BEHAVIORAL AND NEURAL INVESTIGATIONS OF VALUE-DIRECTED STRATEGIC PROCESSING

BY

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DISSERTATION

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ABSTRACT

To effectively and efficiently process the vast amount of information we experience every day, we often selectively attend to information of higher value or importance and inhibit less valuable information, referred to as value-directed strategic processing in this dissertation. In daily life, we often ascribe value to information based on perceptual or conceptual features, but few, if any, studies have directly examined how such features affect value-directed strategic processing. Additionally, although there is emerging work on the structural and functional bases of value-directed strategic processing, no studies have examined the underlying neurophysiological mechanisms which could provide insights into how value-directed strategic processing neurally unfolds. This dissertation investigates the behavioral and neural effects of perceptually and conceptually defined value on value-directed strategic processing in cognitively normal younger and older adults, and older adults with mild cognitive impairment. Chapter 1 reviews historical perspectives and paradigms related to selective attention and behavioral and neuroimaging literature related to value-directed strategic processing. Chapter 2 explores the feasibility of using perceptually defined value for prompting value-directed strategic processing, and whether event-related spectral perturbations (ERSPs) can capture the underlying neurophysiological mechanisms of value-directed strategic processing. Chapter 3 examines whether behavioral and ERSP measures linked to value-directed strategic processing are affected by normal cognitive aging. Chapter 4 investigates whether neurological disorder, specifically mild cognitive impairment, results in behavioral and ERSP alterations related to value-directed strategic processing. Chapter 5 assesses whether defining value based on perceptual versus conceptual features has differential behavioral effects on value-directed strategic processing.

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CHAPTER 1: INTRODUCTION

The human brain is incredibly complex and has extraordinary processing capabilities. We are constantly exposed to vast quantities of information, and whether intentional or not, we only attend to some of this information based on the importance or value we ascribe to it depending on ‘extrinsic’ (e.g., perceptual features; context) and/or ‘intrinsic’ (e.g., personal relevance; goals and/or interests) cues. For example, when listening to and viewing a scientific talk, we may mostly attend to information that the speaker emphasizes in the visual illustration (e.g., bolded text) and/or to information important or relevant to our research, while paying less attention to information that is not emphasized and/or is tangential to our work. This preferential processing of information of higher importance or salience, or in other words value, while ignoring or inhibiting less important or salient information (for reviews see Castel, 2007, 2008) is referred to as value-directed strategic processing in this dissertation. Value-directed strategic processing is engaged during day-to-day activities, such as conversational interactions, reading, watching television, cooking, driving, or shopping, to avoid becoming inundated with information.

Value-directed strategic processing develops through childhood and into young adulthood (ages 5-23 years; e.g., Castel, Humphreys, et al., 2011; Hanten et al., 2007; for review see Stevens & Bavelier, 2012). This ability has been shown to play an important role in educational learning and academic success in younger populations (for review see Stevens & Bavelier, 2012). In older adulthood, despite normal age-related declines in cognitive functions such as attention and inhibition (e.g., Craik & Byrd, 1982; Hasher & Zacks, 1988; Hasher et al., 2007; Park et al., 1989), the ability to strategically process information of higher value or importance appears to remain relatively intact (Castel et al., 2002; Castel, Humphreys, et al., 2011; for review see Castel, 2007). How value-directed strategic processing is affected by age-related brain diseases and disorders is understudied, but a few studies suggest that strategic processing is impaired in older adults with dementia, namely Alzheimer's disease and behavioral variant frontotemporal dementia (Castel et al., 2009; Wong et al., 2018).

Much of the work on value-directed strategic processing comes from behavioral studies conducted using the value-directed remembering paradigm developed by Castel, Benjamin, & Craik (2002). More recently, studies on underlying neural mechanisms that support strategic processing have begun to emerge (Cohen et al., 2014; Cohen et al., 2016; Hennessee et al., 2019; Reggente et al., 2018). These neuroimaging studies have used functional magnetic resonance imaging (fMRI) and diffusion tensor imaging (DTI) to understand the functional and structural bases of value-directed strategic processing. However, to date, no studies have examined how this rapid cognitive process unfolds temporally using neurophysiological approaches such as electroencephalography (EEG).

The goals of my dissertation project are to (i) evaluate the neurophysiological basis of value-directed strategic processing in cognitively normal younger and older adults and in older adults with mild cognitive impairment, and (ii) explore how value-directed strategic processing is differentially affected in cognitively normal younger and older adults when value is manipulated by perceptual versus conceptual features of the stimuli. In this introductory chapter, I will discuss (i) historical perspectives that provide context for value-directed strategic processing, (ii) paradigms used to study selective attention and directed forgetting which provide a foundation for understanding the study of value-directed strategic processing, (iii) behavioral studies using the value-directed remembering paradigm across the lifespan and in clinical populations, and (iv) neuroimaging work conducted using the value-directed remembering paradigm in younger and older adults and the potential utility of EEG.

1.1. Historical perspective

Attention has long been considered a fundamental component in human cognition with an important role in shaping our experiences (James, 1890; Titchener, 1905). We are unable to process everything that takes place around us, so instead, we direct our awareness to process a subset of the information in accordance with our current goals to increase processing efficiency (Bjork, 1989). This mechanism of selecting a subset of information for processing is referred to as selective attention. Selective attention encompasses value-directed strategic processing, which is distinguished by the assignment of explicit values that guide the prioritization of processing and convey the relative importance for remembering the information. Thus, a historical perspective of the study of selective attention provides a framework for understanding value-directed strategic processing.

Much of the initial work on selective attention examined how individuals focused their attention on certain information as guided by the instructions/context (e.g., attend to the sound delivered to the right ear). This work was motivated by Colin Cherry's dichotic listening studies in the 1950s and later expanded into the visual domain in the 1960s. In a dichotic listening study, two auditory messages are presented simultaneously to the right and left ears, and participants are asked to attend to the message in one ear (right or left). Cherry (1953) found that participants could report the message in the attended ear but were often unable to report information from the unattended ear. He suggested that participants allocated attention to certain information while seemingly ignoring other information (for the most part), and this was termed the "cocktail party effect". In fact, participants often did not even notice if the speech stimuli in the unattended ear were reversed or in a foreign language (Cherry, 1953) or were repeated numerous times (Moray, 1959). However, Cherry (1953) found that participants tended to notice certain aspects of the message in the unattended ear, such as the sex of the speaker or the intensity of the message, suggesting that despite focusing much of their attention on processing information based on guided instructions, participants still processed some basic physical characteristics of the unattended message without deeper processing of the message.

This early work led to theoretical speculations about the processes involved in selective attention. Donald Broadbent (1958) proposed the filter model in which he stated that all stimuli that reach sensory systems are processed in parallel for physical characteristics (e.g., pitch, loudness, location). Based on the physical characteristics, some stimuli are allowed to pass through a selective filter for further processing of the message. Broadbent's model is considered an early selection model as the attentional filter excludes stimuli during the early stages of processing based on simple perceptual features before more elaborative processing occurs (e.g., word identity or meaning). This model solely emphasizes the influence of physical characteristics of the stimuli on selectivity and the separation of "important" (attended) from "unimportant" (unattended) information.

Anthony and Diana Deutsch (1963) were among the first to reject early selection models such as Broadbent's filter model, and instead suggested that an attentional filter is engaged in later stages of processing, referred to as a late selection model (Deutsch & Deutsch, 1963; Duncan, 1980; Mackay, 1973; Norman, 1968). More specifically, late selection models proposed that all stimuli are processed in parallel up until the stimuli have semantic labels or their semantic features are known. Only in this later stage of processing does an attentional filter exclude irrelevant information, which is not important for responding to tasks or goals, from further processing (e.g., working memory; for review see Serences & Kastner, 2014). Studies that seemed to demonstrate that unattended information was perceived beyond simple perceptual features were taken as support for late selection models (e.g., Corteen & Dunn, 1974; Lewis, 1970; Mackay, 1973). For example, Lewis (1970) showed that when participants had to repeat target words from the attended ear, their responses were slower when a semantically related word was presented in the unattended ear compared to an unrelated word. The late selection models suggest that whether the information is attended to or ignored is influenced by both perceptual and semantic features.

Taking elements from both early and late selection models, Anne Treisman proposed an attenuation model (1960, 1969) in which the attentional filter *attenuates* unattended information as opposed to completely blocking it out. Treisman's attenuation model was formulated based on others' work and her work showing that information presented to the unattended ear mostly could not be reported by participants, with the exception of certain information. Neville Moray (1959) demonstrated this in his study in which participants would notice when their own name was played in the unattended ear but not much else. Treisman (1960) played a different passage to each ear of the participant and asked them to repeat the message being played to one ear (attended ear) while ignoring the other ear (unattended ear). At some point, the passages switched which ear they were being presented to, but the participants were still only supposed to repeat the message played to the attended ear. Some of the participants repeated the message from the unattended ear (seeming to follow the passage), but this usually only lasted for a few words before they switched back to the attended ear. Thus, Treisman proposed that unattended information is less likely to go through more elaborative processing compared to attended information, but may be more fully processed based on context and intrinsic factors such as saliency (e.g., personal relevance).

The models discussed up to this point were largely based on work in the auditory domain, but Nilli Lavie attempted to reconcile early and late selection models based on her work in the visual domain. Lavie proposed a load theory (1995, 2005, 2010), which suggests that perceptual processing is only selective when a perceptual capacity limit is reached, meaning that whether early or late selection occurs is dependent on the demands of the task. If a task is sufficiently demanding or has a high perceptual load, then less important information is not processed (early selection). If a task is not sufficiently demanding or has low perceptual load, the remaining capacity is automatically allocated to processing the less important information (late selection), which could result in greater distraction and/or decreased efficiency for task completion. The perceptual load of a task can be modulated by the number of items that are being displayed, the perceptual similarity between items, and/or the processing requirements of the task (e.g., color versus color, shape, and position). Lavie's theory demonstrates that selective attention is engaged differently depending on the amount and type of information that is being presented, and thus the processes engaged may vary.

The models and theories presented up to this point have been supported by empirical studies that have used relatively simple stimuli, but selective attention can also be engaged during the processing of more complex information, as has been shown in literature on connected language processing. Within complex language processing literature, it has been shown that people attend to and remember main ideas or the information they deem important. The notion that people focus on the main ideas from a larger body of information was demonstrated in early work by Frederic Bartlett (1932) using the "War of the Ghosts" story where people focused on the most salient points from the story. Bartlett showed that the details from the story that were deemed important (e.g., someone was wounded and later died) were retained, whereas other details were left out, adjusted, or added based on a person's personal preference (e.g., omitting detail of 'hunting seals'; changing 'canoes' to 'boats'). This was an early demonstration of how people use their schemas and experiences ('intrinsic' value) to guide what to attend to versus what to ignore. The importance of extrinsic cues related to context for selectivity was demonstrated by John Bransford and Marcia Johnson (1972). They found that providing context before presenting information resulted in better comprehension than when no context was provided. Contextual constraints provided a framework to determine which information is important to attend to and which information can be inhibited or ignored. This is similar to what was discussed earlier where participants were told which ear to attend to and not attend to, demonstrating that context, or frame of reference, can manifest in various ways to guide selective attention.

