be made. Most of these studies have reported little to no difference in ERP response to these two stimulus types during the first 300 ms after stimulus presentation, which includes the period of the SN component (Anllo-Vento & Hillyard, 1996; Hillyard and Münte, 1984; Anllo-Vento, Luck, & Hillyard, 1998). Therefore, we think it unlikely that these limitations invalidate our findings. However, future studies should attempt to replicate our findings by including a stimulus type that has two requisite target dimensions (color and letter form) as well as a third feature (e.g., different font size or luminance) that signals the need to respond.

Another potential challenge to our formulation could be based on an alternative understanding of the functional significance of the SN. Although we have adopted the traditional view that the SN indexes mechanisms of early feature selection operating in the visual cortex, some researchers have interpreted the SN as a late selection process, reflecting the updating or scanning of memory (Kenemans et al., 1995; Zanto et al., 2010b). Although the current investigation cannot definitively answer questions surrounding the functional significance of the SN, our major findings cannot be dismissed and suggest that the neural processing indexed by this component in response to letter-forms and color is strongly modulated by EC.

In summary, our results indicate that subjects who exhibit higher executive functioning utilize a self-terminating feature selection process of color and letter-form, whereas subjects with lower executive functioning conform to an exhaustive approach. Executing feature selection according to the self-terminating model was associated with increased task accuracy. Subjects with high EC carry out feature selection in a parallel manner, while it is less clear whether subjects with average EC consistently do so. Higher EC was linked to enhanced early selection of target letter-forms. In addition, augmenting task difficulty by increasing the number of letter-forms to keep in mind may attenuate the differential response to target vs. non-target features. Mechanisms utilized for multidimensional feature selection appear to be consistent across the lifespan, although there is age-related slowing of processing speed for early selection of letter features. EC is a critical determinant for how multidimensional feature selection is carried out, and should therefore be carefully measured in future studies. It remains to be seen whether these findings are generalizable to other non-spatial features besides color and letter-forms.

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Highlights

Multidimensional feature selection assessed using different selection negativity ERPs

Impact of executive capacity (EC), age, and task difficulty examined

Average EC subjects used an exhaustive feature selection approach

High EC subjects exhibited much more efficient feature processing

The effect of EC not modulated by age; but processing was slower in older adults

Figure 1.
Illustration of an experimental run.

Figure 2.

SN_{Letter} and SN_{Color} grand average ERP difference waves under both memory loads at ROI LOT for **a)** Young-High (YH) and Old-High (OH) and **b)** Young-Average (YA) and Old-Average (OA) subject groups. Note that the time scale extends to 400 ms. The latest time point to which any measuring interval of the SN was extended was 355 ms.

Figure 3.

Grand average waveforms at ROI LOT showing the first 400 ms in response to target and standard stimuli under the attend and ignore conditions for the low and high load versions of the task, with **a)** displaying the high EC groups and **b)** displaying the average EC groups.

Figure 4.

Stacked bar graphs illustrating the size of the SN_{Letter} and SN_{Color} at ROI LOT under different conditions or stimulus types within each memory load, for all four groups. Note that for the high EC groups, the top color (attend/targets) is larger than the bottom color (ignore/standards), while this is not the case for the average EC groups.

Table 1

Model-Predicted ERP Results

Model	Amplitude Results	Latency Results
Serial Exhaustive	SN _{Color} same size to standards or targets SN _{Letter} same size under attend or ignore	SN _{Color} and SN _{Letter} have different peak latencies
Serial Self-Terminating	SN _{Color} same size to standards or targets No SN _{Letter} under ignore condition	SN _{Color} and SN _{Letter} have different peak latencies
Parallel Exhaustive	SN _{Color} same size to standards or targets SN _{Letter} same size under attend or ignore	SN _{Color} and SN _{Letter} may or may not differ in peak latency
Parallel Self-Terminating	SN _{Color} reduced in size to standards SN _{Letter} reduced in size to ignore	SN _{Color} and SN _{Letter} may or may not differ in peak latency

Table 2

Subject Characteristics (Mean (SD))

