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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.

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 and Duncan, 1995; Lavie et al., 2004; Rutman et al., 2010). Theoretically, selective attention improves processing efficiency and conserves resources of the capacity-limited decision making system (Awh and Jonides, 2001; de Fockert et al., 2001; Gazzaley et al., 2005; Zanto and Gazzaley, 2009). Individual differences in top-down control mechanisms vary as a function of executive capacity (EC) and age (de Fockert et al., 2009; Riis et al., 2008). There is evidence that individuals with lower EC or with advanced age exhibit sub-optimal mechanisms of selective attention (Gazzaley et al., 2005; Gazzaley and D'Esposito, 2007a; Haring et al., 2013; Vogel et al., 2005; Zanto et al., 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 et al., 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

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features can be reduced or inhibited (Hawkins, 1969; Zehetleitner et al., 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 and Deutsch, 1963; Norman, 1968; Zehetleitner et al., 2008). In addition, stimulus processing may be carried out in a serial (Egeth, 1966) or parallel (Hansen and 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 and Aine, 1984; Hillyard and Anllo-Vento, 1998; Kopp et al., 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 and Anllo-Vento, 1998; McGinnis and Keil, 2011) (but see Kenemans et al., 1995; Zanto et al., 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 and Anllo-Vento, 1998; Keil and Muller, 2010; Martin-Loeches et al., 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, 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 (1997) study did not address the potential impact of EC, age, or task difficulty, and to our knowledge, no further investigation of 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 and Anllo-Vento, 1998; Keil and 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 and 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