1.2. Paradigms used to study selective attention

The theories, models, and studies discussed above provide a basis to understand how extrinsic cues (e.g., perceptual features; context such as which ear to attend to), semantic characteristics of the stimuli, and/or intrinsic value ascribed to the stimuli (e.g., personal relevance) influence selective attention. Building from this early selective attention work, researchers increasingly utilized visual paradigms to further understand how these factors affect selective attention. These studies manipulated visual characteristics of the stimuli and the context to study selective attention (for reviews see Pashler, 1998; Zanto & Gazzaley, 2014).

One commonly used task is the flanker task (Eriksen & Eriksen, 1974) which examines selectivity to specific information in the presence of similar looking distractors. In this task, a line of items (e.g., arrows; letters) are presented where the central item is flanked by either congruent (e.g., HHHHHHH) or incongruent (e.g., HHHSHHH) items. Participants must attend and respond to the central item while ignoring the flankers. Better performance, i.e., faster reaction times and greater accuracy, is observed when attending to a central item with congruent flankers compared to incongruent flankers. Smaller reaction time and/or accuracy differences between congruent and incongruent conditions are commonly taken as evidence for better attentional selectivity.

Visual search tasks (e.g., Duncan & Humphreys, 1989; Plude & Hoyer, 1985; Plude & Hoyer, 1981; Rabbitt, 1965; Treisman & Gelade, 1980; Wolfe et al., 1989) have also been used to study selective attention, where participants must identify a target item from multiple non-target, or distractor, items. If the target differs by certain stimulus features, such as color, shape, or size (e.g., the target is a green square and distractors are red circles), it is easier and more efficient to direct attention to that item. However, this can be affected by the number of items on the display (Treisman & Gelade, 1980), or in other words, the context. Additionally, directing attention to the target is less efficient if the target shares any features with the distractors (e.g., the target is a red square and distractors are red circles; Hommel et al., 2004; McDowd & Shaw, 2000). These types of tasks involve both selectivity to the relevant stimulus and inhibition of the distracting stimuli and demonstrate the importance of both perceptual features and context for successful performance.

The flanker and visual search tasks use multiple stimuli where some of the stimuli serve as targets that should be selectively attended to while others are distractors that should be ignored. However, the ability to attend to and ignore certain features within the *same* stimulus has also been studied using the popular Stroop task (Stroop, 1935). In this task, color words are printed in different color ink (e.g., the word RED printed in blue ink) and participants must attend to and say the color of the ink while ignoring the text word (e.g., saying ‘blue’, not ‘red’). Participants have longer reaction times when saying the color of the ink for these mismatched words as compared to saying words that are printed in the same color ink as their name. Traditional Stroop tasks highlight the ability to selectively attend to target information defined by perceptual features while inhibiting other distracting information.

The selective attention work discussed up to this point has focused on directing people to attend to certain information, but work from directed forgetting tasks helps to elucidate what happens when people are directed to forget, or inhibit, certain information (Bjork, 1989; Bjork et al., 1968; Woodward & Bjork, 1971). Directed forgetting tasks use cues to direct people to forget specific information (for review see MacLeod, 1998), typically within the context of a list learning procedure. There are two different methodologies used in directed forgetting tasks: the item method and the list method. In the item method, remember (R) or forget (F) cues are given immediately after a word is presented and recall is elicited after all items have been presented. In the list method, an R or F cue is provided at the end of the first list of words, and then a second list of words is presented, with each list consisting of 10-20 words each. The recall is elicited after both lists are presented (for review see Anderson & Hanslmayr, 2014). In the item method, to-be-forgotten items are poorly recalled *and* poorly recognized, whereas in the list method they are poorly recalled, but well recognized. Such findings suggest that immediately providing cues aids not only in more efficient selective attention but supports more efficient encoding and retrieval of important information.

Studies on directed forgetting have classically cited inhibitory processes as being required for to-be-forgotten items in the list method, but only in later years did researchers suggest that the item method may also involve inhibitory processes for to-be-forgotten items

(Zacks et al., 1996; for review see Anderson & Hanslmayr, 2014). Evidence for this claim came from studies that used a directed forgetting task with an additional task requiring a motor response. Reaction times were slower after an F cue than an R cue, which was posited to reflect high cognitive load for the F cues due to inhibitory processes and thus F items did not simply "passively decay" (for review see Anderson & Hanslmayr, 2014). This is important for demonstrating that information deemed to be less important or valuable still requires active processing, in particular inhibitory processes. Collectively, this work from a variety of paradigms has helped demonstrate the importance of stimulus characteristics and context for both selectively attending to and selectively forgetting information, as well as the importance of the balance between attention and inhibition for selective attention.

1.3. Value-directed remembering task

A form of selective attention, guided by an objective metric of numerical value and operationally defined as value-directed strategic processing in this dissertation, has been studied in the visual modality by Castel and colleagues using the value-directed remembering (VDR) task (Castel et al., 2002). In a VDR task, there are multiple lists of words, where each word is paired with a different numerical value (e.g., values ranging from 1 to 12 points). Unlike traditional episodic list learning tasks which repeat the same list of words (e.g., Rey Auditory Verbal Learning Test [Schmidt, 1996]; California Verbal Learning Test [Delis et al., 2000]), VDR tasks utilize a unique set of words for each word list to better assess value-directed strategic processing of new information across lists and not episodic learning of a repeated list of words. Participants are instructed to recall words at the end of a word list with the goal of maximizing their score. It is important to note here that strategic processing is estimated from the participant's ability to preferentially recall items of higher value. After each list, participants are given feedback about their score as a method to try to encourage better performance on the next list. The premise behind this task is that with the relatively quick presentation of words (1-2 seconds) and a large number of words to process and remember, participants will need to strategically attend to words of higher value in order to maximize their scores. Additionally, to be successful in the task, participants need to strategically block or inhibit words of lower value to minimize interference and to promote recall of higher value words. Performance on a VDR task can be assessed by the number of high- and low-value words recalled.

The VDR task as described above provides an overview of the general procedures, but studies have used various task manipulations to further our understanding of value-directed strategic processing. Some of the manipulations will briefly be discussed below.

Number of lists. Most VDR studies utilize multiple word lists as there is evidence that many people require an initial trial to at least begin optimizing their strategic processing ability (e.g., Middlebrooks et al., 2017). Some show slight improvements across the first lists and then typically show a stabilization in strategic processing performance (e.g., Castel et al., 2002, 2007; for review see Castel, 2007). However, there is evidence for strategic processing even if only one list is used with more high- than low-value words recalled (e.g., Friedman & Castel, 2011), pointing to the inherent nature of value-directed strategic processing.

List length. VDR studies have used a variety of word list lengths, ranging anywhere from 12 words per list (e.g., Castel et al., 2002, 2007, 2009, 2013; Castel, Humphreys, et al., 2011; Castel, Lee, et al., 2011; Middlebrooks & Castel, 2018) up to 40 words per list (e.g., Friedman & Castel, 2011, 2013). To the best of my knowledge, no studies have directly compared the effects of different word lists lengths in the context of the VDR task. However, regardless of list length, studies continually show greater recall of information of higher value compared to information of lower value.

Point values. Studies have defined point values in various ways, including continuous point values (e.g., 1-12 points; Castel et al., 2002, 2007, 2009, 2013; Castel, Humphreys, et al., 2011; Castel, Lee, et al., 2011; Middlebrooks & Castel, 2018), categorical point values (e.g., 1, 5, or 10 points; Castel et al., 2007; Wong et al., 2018), or a combination of the two (e.g., 1, 2, and 3 points are low-value words and 10, 11, and 12 points are high-value words (Cohen et al., 2014, 2016; Hennessee et al., 2017, 2019; Reggente et al., 2018). Other iterations of the VDR task have incorporated negative point values, which incur a “penalty” if recalled in the form of a loss of points, and serve as a measure of value-directed forgetting (e.g., Castel et al., 2007; Friedman & Castel, 2011; Hayes et al., 2012; for review see Castel, 2007). This manipulation stemmed from the work of item-method directed forgetting studies but proposed that negative point values are more salient than the F cue to forget an item (Friedman & Castel, 2011). These studies have shown that younger adults can effectively inhibit both recall and recognition of the negative value information. It has been suggested that incorporating negative point values can provide further insights into the inhibition of information in the context of maximizing score (e.g., Castel, 2007; Friedman & Castel, 2011, 2013).

Sequential versus simultaneous presentation. The most common presentation method for the VDR task is a sequential presentation of words, where each word appears one at a time on the screen, but a few studies have explored simultaneous presentation of words, where all words are presented at the same time on the screen (Castel et al., 2013; Middlebrooks & Castel, 2018; Siegel & Castel, 2018a, 2018b). Sequential presentation is thought to require maintenance of information in working memory so that item-by-item decisions can be made, whereas simultaneous presentation allows participants to have all information available during the entirety of the study period, resulting in greater availability of cognitive resources as there is less attentional and/or working memory load during the encoding period (Siegel & Castel, 2018b). Regardless of the presentation type, both younger and older adults have shown greater recall of high-value than low-value information (Castel et al., 2013; Middlebrooks & Castel, 2018; Siegel & Castel, 2018a, 2018b), but greater selectivity has been noted for simultaneous versus sequential presentation (Middlebrooks & Castel, 2018). Participants showed slight improvements in value-directed strategic processing across lists for sequential presentation but consistently engaged in value-directed strategic processing across word lists for simultaneous presentation (Siegel & Castel, 2018a).

Study time. The amount of time given to participants to study words and their associated values have also been manipulated for the VDR task to determine how study time affects value-directed strategic processing (Middlebrooks et al., 2016). In one study using sequential presentation, participants studied words for one second, five seconds, or at their own speed (self-paced). For all three study times, participants showed greater recall of higher value words compared to lower value words, demonstrating that they were selective regardless of time limitations (Middlebrooks et al., 2016). In a study using simultaneous presentation, participants were given two minutes in total to study the words and their values, which they did by clicking on a value to see the word paired with that value. Thus, they could choose how to allocate their study time. Both younger and older adults engaged in value-directed strategic processing, but the older adults showed different patterns from the younger adults during the study period. Older adults studied fewer words overall, they were more selective in that they spent more time studying the higher value words, and they studied each individual word for more time.