	Young-High	Young-Average	Old-High	Old-Average
Number of Subjects	13	13	15	14
Gender (female:male)	8:5	6:7	9:6	6:8
Age	22.54 (1.66)	22.62 (2.72)	73.93 (3.67)	71.64 (3.79)
Years of Education	15.88 (1.58)	14.42 (1.13)	16.47 (3.72)	15.89 (2.63)
AMNART (Estimated IQ) ^a	119.15 (4.63)	114.31 (7.67)	121.13 (8.53)	115.29 (10.41)
Executive Capacity (%ile) ^a	80.71 (8.20)	54.05 (11.46)	81.50 (7.54)	54.81 (9.20)
MMSE	29.92 (.28)	29.77 (.44)	29.53 (.74)	29.29 (.91)
BDI/GDS	4.15 (4.60)	5.38 (4.61)	2.733 (2.91)	3.00 (1.80)
Visual Acuity ^b	1.01 (0.18)	1.04 (0.20)	0.75 (0.17)	0.74 (0.14)

Note: AMNART = American National Adult Reading Test; Executive Capacity = average (composite) percentile performance relative to age-appropriate norms on the following tests: Digit Span Backward, Controlled Oral Word Association Test, Letter-Number Sequencing, Trail Making Test Parts A and B, and Digit-Symbol Coding; MMSE = Mini-Mental State Exam; BDI = Beck Depression Inventory; GDS = Geriatric Depression Scale.

^a Effect of executive capacity group, $p < .001$ (High > Average)

^b Effect of age group, $p < .001$ (Young > Old)

Table 3

Latency Values (in ms) Used To Determine The Temporal Intervals for Calculating SN Mean Amplitudes

SNLetter	SNColor							
	Attend		Ignore		Targets		Standards	
	Low Load	High Load	Low Load	High Load	Low load	High Load	Low Load	High Load
Young-High	265	330	280	325	270	290	270	290
Young-Average	265	330	300	325	270	315	270	315
Old-High	310	330	325	325	300	290	300	290
Old-Average	310	330	325	325	300	315	300	315

Note: The SN amplitude was calculated as the mean amplitude of the 50 ms interval centered at the peak latencies presented in the table.

Table 4

Accuracy and Mean RT (Mean (SD))

	Young-High	Young-Average	Old-High	Old-Average
Accuracy (%)				
Low Load	96.82 (5.96)	96.44 (2.99)	96.96 (2.63)	97.37 (3.15)
High Load	91.73 (7.32)	84.86 (6.29)	93.09 (4.97)	89.24 (9.54)
Mean RT (ms)				
Low Load	487 (38)	514 (53)	528 (63)	546 (62)
High Load	592 (40)	628 (57)	631 (59)	658 (59)

Table 5SN_{Letter} and SN_{Color} Peak Latency ANOVAs

Comparison:	SN _{Letter} Attend vs. SN _{Color} Standards		SN _{Letter} Attend vs. SN _{Color} Targets		SN _{Letter} Ignore vs. SN _{Color} Standards		SN _{Letter} Ignore vs. SN _{Color} Targets	
	F	p	F	p	F	p	F	p
EC	6.23	.02	10.14	.002	1.25	.27	7.17	.01
AG	0.08	.79	0.02	.89	0.93	.34	0.17	.69
L	0.03	.86	0.56	.46	3.72	.06	0.97	.33
EC × AG	1.89	.18	0.81	.37	0.85	.36	0.53	.47
L × EC	0.09	.76	0.68	.41	0.07	.80	0.63	.43
L × AG	0.50	.48	0.64	.43	1.71	.20	4.01	.05
L × EC × AG	0.58	.45	0.25	.62	0.07	.79	0.12	.74
DW	1.75	.19	6.20	.02	5.92	.02	7.55	.008
DW × EC	3.22	.08	6.34	.02	1.51	.22	1.50	.23
DW × AG	9.70	.003	3.18	.08	10.72	.002	1.22	.28
DW × L	0.12	.73	6.63	.01	0.73	.40	2.32	.13
DW × EC × AG	1.23	.27	3.33	.07	1.02	.32	1.40	.24
DW × L × EC	2.91	.09	2.88	.10	4.76	.03	3.02	.09
DW × L × AG	0.20	.66	0.27	.61	0.001	.97	0.009	.93
DW × L × EC × AG	0.71	.40	0.16	.68	0.23	.63	0.74	.39

Note: The ANOVAs included the factors difference wave (DW: SN_{Letter} or SN_{Color}), load (L: high or low), executive capacity (EC: high or average), and age group (AG: young or old). Degrees of freedom for all ANOVAs were 1,51. See text for a breakdown of significant interactions with and main effects of DW