Free recall versus recognition. Most VDR tasks utilize free recall where participants verbally provide as many words as they can remember from a given list, but a few have also examined whether giving a recognition test affects value-directed strategic processing. These studies have found that the effect of value is reduced when using a recognition test compared to free recall (Castel et al., 2007; Hennessee et al., 2017). Although the effect is reduced, it does not disappear entirely. Participants still recognized higher value words more accurately than lower value words and provided higher ratings of "remembering" the higher value words (versus "knowing" the words, a measure of familiarity; Hennessee et al., 2017). Interestingly, Castel et al. (2007) found that while both younger and older adults did not recall negatively valued words, when given a surprise recognition test, older adults reported recognizing more negatively valued words than the younger adults. This is similar to the work on directed forgetting where older adults identified more of the to-be-forgotten items (Zacks et al., 1996). Such findings suggest that older adults have poorer inhibitory control compared to younger adults, perhaps due to issues with inhibition at encoding and/or retrieval (Hasher & Zacks, 1988; Hasher et al., 2007).

Score feedback. In the standard VDR task, providing immediate feedback is assumed to help encourage participants to be more strategic on subsequent lists by trying to increase their score. However, strategic processing, where more high- than low-value words are recalled, is still observed even if feedback is not provided (Friedman & Castel, 2011).

Across these various manipulations of the VDR task, a strong and consistent finding emerges: people strategically, or preferentially, attend to information that is considered to be of higher value than information of lower value. Although this work on value-directed strategic processing has allowed for a greater understanding of how assigning arbitrary numerical point values to words can prompt strategic processing, in the real world, processing is often driven by perceptual and conceptual properties of the information around us. For example, with regard to perceptual properties, items that are visually contrastive (e.g., different fonts, colors) tend to draw our attention differentially. As for conceptual properties, we often group information into categories (e.g., animals) based on conceptual similarities (e.g., has four legs) as this can help with processing efficiency. ***As such, the existing evidence on value-directed strategic processing can be advanced by using tasks similar to the VDR task, but instead of tagging each individual word with a numerical value, value is tied to perceptual and conceptual features of the words.*** One easy perceptual manipulation would be to manipulate value (e.g., high-value vs. low-value; 10 points vs. 1 point) by varying the physical properties of words in a list using letter case (i.e., uppercase and lowercase letters). Such perceptual manipulation of value will be explored in Chapters 2-4 of this dissertation. Along a similar vein, value can be manipulated conceptually using binary values defined by categories (e.g., animals and household items). Differences between manipulating value perceptually versus conceptually will be investigated in Chapter 5 of this dissertation.

1.4. Behavioral studies using the value-directed remembering task

1.4.1. Value-directed strategic processing in children and young adults

Value-directed strategic processing has been shown to be important for children and young adults for learning and academic success (e.g., Hanten et al., 2007; for review see Stevens & Bavelier, 2012). In an examination of the development of strategic processing, Hanten et al. (2007) studied children aged 6-18 years using an auditory VDR task. They found that older children recalled more total words than younger children, and showed greater ability to strategically process information, i.e., they recalled more high- than low-value words. Numerous behavioral studies using the VDR task have consistently shown that younger adults (i.e., college undergraduates aged 18-23 years) engage successfully in strategic processing, as they recall more high-value information than low-value information (e.g., Castel et al., 2002, 2007; Castel, Humphreys, et al., 2011). Hanten et al. (2002) demonstrated that strategic processing is improved when the value of the information is provided prior to the study or encoding period compared to studying all the information and finding out the value afterward. As an example within the classroom, students may benefit from seeing an outline of the topics to be covered during a given lesson so that they can understand both the value and the context of the information they will be learning. This notion also traces back to the work of Bransford and colleagues (discussed earlier; Bransford & Johnson, 1972) in which providing context, or a frame of reference, is important for improving comprehension and recall. These findings have important implications for academic success throughout development as the ability to strategically process important information over less important information is essential for classroom learning in which large quantities of information are presented over the course of a day (also see Stevens & Bavelier, 2012).

1.4.2. Value-directed strategic processing in normal cognitive aging

Value-directed strategic processing has been examined in a number of studies within the context of normal cognitive aging. These studies have found that older adults typically recall fewer words overall compared to younger adults (Castel et al., 2002; Castel et al., 2007; Castel, Humphreys, et al., 2011). Interestingly, older adults have shown some similarities to young adults, with greater recall of high- compared to low-value words, demonstrating that the ability to strategically process information is retained with aging, at least to some extent. In a study examining strategic processing across the lifespan, Castel, Humphreys, et al. (2011) found that the total number of words recalled was lower for the younger-old (ages 65-79 years) and older-old (80-96 years) groups compared to all younger age groups (children [5-9 years], adolescents [10-17 years], younger adults [18-23 years], and middle-age adults [45-64 years]), but that the two old groups did not differ from one another. However, they found that the younger-old group was similar to the younger and middle-aged adults with regard to selectivity for high-value words, whereas the older-old group performed significantly worse, suggesting that strategic processing ability may be maintained until old-old age. When negative point values were included in the VDR task, older adults performed similarly to younger adults during recall, namely that they recalled few negatively valued words (Castel, 2007). When given a recognition test, however (i.e., read through a list of words and determine which ones were part of the original list they saw), older adults identified more negative value words than younger adults, which was taken as evidence for a problem with inhibiting the negatively valued information (Castel, 2007).

These studies demonstrate that there are some changes in value-directed strategic processing with age, consistent with the large body of work on normal cognitive aging that has described declines in various cognitive domains relevant to value-directed strategic processing, such as attention and inhibition (e.g., Craik & Byrd, 1982; Hasher & Zacks, 1988; Hasher et al., 2007; Park et al., 1989). Age-related changes in the ability to attend to information of higher value could be attributed to a few different factors or a combination of these factors. One, it could be that reduced processing speed with age makes it more difficult to differentially process the value of information rapidly (Salthouse, 1996, 2000). Two, age-related reductions in the availability or allocation of attentional resources (e.g., Craik & Byrd, 1982; Rabinowitz et al., 1982) may result in reduced ability to allocate resources effectively to higher valued information.

Three, age-related decreases in the ability to effectively inhibit irrelevant information (e.g., Darowski et al., 2008; Hasher & Zacks, 1988; Hasher et al., 2007), or information of lower value, could impair attention to and processing of higher value information. In fact, studies with young adults have shown that ignoring low-value information is an effective strategy for recalling more high-value information (Ariel et al., 2015; Robison & Unsworth, 2017) as there is a limited capacity to the number of items one can remember during recall.

1.4.3. Value-directed strategic processing in clinical populations

To determine if and how value-directed strategic processing may be altered as a result of brain injury, diseases, and disorders, this ability has been investigated in various clinical populations, including attention-deficit/hyperactivity disorder (ADHD) and traumatic brain injury (TBI) in children, and dementia in older adults. A study of children with and without ADHD (aged 6-9 years) using a VDR task found that both groups had similar performance for overall recall of words (Castel, Lee, et al., 2011). Children with and without ADHD both recalled more high- than low-value words, but children with ADHD were significantly less selective in their recall, suggesting impaired strategic processing (Castel, Lee, et al., 2011). The authors suggested that because ADHD has been associated with inhibitory control issues (Barkley, 1997) and poor memory strategy use (O'Neill & Douglas, 1996), their value-directed strategic processing impairments may be due to poor selectivity of high-value words either through deficits in allocating attention to these words or in inhibiting low-value words.

An auditory VDR task was used to study strategic attention in children (aged 6-16 years) who had sustained a severe TBI at least one year prior to the study (Hanten et al., 2004). Children with TBI recalled a similar number of total words to children without TBI (although there was a trend for fewer words recalled), but they were not as effective at recalling more high- than low-value words, demonstrating strategic processing impairments. The authors proposed that the results were due to deficits in both attention and inhibition, where children with TBI had difficulties both selecting or attending to the more valuable information and inhibiting less valuable information.

Strategic processing has also been studied in the context of dementia, namely Alzheimer's disease (AD) and behavioral variant frontotemporal dementia (bvFTD). In a VDR task with individuals with AD, Castel, Balota, and McCabe (2009) found reductions in total words recalled with age and disease severity (i.e., cognitively normal young adults > cognitively normal older adults > very mild AD > mild AD). However, when examining a measure of strategic processing, they found that the very mild and mild AD groups differed from both the cognitively normal younger and older adults, with impairments in preferential recall of high- over low-value information, but did not statistically differ from each other. Overall, they found that while older adults showed impairments on recall performance, those with very mild and mild AD were impaired for both recall and strategic processing performance (Castel et al., 2009).

Wong et al. (2018) examined performance of both AD and bvFTD patients using a VDR task with three word lists, where each word was given one of three point values: low (1 point), medium (5 points), and high (10 points). Important to note, they used a "simplified" version of the VDR task as the three word lists contained the same words, meaning that episodic learning of the words was possible. Cognitively normal older adults performed better than both patient groups, but the two patient groups showed interesting differences. For individuals with AD, the number of high- versus low-value words recalled did not differ on List 1 or 2, but they recalled more high- versus low-value words on List 3, demonstrating improved strategic processing by the final list. However, individuals with bvFTD never showed a difference across the three lists, suggesting they did not learn to strategically process the information. Preferential processing ability was not associated with inhibitory function in AD patients but was in bvFTD patients, which was not surprising, given the greater inhibitory impairments that characterize bvFTD (Bozeat et al., 2000; Hornberger et al., 2008). This work demonstrates that inhibition plays a critical role in strategic processing, such that impaired inhibition can result in impaired value-directed strategic processing abilities. Collectively, behavioral work using the VDR task has shown that value-directed strategic processing is affected in individuals undergoing normal cognitive aging to an extent and in individuals with different types of dementia more significantly. ***To date, no studies have examined how value-directed strategic processing may be impacted by subtle age-related cognitive changes, such as those seen in individuals with mild cognitive impairment (MCI).*** Value-directed strategic processing in older adults with MCI will be examined in Chapter 4 of this dissertation.

1.5. Neuroimaging studies using the value-directed remembering task

In addition to the behavioral work described above, emerging neuroimaging studies are beginning to clarify the structural and functional neural substrates of strategic processing in both cognitively normal younger (Cohen et al., 2014; Reggente et al., 2018) and older (Cohen et al., 2016; Hennessee et al., 2019) adults using functional magnetic resonance imaging (fMRI) and diffusion tensor imaging (DTI).

1.5.1. Functional magnetic resonance imaging (fMRI) work

Using a VDR task, whole brain analyses of fMRI data from both younger and older adults showed that, during the encoding period of a word, there was greater activity for high- compared to low-value words in left inferior frontal gyrus, left superior temporal gyrus, and left lateral temporal cortex (Cohen et al., 2014, 2016). The left inferior frontal gyrus has previously been associated with deep semantic processing (Binder et al., 2009; Binder & Desai, 2011), effective semantic encoding strategy use (Kirchhoff & Buckner, 2006; Miotto et al., 2006; Savage et al., 2001), and control processes of semantic retrieval (Badre et al., 2005; Badre & Wagner, 2007; Thompson-Schill et al., 1997), while the temporal cortex has been associated with semantic information retrieval (Wagner et al., 2001; Whitney et al., 2011). As such, these findings suggest that preferential processing of high-value words involves engaging deeper semantic processing and/or semantic strategy use. A region of interest (ROI) investigation using a semantic ROI found greater activity for high- than low-value words for both younger and older adults (Cohen et al., 2016). Interestingly though, correlations between high- and low-value recall and this semantic ROI showed differential effects for younger and older adults. Younger adults showed a positive correlation between activity in the semantic ROI and number of high-value words recalled, whereas older adults showed a negative correlation between semantic ROI activity and number of low-value words recalled (Cohen et al., 2016). This suggests better value-directed strategic processing ability is due to enhanced semantic processing of high-value words for young adults, but reduced semantic processing of low-value words for older adults.

1.5.2. Diffusion tensor imaging (DTI) work

The DTI studies (Hennessee et al., 2019; Reggente et al., 2018) have focused on white matter integrity of the uncinate fasciculus (UF), a tract connecting part of the inferior prefrontal cortex and the anterior temporal lobe, and the inferior fronto-occipital fasciculus (IFOF), a tract connecting ventrolateral prefrontal cortex and posterior portions of the temporal cortex. The UF has been associated with semantic processing (de Zubicaray et al., 2011) and the IFOF with semantic memory performance and control and retrieval of semantic information (de Zubicaray et al., 2011; Nugiel et al., 2016). In young adults, Reggente et al. (2018) found that greater white matter integrity, as measured by fractional anisotropy, in both the UF and IFOF was associated with recall of high-value words, but not low-value words. However, when removing parts of the IFOF that overlapped with the UF, this correlation disappeared, suggesting that a robust UF may be more important when utilizing semantic encoding strategies for higher valued information in young adults. Hennessee et al. (2019) found that older adults had diminished left IFOF integrity, measured using mean diffusivity, suggesting a loss of structural integrity in this tract with age. However, they did find that greater IFOF integrity in older adults was associated with greater recall of high-value words, but not low-value words, and this association was not seen in younger adults. Interestingly, the opposite was true for UF, where younger adults showed an association between UF integrity and high-value word recall and not low-value recall, whereas older adults did not show this association. Collectively, these DTI studies seem to suggest that preferential recall of high-value words is more dependent on UF integrity in younger adults, but IFOF integrity in older adults.

The neuroimaging studies have helped us begin to understand the neural substrates of value-directed strategic processing, but strategic processing is a dynamic process that unfolds quickly. ***To the best of my knowledge, techniques with a greater temporal resolution, such as event-related electroencephalography (EEG), have not been used to further our understanding of the underlying neural mechanisms related to value-directed strategic processing.*** In particular, the examination of the spectral and temporal characteristics of oscillatory brain activity derived from event-related EEG could be used to better understand the neural underpinnings of strategic processing.

EEG is a viable tool for examining neurocognitive functions as it records the electrical voltages of large populations of synchronized neurons in the cortex with high temporal resolution from the level of the scalp. EEG data can be analyzed with a variety of techniques, including analysis of the spectral and temporal features of the EEG signal, which allows for examination of how the neurons generating the EEG signal are oscillating at different frequencies. This method is based on Fourier's theorem which asserts that a periodic signal can be decomposed into the simplest set of possible sine waves of different frequencies and amplitudes. In human EEG, there are five typically defined frequency bands or brain rhythms, delta (1-4 Hz), theta (4-8 Hz), alpha (8-12 Hz), beta (12-30 Hz), and gamma (> 30 Hz). The amount of energy at each frequency is the spectral power, which can fluctuate and change as a result of cognitive tasks.

Event-related spectral perturbations (ERSPs) are measures of the dynamic changes in spectral power in different frequency bands across time that correspond to cognitive events (Makeig et al., 2004). These changes in spectral power are commonly discussed in terms of event-related synchronization and event-related desynchronization, which refer to event-related power increases or decreases relative to a baseline period, respectively, and are considered to reflect increases or decreases in the synchrony of underlying neuronal populations (for review see Pfurtscheller & Lopes da Silva, 1999).

Each frequency band has been related to diverse cognitive functions, such as memory, attention, and inhibition (for reviews see Başar et al., 2001; Klimesch, 1996, 1999; Rossini et al., 2007). For the purposes of this dissertation, only the theta and alpha bands will be described in greater detail given that they have been related to cognitive functions important for value-directed strategic processing (e.g., Babu Henry Samuel et al., 2018; Cavanagh & Frank, 2014; Jensen & Tesche, 2002; Klimesch et al., 2007). Theta band activity has been related to cognitive control, selective attention (Cavanagh & Frank, 2014; Cavanagh & Shackman, 2015), and executive control in working memory (e.g., Jensen & Tesche, 2002; Kawasaki et al., 2010). Frontal theta synchronization has been implicated in the recruitment of inhibitory processes (Cohen & Donner, 2013; Nigbur et al., 2011). Alpha band activity has shown associations with selective attention (Klimesch, 2012; Sadaghiani & Kleinschmidt, 2016) and the encoding and maintenance of information in working memory (e.g., Babu Henry Samuel et al., 2018; Bashivan et al., 2014). Alpha synchronization has been associated with inhibition of irrelevant information (Klimesch, 1999; Suffczynski et al., 2001), while alpha desynchronization has been related to attention and increasing task complexity (for reviews see Klimesch, 2012; Pfurtscheller & Lopes da Silva, 1999), as well as semantic processing (for reviews see (Klimesch, 1999; Klimesch et al., 2007; Pfurtscheller & Lopes da Silva, 1999). The potential utility of the theta and alpha bands as measures of the neurophysiological underpinnings of value-directed strategic processing will be examined in Chapters 2-4 of this dissertation.

1.6. Overview of the dissertation work

This dissertation work is comprised of four studies that aim to (i) characterize ERSP markers related to value-directed strategic processing using a list learning task where binary values were defined perceptually using letter case (Letter Case task; Chapters 2-4), and (ii) begin exploring how value-directed strategic processing is differentially affected when value is defined perceptually (Letter Case task) versus conceptually using categories (Categories task; Chapter 5). Both the Letter Case task and the Categories task used visually presented word lists where the words were assigned to be either high-value (10 points) or low-value (1 point). Value assignments were based on perceptual features of letter case (i.e., uppercase or lowercase letters) in the Letter Case task and on categories (i.e., animals or household items) in the Categories task. In both tasks, participants were asked to recall words at the end of each word list with the goal of scoring maximal points.

Study 1: Identify ERSP markers linked to value-directed strategic processing in cognitively normal young adults (Chapter 2). Approach: Cognitively normal young adults completed the Letter Case task while EEG was recorded. Measures: The number of high- and low-value words recalled across the five word lists, and theta and alpha band power linked to processing of high- versus low-value words. Hypotheses: Greater recall of high- compared to low-value words. Greater theta synchronization for low- compared to high-value words. Greater alpha band desynchronization for high- compared to low-value words.

Study 2: Examine how ERSP markers related to value-directed strategic processing are modulated by normal cognitive aging (Chapter 3). Approach: Cognitively normal younger and older adults completed the Letter Case task while EEG was recorded. Measures: Differences between younger and older adults for the number of high- and low-value words recalled across the five word lists, and theta and alpha band power. Hypotheses: Greater recall of high- compared to low-value words for both younger and older adults. Differences in theta synchronization for low- versus high-value words in older adults. Differences in alpha desynchronization for high- versus low-value words in older adults.

Study 3: Investigate how ERSP markers related to strategic processing are altered as a result of neurological disease, specifically mild cognitive impairment (Chapter 4). Approach: Cognitively normal older adults (CN) and older adults with mild cognitive impairment (MCI) completed the Letter Case task while EEG was recorded. Measures: Differences between MCI and CN individuals for the number of high- and low-value words recalled across the five word lists, and theta and alpha band power. Hypotheses: Poorer recall of total and high-value words, but greater recall of low-value words in MCI participants compared to CN participants. Greater theta synchronization for low- compared to high-value words and differences between groups. Greater alpha desynchronization for high- compared to low-value words and differences between groups.

Study 4: Explore how value-directed strategic processing is affected when value is defined by perceptual versus conceptual features in cognitively normal younger and older adults (Chapter 5). Approach: Cognitively normal younger and older adults completed two value-directed strategic processing tasks: the Letter Case task and the Categories task. Measures: Differences in the number of high- and low-value words recalled between the Letter Case and Categories tasks within both the younger and older adult groups, as well as between the two groups. Hypotheses: Greater recall of total words and high-value words, and no difference for low-value words, for the Categories task compared to the Letter Case task in both younger and older adults. Greater recall of total words and high-value words, and no difference for low-value words, for younger compared to older adults in the Categories task. No difference in recall of total words, high-value words, or low-value words between younger and older adults in the Letter Case task.

CHAPTER 2: THETA AND ALPHA BAND OSCILLATIONS DURING VALUE-DIRECTED STRATEGIC PROCESSING[1]

ABSTRACT

Strategic processing allows for value-based preferential encoding of information. Event-related spectral perturbations can provide insights into neural processes linked to the different aspects of strategic processing. This study examined theta and alpha band power differences linked to processing of high- versus low-value information. Thirty-three young adults (17F; mean age: 21.2 ± 1.5 years) completed a value-directed word list learning task. The task consisted of five word lists that each contained a unique set of high- and low-value words that were visually presented one at a time and EEG corresponding to these words were examined. To encourage strategic processing, participants were informed that after each list they would be asked to recall as many words as possible with their goal being to maximize their score. Overall, participants recalled more high-value words for each of the five lists as compared to low-value words, which supports that participants engaged in strategic processing. Frontal theta band power showed greater positivity during processing of low- compared to high-value words, whereas parietal alpha band power showed greater negativity during processing of high- compared to low-value words. These findings suggest that theta and alpha bands index different aspects of strategic processing, inhibition and selective attention, respectively, and have future applications for understanding the effects of aging and brain diseases/disorders.

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[1] Chapter 2 is a reprint of a publication in Behavioural Brain Research and is referred to in this dissertation as “Nguyen et al., 2019”. The full citation is Nguyen, L.T., Marini, F., Zacharczuk, L., Llano, D.A., & Mudar, R.A. (2019). Theta and Alpha Band Oscillations During Value-Directed Strategic Processing. *Behavioural Brain Research*, *367*, 210-214. https://doi.org/10.1016/j.bbr.2019.03.052. This publication is reprinted under the Creative Commons CC-BY-NC- ND license.

Strategic processing allows for value-based preferential processing of information (Castel, 2007). We often attend to information of greater importance while inhibiting less important information when engaging in routine activities such as reading or having a conversation. This process is crucial to daily functioning as it allows us to direct our attentional resources to more relevant or salient information to facilitate encoding and storage for later recall (Castel, 2007). Studies examining strategic processing have commonly used word list learning tasks in which words are paired with different values ranging from high to low (e.g., Castel et al., 2002; Castel et al., 2007; Castel et al., 2011). Unlike traditional word list learning studies where total number of words recalled is used as a measure of episodic learning and memory, studies on strategic processing make inferences about strategic processing based on the ability to preferentially recall items of higher value, often referred to as value-directed remembering. Behavioral studies have shown that both cognitively normal younger and older adults are able to preferentially encode and recall high-value information better than low-value information (e.g., Castel et al., 2002; Castel et al., 2007; Castel et al., 2011). Such preferential processing has also been observed in the visual attention and reward literature (for reviews Chelazzi et al., 2013; Desimone & Duncan, 1995) even in the presence of distractors (Middlebrooks et al., 2017). However, few studies have examined the neural basis of such strategic allocation of resources to attend to and inhibit value-based information independent of encoding efficiency.

A small set of functional neuroimaging studies have examined neural substrates linked to value-directed strategic processing (Cohen et al., 2014, 2016). These studies have found greater activation in left ventral and posterior prefrontal cortex (particularly left inferior frontal gyrus) during processing of high- compared to low-value words in both healthy younger (Cohen et al., 2014) and older adults (Cohen et al., 2016). Additionally, less activation in structures associated with the default mode network (Cohen et al., 2014, 2016) and greater activation of frontoparietal regions and mesolimbic reward systems have been observed during processing of high- compared to low-value words (Cohen et al., 2014). Although functional neuroimaging studies are beginning to disentangle brain regions linked to value-directed strategic processing, the temporal unfolding of these processes from a neurophysiological standpoint remains largely unexplored. Techniques with high temporal resolution, such as electroencephalography (EEG), best capture rapid cognitive processes and are most useful for this purpose.

Event-related spectral perturbations (ERSPs), which provide time-resolved information on phase-locked and non-phase-locked spectral activity in the EEG signal (Makeig et al., 2004), could help clarify how oscillatory brain responses linked to strategic processing unfold. Of primary interest to the current study are the theta (4-8 Hz) and alpha (8-13 Hz) frequency bands, as both have been implicated in cognitive functions that enable strategic processing (e.g., Babu Henry Samuel et al., 2018; Bashivan et al., 2014; Jensen & Tesche, 2002; Kawasaki et al., 2010; Xie et al., 2016; for reviews Cavanagh & Frank, 2014; Klimesch et al., 2007). In particular, frontal theta activity has been associated with cognitive inhibition, selective attention (e.g., Cohen & Donner, 2013; Ishii et al., 1999; Nigbur et al., 2011; for review (Cavanagh & Frank, 2014), and executive control in working memory (e.g., Jensen & Tesche, 2002; Kawasaki et al., 2010). Posterior alpha band activity has been linked to selective attention (for reviews Chelazzi et al., 2019; Klimesch, 2012; Sadaghiani & Kleinschmidt, 2016) and encoding and maintenance of information in working memory (Babu Henry Samuel et al., 2018; Bashivan et al., 2014; Xie et al., 2016).

The current study examined whether processing of high- versus low-value information in the context of a value-directed word list learning task differentially affects power in the theta (4-

8 Hz), alpha1 (8-10 Hz), and alpha2 (11-13 Hz) bands in healthy young adults independent of successful encoding and recall. This is common practice in studies of strategic processing (Cohen et al., 2014, 2016) and represents a sharp distinction relative to memory studies, in which the typical analyses distinguish between successfully recalled and non-recalled items (for review Hanslmayr & Staudigl, 2014). Accordingly, behavioral data is presented only to demonstrate that participants indeed engaged in strategic processing. We hypothesized that we would observe greater synchronized (i.e., more positive) theta power for low-value words, reflecting inhibition, and greater desynchronized (i.e., more negative) alpha power for high-value words, reflecting selective attention.

Participants included 33 young adults (17 female; ages: 18-24 years, mean age: 21.2 ± 1.5 years; mean education: 14.8 ± 1.2 years) who were all right-handed and native English speakers. Participants had no history of learning disabilities, communication disorders, neurological disorders, psychiatric disorders, traumatic brain injury, or uncorrected visual or auditory impairments. All participants signed a written informed consent in accordance with protocols approved by the Institutional Review Boards of the University of Illinois Urbana-Champaign before completing the study protocol.

Participants completed a strategic processing task, which was a value-directed word list learning task developed in-house. Stimuli consisted of 200 single syllable four letter nouns from the databases SUBTLEX and MRC Psycholinguistic Database. Words were controlled for concreteness (range: 501-637; mean: 571.8), frequency (range: 1-96; mean: 25.3), familiarity (range: 370-615; mean: 524.4), and imageability (range: 439-659; mean: 571.1). The 200 words were divided into five lists of 40 words each. Each list consisted of a different set of words, as opposed to the same set of words like is typical in episodic learning tasks (e.g., California Verbal

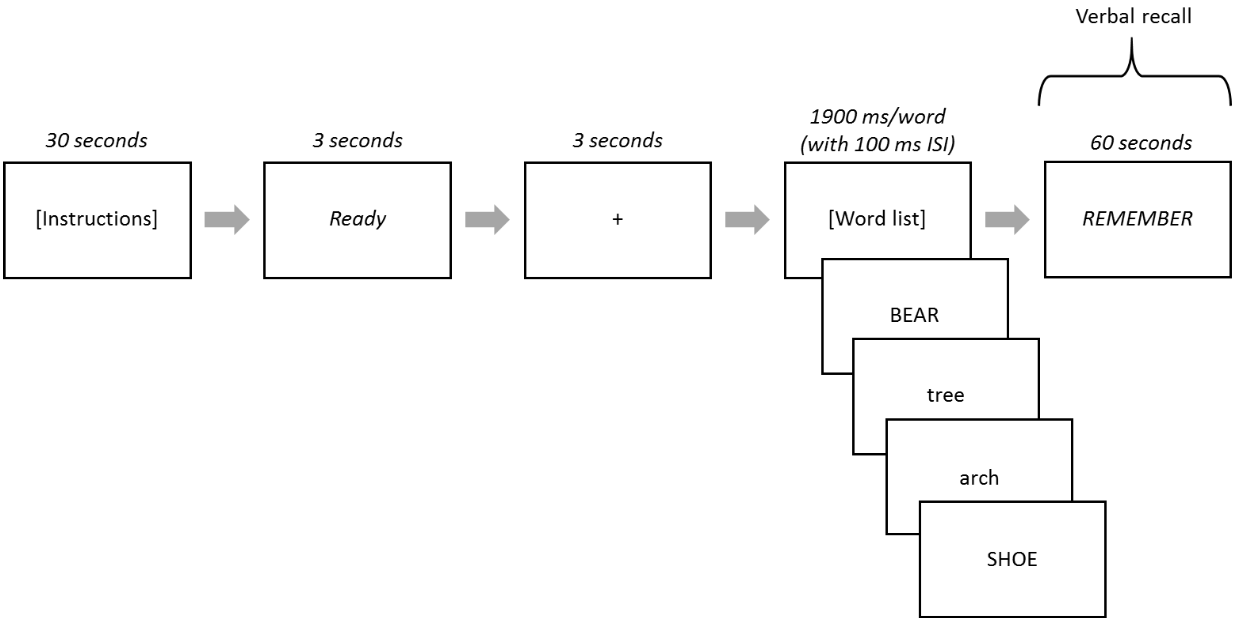
Learning Test), as the task was designed to evaluate strategic processing, not episodic learning. Interference from previous lists did not impact results as only 0.29% of recalled words were from previous lists. The five lists did not statistically differ in concreteness, $F(4,195) = .59$, $p = .67$, frequency, $F(4,195) = .32$, $p = .87$, familiarity, $F(4,195) = .58$, $p = .68$, or imageability, $F(4,195) = .31$, $p = .87$. In each of the five lists, half of the words (n = 20) were assigned to the high-value condition (worth 10 points) and half (n = 20) were assigned to the low-value condition (worth 1 point). The value of the words was differentiated by the letter case, where the words were written in either all uppercase letters (e.g., LAMB) or all lowercase letters (e.g., lamb). Font size was controlled so uppercase and lowercase letters all appeared as the same size. Word order was pseudorandomized for each list. Four versions of the task were developed and counterbalanced for word value and letter case: two versions had high-value words presented in uppercase letters and low-value words presented in lowercase letters, and two versions had high-value words presented in lowercase letters and low-value words presented in uppercase letters. Versions were randomly assigned to participants.

The following instructions were presented on screen to participants: “You will see words appear on the screen one at a time. Some words are in uppercase and some words are in lowercase. The uppercase words *[or lowercase words]* are worth 10 points each (high value words). The lowercase words *[or uppercase words]* are worth 1 point each (low value words). At the end of the list you will see the word “REMEMBER” on the screen. Your task is to remember as many of the words from the list as possible with the goal of scoring the maximum number of points. This is similar to a game in which words are worth different amounts of money”. The experimenter ensured participants understood how many points the uppercase and lowercase words were worth depending on the assigned version. Following the instructions, the word

“Ready” was displayed in the center of the screen for 3 seconds followed by a fixation (+) for 3 seconds. All 40 words were then displayed sequentially in the center of the screen for a duration of 1900 ms each with an inter-stimulus interval of 100 ms (blank screen). The word “REMEMBER” appeared at the end of each list and remained on the screen for 60 seconds while participants’ recall was manually recorded on a score sheet (see Figure 2.1 for task schematic). Participants were given immediate feedback after each list about their score before the next list was presented.

Figure 2.1

Strategic Attention Task Schematic



Lowercase or uppercase words served as high- or low-value words depending on task version. When the word “REMEMBER” was presented, participants verbally recalled words from that list. Responses were recorded on paper and scored for each of the five lists.

Continuous EEG was recorded while participants performed the task. A 64-electrode elastic cap (Neuroscan Quickcap) using a Neuroscan SynRT amplifier and Scan v4.5 software (sampling rate: 1kHz, bandpass filter: DC-200Hz) with impedances typically below 10 kΩ was used. The reference electrode was located at midline between Cz and CPz and vertical electrooculogram was recorded at sites above and below the left eye. Raw EEG data from all five lists (obtained during a single recording session) were appended together to have enough trials per condition for analysis. Raw EEG data were processed offline. Poorly functioning electrodes were identified by visual inspection and excluded from analysis (0.5%). Eye blinks were corrected using spatial filtering in Neuroscan. The data were epoched from 500 ms before stimulus onset to 2000 ms after stimulus offset. Thus, epochs were partially overlapping, which was necessary for time-frequency decomposition as this process excises data at the edges of both sides of the epochs. Epochs with peak signal amplitudes of ±75 μV were rejected (rejection rates: 11.3% for high-value and 11.6% for low-value conditions). EEG data were re-referenced to the average potential over the entire scalp.

EEG data were analyzed using EEGLAB toolbox (Version 14.1.1b; Delorme & Makeig, 2004) running under Matlab 2013b (MathWorks, Natick, MA, USA). Time-frequency decomposition was performed using short-time Fourier transform with Hanning window tapering as implemented in the EEGLAB function *newtimef.m*. Time-frequency data were obtained using a 256-ms sliding window with a step-size of 10 ms and a pad ratio of 2, resulting in a frequency resolution of approximately 1 Hz. Baseline correction was done in accordance with a gain model (Delorme & Makeig, 2004; Grandchamp & Delorme, 2011), where each time-frequency time point was divided by the average pre-stimulus baseline power from -500 to -300 ms relative to stimulus onset at the same frequency. Mean power was estimated in the theta band (4-8 Hz) at frontal sites (average of Fz, F1, F2) and in the alpha1 (8-10 Hz) and alpha2 (10-12 Hz) sub-bands at parietal sites (average of Pz, P1, P2). These electrode sites were selected based on work demonstrating greater prominence of theta band at frontal sites and alpha band at parietal/posterior sites (e.g., Cavanagh & Frank, 2014; Ishii et al., 1999; Kawasaki et al., 2010). Mean power was computed for high- and low-value conditions in 100 ms time windows from 0 ms to 1000 ms, resulting in ten time windows for analysis.

Task-related behavioral data, specifically the total number of high- and low-value words recalled, were examined using a standard general linear model (GLM) with value (high/low) and List (1/2/3/4/5) as within-subject measures. EEG data (theta, alpha1, and alpha2 mean power) combined across five lists were examined using standard GLMs, with value (high /low) and the ten time windows (100 ms time windows between 0 and 1000 ms post-stimulus), as well as the interaction term, as within-subject GLM predictors. Significance values for multiple comparisons were corrected with the Bonferroni method at a threshold of $p < .05$. IBM SPSS Statistics 24 was used for analysis. The reported p-values, where not specified otherwise, are derived from F-statistics.

Behavioral data showed significant differences between the total number of high- and low-value words recalled for each of the five lists ($p < .001$ for all five lists) as expected, where more high- compared to low-value words were recalled for all five lists (Table 2.1). Comparisons across lists showed significant differences for high-value, $F(1,4) = 6.41$, $p < .001$, and low-value, $F(1,4) = 11.98$, $p < .001$, words. Pairwise comparisons revealed that List 1 differed significantly from List 2 ($p < .05$), List 3 ($p < .001$), List 4 ($p < .001$), and List 5 ($p < .001$), with fewer high-value words and more low-value words recalled in List 1 compared to others. There was no significant difference in the total number of high- and low-value words recalled between versions in which high-value was assigned to uppercase or lowercase words ($p > .05$ for all five lists), indicating that case did not have an effect on recall.

Table 2.1

Average Number of High- and Low-Value Words Recalled For Each List

	Mean (SD)
List 1	
High-value	5.6 (1.9)
Low-value	2.4 (1.5)
List 2	
High-value	7.2 (2.3)
Low-value	1.3 (1.5)
List 3	
High-value	7.4 (2.0)
Low-value	0.9 (1.2)
List 4	
High-value	7.5 (1.9)
Low-value	1.0 (1.3)
List 5	
High-value	7.6 (2.5)
Low-value	0.6 (0.8)

These findings demonstrate that healthy young adults strategically encoded, stored, and recalled high-value words better than low-value words across all five lists of the task, consistent with other studies (e.g., Castel et al., 2002; Castel et al., 2007; Castel et al., 2011) and our predictions. Implementation of strategic skills and executive control, including selective attention for high-value information and active inhibition of low-value information, have been proposed as underlying bases of these results (e.g., Castel et al., 2007; Castel et al., 2011). It is important to note that participants were not given explicit instructions to attend to high-value words despite which, they implicitly utilized a value-driven or salience-driven approach to processing. The differences observed between List 1 and the other four lists were not surprising given that List 1 was the first opportunity for participants to become familiar with the task and develop a strategy to respond. Therefore, differences between high- and low-value words, although still present in List 1, were less pronounced compared to subsequent lists.

EEG analysis revealed greater synchronization (i.e., more positive) frontal theta power differed for low- compared to high-value words in the 500-700 ms time window (Table 2.2; Figure 2.2). Previous studies have demonstrated an association between frontal theta and cognitive control (for review Cavanagh & Frank, 2014), in particular with regard to the detection and inhibition of conflicting information on tasks such as Stroop, Go/NoGo, flanker, and Simon tasks (Cohen & Donner, 2013; Hanslmayr et al., 2008; Nigbur et al., 2011). Additionally, studies suggest a role of frontal theta in executive control within the context of working memory paradigms (e.g., Jensen & Tesche, 2002; Kawasaki et al., 2010). Based on these results, our frontal theta findings might reflect strategic processing linked to active inhibitory control or blocking of low value words. Interestingly, these theta power effects occur in a “burst” (200 ms time period), suggesting brief active suppression of the low-value words.

Table 2.2

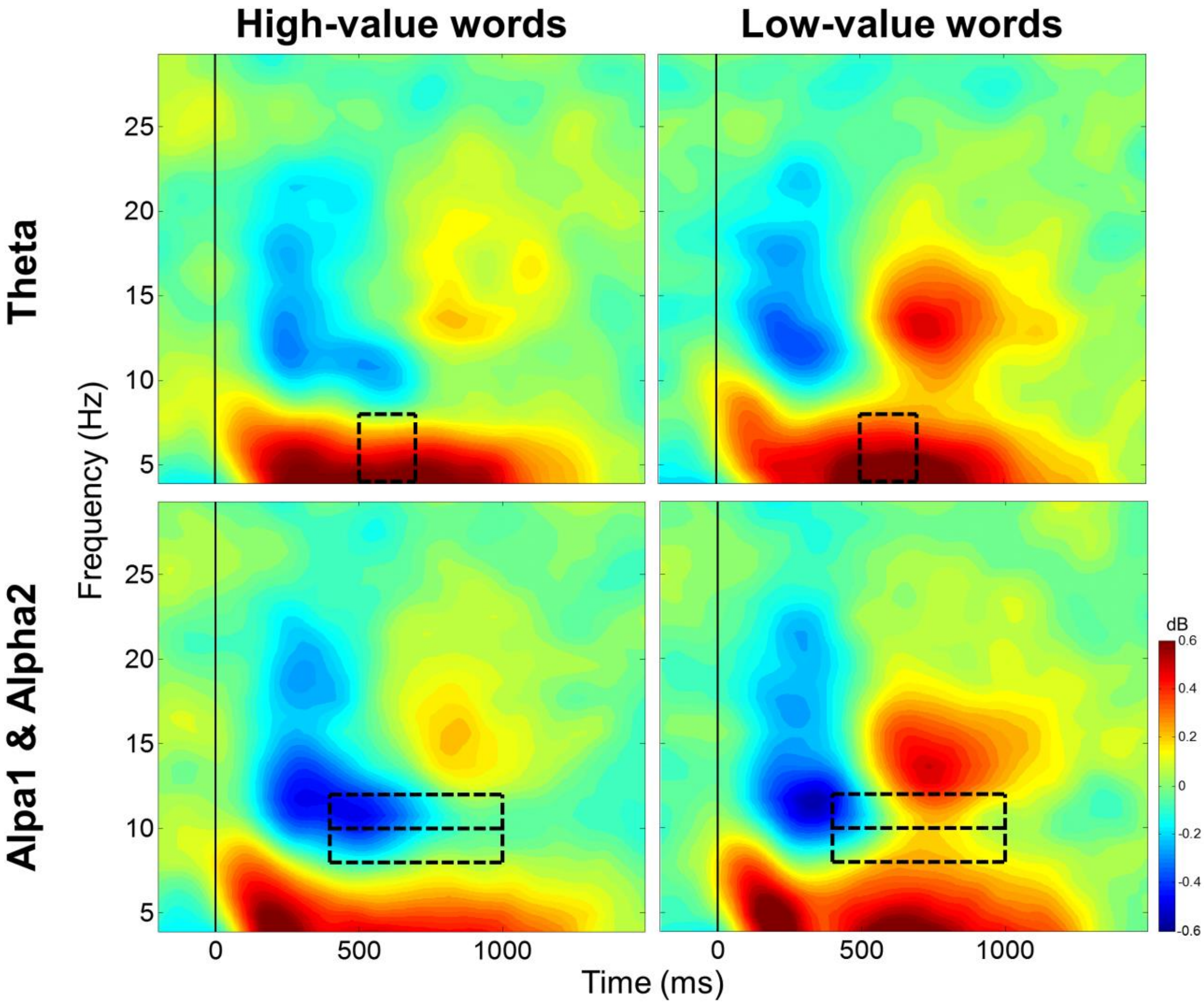
Statistical results for theta, alpha1, and alpha2 mean power

	Time (ms)									
	0-100	**100-200**	**200-300**	**300-400**	**400-500**	**500-600**	**600-700**	**700-800**	**800-900**	**900-1000**
Theta	$F = 0.71$ $p = 0.407$	$F = 0.04$ $p = 0.850$	$F = 1.69$ $p = 0.203$	$F = 0.86$ $p = 0.362$	$F = 1.81$ $p = 0.188$	$F = 5.39$ $p = 0.027$	$F = 5.45$ $p = 0.026$	$F = 1.94$ $p = 0.174$	$F = 2.12$ $p = 0.156$	$F = 1.13$ $p = 0.296$
Alpha1	$F = 0.01$ $p = 0.946$	$F = 0.42$ $p = 0.522$	$F = 0.73$ $p = 0.400$	$F = 0.01$ $p = 0.938$	$F = 8.38$ $p = 0.007$	$F = 24.7$ $p < .001$	$F = 24.6$ $p < .001$	$F = 20.1$ $p < .001$	$F = 9.41$ $p = 0.004$	$F = 3.26$ $p = 0.081$
Alpha2	$F = 0.54$ $p = 0.466$	$F = 1.56$ $p = 0.221$	$F = 0.62$ $p = 0.438$	$F = 1.20$ $p = 0.282$	$F = 3.99$ $p = 0.054$	$F = 23.1$ $p < .001$	$F = 34.0$ $p < .001$	$F = 30.5$ $p < .001$	$F = 12.8$ $p = 0.001$	$F = 4.15$ $p = 0.050$

All F-values have 32 degrees of freedom. Shaded cells correspond to significant differences in mean power between high- and low-value words.

Figure 2.2

Comparison of High- and Low-Value Words For Theta, Alpha1, and Alpha2 Bands



Spectrograms illustrate power differences between high- and low-value words for theta (4-8 Hz) at frontal sites (average of Fz, F1, F2) and alpha1 (8-10 Hz) and alpha2 (10-12 Hz) at parietal sites (average of Pz, P1, P2). Dashed black rectangles represent significant differences between conditions (high-/low-value). The 0 ms time point (solid vertical line) represents stimulus onset.

Greater desynchronized (i.e., more negative) parietal alpha1 power and alpha2 power was seen for high- compared to low-value words in the 400-900 ms and 500-1000 ms time windows, respectively (Table 2.2; Figure 2.2). Given that the alpha sub-bands showed almost identical results, they will be discussed as a whole. However, data related to both sub-bands is reported as we plan to utilize this task with cognitively normal older adults and clinical populations, for which differences between alpha sub-bands have been observed (e.g., Nguyen et al., 2017). Desynchronized alpha power has been linked to cognitive processes, such as selective attention (Klimesch, 2012) and working memory (Babu Henry Samuel et al., 2018; Bashivan et al., 2014; Xie et al., 2016). It appears that our alpha power findings might be indicative of greater selective attention for high-value words. Although speculative, the sustained alpha band desynchronization beginning 400 ms and lasting until 900-1000 ms post-stimulus onset may reflect maintenance of high-value words in a short-term store (or "episodic buffer") driven by goal-relevant strategic control in preparation for encoding and storage for later recall (Baddeley & Hitch, 1974; Baddeley et al., 2018). Future studies should examine whether various point values (e.g., points ranging from 1-12; Castel et al., 2002; Castel et al., 2007; Castel et al., 2011) yield similar results.

For the ERSP data, a posteriori analyses were conducted to determine if the findings were affected by the significant differences in the number of high- and low-value words recalled between List 1 and the other four lists. After removing List 1 from the EEG analysis, the ERSP findings did not change in regard to the direction and time periods of effects for theta, alpha1, and alpha2 power. Additionally, no significant difference was observed for ERSPs between versions in which high-value was assigned to uppercase or lowercase words ($p > .05$ for all five lists), indicating that case did not have an effect.

In summary, our study showed differences in cortical brain dynamics related to high- and low-value words in a value-directed strategic processing task. Both behavioral and oscillatory brain responses were modulated by value or salience even though participants were not explicitly instructed to focus on high-value words and ignore low-value words. Importantly, the spectral power of brain activity in different frequency bands appear to capture different aspects of strategic processing. Theta band captured inhibition of low-value information, whereas the alpha bands reflected selective attention to high-value information. Findings from this study will be useful in evaluating neurophysiological changes related to strategic processing in normal cognitive aging and clinical populations (e.g., traumatic brain injury, dementia) given that behavioral studies on individuals with dementia have shown alterations in strategic processing (Castel et al., 2009; Wong et al., 2019). ERSPs may serve as affordable, non-invasive markers for evaluating the effects of pharmaceutical and non-pharmaceutical interventions in alleviating cognitive decline (Nguyen et al., 2017).

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CHAPTER 3: INVESTIGATING EEG THETA AND ALPHA OSCILLATIONS AS MEASURES OF VALUE-DIRECTED STRATEGIC PROCESSING IN COGNITIVELY NORMAL YOUNGER AND OLDER ADULTS[2]

ABSTRACT

Value-directed strategic processing is an ability that appears to be relatively preserved with aging, but the neurophysiological mechanisms underlying strategic processing in older adults are not well understood. The current study examined age-related spectral power differences in EEG oscillations linked to processing of high-value versus low-value information in a value-directed strategic processing task in 24 younger adults (mean age: 22.4 ± 1.2 years) and 24 older adults (mean age: 63.2 ± 6.4 years). Both groups exhibited comparable strategic processing ability behaviorally with preferential recall of high- compared to low-value words. Both groups exhibited comparable theta band power with greater synchronization for low- compared to high-value words, but age-related differences in processing were noted in alpha band power. Older adults showed more prolonged alpha desynchronization for high- compared to low-value words relative to younger adults. This neurophysiological modulation in the alpha band in older adults might reflect a compensatory neural mechanism or increased effort linked to selective engagement of neural resources, allowing them to perform similarly to younger adults behaviorally on a value-directed strategic processing task.

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[2] Chapter 3 is a reprint of a publication in Behavioural Brain Research and is referred to in this dissertation as "Nguyen et al., 2020". The full citation is Nguyen, L.T., Marini, F., Shende, S.A., Llano, D.A., & Mudar, R.A. (2020). Investigating EEG theta and alpha oscillations as measures of value-directed strategic processing in cognitively normal younger and older adults. *Behavioural Brain Research, 391*, 112702. https://doi.org/10.1016/j.bbr.2020.112702. This publication is reprinted under the Creative Commons CC-BY-NC-ND license.

3.1. Introduction

During each moment of our lives, we are exposed to vast amounts of information, but it would be inefficient and impossible for us to fully process all the stimuli we receive from the environment at any given time. Instead, we selectively process valuable or relevant information while inhibiting less valuable or irrelevant information, referred to as strategic processing (Castel, 2007, 2008). This value-directed preferential processing of information is crucial for routine activities, including reading, watching television, or having conversations. For example, when watching the news on television, we typically process and remember the most salient stories or pieces of information. As such, strategic processing can help increase the efficiency of memory-related processes, i.e., encoding, storage, and retrieval of information (Castel, 2007), by keeping us from becoming cognitively overburdened.

It is important to make a conceptual distinction between strategic processing ability and memory capacity (Castel et al., 2012). Strategic processing refers to preferential processing, or prioritization, of information based on its inherent or learned value through selectivity mechanisms (Castel et al., 2011; Siegel & Castel, 2019). Memory capacity refers to how much information can be remembered irrespective of its inherent value through memory mechanisms, i.e., encoding, storage, and retrieval. Given these conceptual differences, it is no surprise that tasks used to investigate strategic processing differ from those used to assess memory capacity. Traditional behavioral memory capacity studies use word-list learning tasks where the same list of words are repeated over multiple trials and the total number of words recalled for each trial and across trials are used as measures of episodic learning and memory capacity. Conversely, strategic processing studies typically use word-list learning tasks in which unique lists of words are presented for each trial where each word is associated with a corresponding value (e.g., high-value or low-value). For example, studies have paired words with values, where the values have ranged between 1-12 points (Castel et al., 2002; Castel et al., 2011), 1-16 points (Castel et al., 2007), 1-30 points (Castel et al., 2013), or -16-16 points (Castel et al., 2007). The difference in the number of higher versus lower valued words recalled is used as a behavioral metric of strategic processing ability.

Several behavioral studies have examined whether strategic processing ability changes with age (e.g., Castel et al., 2002; Castel et al., 2007; Castel et al., 2011; Castel et al., 2013) and whether it is related to the extensively studied age-related declines in memory capacity (e.g., Craik & McDowd, 1987; Harada et al., 2013; Nyberg et al., 1996; Nyberg et al., 2012; Park & Festini, 2016; Rönnlund et al., 2005). The strategic processing studies have shown that unlike declines in episodic learning and memory capacity with aging, cognitively normal older adults perform similarly to younger adults on value-directed strategic processing tasks with greater preferential recall of high- compared to low-value information (e.g., Castel et al., 2002; Castel et al., 2007; Castel et al., 2011; Castel et al., 2013). Furthermore, no significant correlation between episodic memory capacity and strategic processing has been observed in younger or older adults (Castel et al., 2011). This evidence suggests that strategic processing and memory capacity are reasonably dissociable and may be differentially impacted by aging (Castel et al., 2011; Siegel & Castel, 2019).

The lack of differences in strategic processing between younger and older adults on behavioral metrics is surprising given that the processes subsumed under strategic processing, such as selective attention and inhibition (Castel, 2008), have been shown to become less efficient with age (e.g., Craik & Byrd, 1982; Hasher & Zacks, 1988). One plausible explanation comes from the compensation-related utilization of neural circuits hypothesis (CRUNCH)

(Reuter-Lorenz & Cappell, 2008; Reuter-Lorenz & Lustig, 2005). CRUNCH proposes that older adults recruit more neural resources to overcome processing inefficiencies/deficiencies so that they can perform at levels similar to younger adults. Alternatively, as suggested in Hess' selective engagement theory (Hess, 2014), it may be that older adults respond to age-related changes by being more selective about when to engage more cognitive and neural resources, such as for tasks that they deem important or for information that is more salient (Hess & Ennis, 2012; Hess et al., 2016). Thus, examining the underlying neural bases of strategic processing may provide useful insights into why younger and older adults do not show behavioral differences.

To the best of our knowledge, two functional neuroimaging studies have examined neural substrates linked to value-directed strategic processing in both younger and older adults (Cohen et al., 2016; Hennessee et al., 2019). Cohen et al. (Cohen et al., 2016) found similarities between younger and older adults using functional magnetic resonance imaging (fMRI), with greater activation in the left ventral and posterior prefrontal cortex during processing of high- compared to low-value words. This activation was interpreted as being related to the recruitment of semantic processes for encoding high-value words, given that left prefrontal areas have previously been related to semantic processing and use of verbal encoding strategies (e.g., Badre & Wagner, 2007; Miotto et al., 2014; Savage et al., 2001; Thompson-Schill et al., 1997). However, region-of-interest analyses in semantic network areas revealed that better strategic processing in older adults, as measured behaviorally, was related to reduced activation for low-value words, whereas in younger adults better behavioral performance was related to enhanced activation for high-value words. These findings attest to age-related neural differences in strategic processing, with older adults relying more on inhibiting semantic processing of low-value words and younger adults relying more on enhancing semantic processing of high-value words. Hennessee et al. (Hennessee et al., 2019) used diffusion tensor imaging to examine white matter integrity in the left inferior fronto-occipital fasciculus (IFOF) and the left uncinate fasciculus (UF), which are both pathways that have been related to semantic processing. They found that higher IFOF integrity in older adults was correlated with greater recall of high-value words and not low-value words, whereas no correlations were found for younger adults. Additionally, higher UF integrity was correlated with greater recall of high-value words for younger adults, but not for older adults. These results were taken to suggest that left IFOF may provide a compensatory mechanism through which older adults engage in deeper semantic processing of high-value information. While these functional neuroimaging studies (Cohen et al., 2016; Hennessee et al., 2019) provide valuable insights into the neural substrates linked to value-directed strategic processing in normal cognitive aging, the temporal unfolding of these processes from a neurophysiological standpoint still remains largely unknown. Techniques with a high temporal resolution, such as electroencephalography (EEG), that best capture rapid cognitive processes online are useful for this purpose and may help to elucidate contrasting patterns of processing between younger and older adults.

Event-related spectral perturbations (ERSPs), which provide time-resolved information on phase-locked and non-phase-locked spectral activity in the EEG signal (Makeig et al., 2004), can help determine how oscillatory brain responses linked to strategic processing unfold (Nguyen et al., 2019). In particular, ERSPs can provide a more direct examination of strategic processing because they can reveal how information is processed online at a millisecond-level resolution, thereby adding to the existing behavioral and functional neuroimaging work on strategic processing. One common ERSP measure is spectral power in different frequency bands.

Changes in ERSP spectral power can be quantified as either an increase or decrease in power relative to a baseline period, referred to as event-related synchronization or desynchronization, respectively (for review see (Pfurtscheller & Lopes da Silva, 1999). ERSP power can be examined in different frequency bands, including delta (1-4 Hz), theta (4-8 Hz), alpha (8-12 Hz), beta (12-30 Hz), and gamma (> 30 Hz) bands. Changes in spectral power within each of these bands has been related to different cognitive processes depending on the frequency band and the direction of the changes (i.e., synchronization or desynchronization). The theta and alpha bands have been related to cognitive processes that are considered to contribute to strategic processing, including inhibition, selective attention, and semantic processing (e.g., Babu Henry Samuel et al., 2018; Cavanagh & Frank, 2014; Hanslmayr et al., 2012; Jensen & Tesche, 2002; Klimesch et al., 2007), as well as being sensitive to both cognitively normal and pathological aging (for review see (Ishii et al., 2017).

Theta and alpha band synchronization have been linked to inhibition which, in the context of strategic processing, is important for blocking the processing of low-value information to minimize memory overload and to avoid interference from this information. Specifically, frontal theta synchronization has been related to inhibition (e.g., Cavanagh & Frank, 2014; Cavanagh & Shackman, 2015; Nigbur et al., 2011) and executive control in working memory (e.g., Jensen & Tesche, 2002; Kawasaki et al., 2010), and synchronization in alpha band has also been associated with inhibition (e.g., Klimesch, 1999; Rihs et al., 2007; Suffczynski et al., 2001). Additionally, desynchronization in the alpha band has been linked to selective attention (Klimesch, 2012; Pfurtscheller & Lopes da Silva, 1999; Sadaghiani & Kleinschmidt, 2016) and semantic processing (Klimesch, 1999; Klimesch et al., 2007; Pfurtscheller & Lopes da Silva, 1999), both of which are important for deeper processing of high-value information. Given that

Cohen et al. (Cohen et al., 2016) provided fMRI evidence that younger and older adults rely on enhancing and inhibiting semantic processing differentially for strategic processing, both the theta and alpha bands appear to be well-suited to examine the neurophysiological basis of strategic processing in younger and older adults.

Indeed, a recent EEG study on value-directed strategic processing in young adults conducted by our group, using the same task that was used in the current study, showed differences in theta and alpha bands related to value-directed strategic processing (Nguyen et al., 2019). We found greater theta synchronization during the processing of low- compared to high-value words and greater alpha desynchronization during the processing of high- compared to low-value words. We interpreted these findings in the context of extant literature (Cohen & Donner, 2013; Hanslmayr et al., 2008; Klimesch, 2012; Nigbur et al., 2011), suggesting that theta synchronization was associated with active inhibitory control (blocking of low-value words), whereas alpha desynchronization was linked to selective attention and semantic processing (attention to and deeper processing of high-value words). Our findings indicated that these ERSP measures can capture strategic processing of information. Our next logical step was to investigate how strategic processing differs for younger versus older adults using the same ERSP measures.

Accordingly, the goal of the current study was to investigate potential differences in behavioral data and ERSP signatures of strategic processing in theta and alpha bands between younger and older adults. Based on our previous findings with younger adults using the same task used in the current study (Nguyen et al., 2019) and work by Castel and colleagues (e.g., Castel et al., 2002; Castel et al., 2007; Castel et al., 2011; Castel et al., 2013), we hypothesized that the behavioral data would show greater recall for high- compared to low-value words for both younger and older adults. However, we expected differences in the ERSP data, specifically (i) differences in theta band synchronization for low- versus high-value words in older adults, reflecting changes in neural inhibition, and (ii) differences in alpha band desynchronization for high- versus low-value words in older adults, reflecting changes in selective attention.

3.2. Material and methods

3.2.1. Participants

Twenty-four cognitively normal young adults (*M* = 22.4, SD = 1.2 years) and 24 cognitively normal older adults (*M* = 63.2, *SD* = 6.4 years) participated in the study (see Table 3.1 for full demographics). Younger adults were recruited from the University of Illinois campus and Urbana-Champaign neighborhoods. Older adults were recruited from a pool of control participants who were rigorously screened using a cognitive battery to exclude those with cognitive impairment. None had self-reported cognitive complaints and all had normal global cognitive screening scores on the Montreal Cognitive Assessment (*M* = 27.7, *SD* = 1.5). Additional information about their cognitive scores can be found in Supplementary Table 3.1 of the Supplementary Material. The two groups were significantly different for age, $F(1,47) = 951.68$, $p < .001$, but not for years of education, $F(1,47) = 2.19$, $p = .145$, or sex, $\chi^2(1, N = 48) = 2.64$, $p = .104$. All participants were native English speakers, right-handed, and did not have any history of communication disorders, neurological disorders, psychiatric disorders, traumatic brain injury, learning disabilities, or uncorrected visual or auditory impairments. Written informed consent was obtained from all participants in accordance with the University of Illinois at Urbana-Champaign Institutional Review Board protocols before completing the study.

Table 3.1

Participant Demographics

	Younger adults	**Older adults**
Total N	24	24
Age (yrs)	22.4 (1.2)	63.2 (6.4)
Education (yrs)	16.0 (1.1)	16.7 (2.1)
Sex	15F/9M	20F/4M

Cells represent mean (standard deviation).

3.2.2. Strategic processing task and procedures

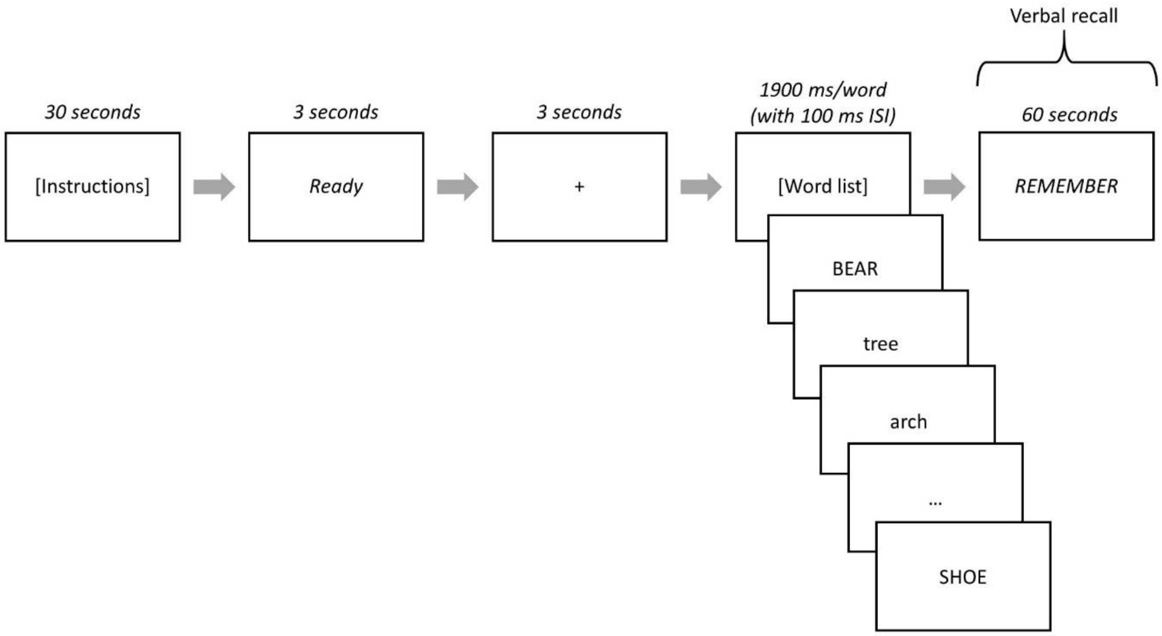
All participants completed a strategic processing task, which was a value-directed word list learning task developed in-house. The word stimuli consisted of 200 single syllable four letter nouns from the MRC Psycholinguistic Database (Coltheart, 1981) and SUBTLEX$_{US}$ database (Brysbaert & New, 2009). Words were controlled for frequency (mean: 25.3 ± 22.7; range: 1-96), imageability (mean: 571.1 ± 40.0; range: 439-659), concreteness (mean: 571.8 ± 40.7; range: 501-637), and familiarity (mean: 524.4 ± 51.7; range: 370-615). The 200 word stimuli were divided into five lists of 40 words each. Given that the task was designed to evaluate strategic processing, each of the five lists contained a unique set of words, unlike typical episodic learning and memory tasks (e.g., California Verbal Learning Test) which repeat the same words in each list. The words were comparable in frequency, $F(4,195) = 0.32$, $p = .868$, imageability, $F(4,195) = 0.31$, $p = .874$, concreteness, $F(4,195) = 0.59$, $p = .668$, and familiarity, $F(4,195) = 0.58$, $p = .681$, across the five lists.

For each of the five lists, half of the words ($n = 20$) were assigned high-value (worth 10 points) and half ($n = 20$) were assigned low-value (worth 1 point). High- and low-value words were differentiated by letter case (i.e., uppercase letters [LAMB] versus lowercase letters [lamb]). Participants were randomly assigned to one of four versions of the task, and each version was counterbalanced for word value and letter case. In two versions, words in uppercase letters were assigned high-value and words in lowercase letters were assigned low-value. In the other two versions, words in lowercase letters were assigned high-value and words in uppercase letters were assigned low-value. The font size was controlled for the height of the words. This ensured that uppercase and lowercase words, all of which were four-letter words, appeared to have comparable sizes on the screen.

The following instructions were presented on screen to participants: “You will see words appear on the screen one at a time. Some words are in uppercase and some words are in lowercase. The uppercase words *[lowercase words]* are worth 10 points each (high-value words). The lowercase words *[uppercase words]* are worth 1 point each (low-value words). At the end of the list, you will see the word “REMEMBER” on the screen. Your task is to remember as many of the words from the list as possible with the goal of scoring the maximum number of points. This is similar to a game in which words are worth different amounts of money”. The research assistant conducting the experiment confirmed that participants understood the point values for the uppercase and lowercase words, which was dependent on their assigned version. Importantly though, the research assistant did not provide specific instructions on how to be strategic, such as only focusing on the high-value words. Following the instructions, the word “Ready” was displayed on the center of the screen for 3000 ms followed by a fixation (+) for 3000 ms. The 40 words from one list were then displayed sequentially in the center of the screen for 1900 ms each with an inter-stimulus interval of 100 ms (blank screen). The word “REMEMBER” appeared at the end of each list at which point participants had 60 seconds to verbally recall words from that list while their responses were manually recorded on a score sheet (see Figure 3.1 for task schematic). Participants received immediate feedback from the research assistant about their score after each list and before the next list was presented. After all five lists were completed, participants completed a brief post-experiment interview about whether they used any strategies during the task, and if so, what types of strategies they used (e.g., sorting words by categories; words that rhyme).

Figure 3.1

Strategic Processing Task Schematic



High- and low-value words were represented by lowercase or uppercase words depending on the task version. When the word "REMEMBER" was presented, participants verbally recalled words from the list and their responses were recorded on paper and scored. This process was repeated for all five lists.

3.2.3. EEG data collection and preprocessing

Continuous EEG was recorded for each of the five lists using a 64-electrode Lycra cap (Neuroscan Quikcap) using a Neuroscan SynAmps RT amplifier and Scan v4.5 software (sampling rate: 1kHz, bandpass filter: DC-200Hz) with impedances typically below 10 kΩ. The reference electrode was located at midline between Cz and CPz and vertical electrooculogram (VEOG) was recorded at sites above and below the left eye. EEG data were processed offline using Neuroscan Edit. Raw EEG data from each of the five lists (obtained during a single testing session) were appended together to have enough trials per value type for analysis (i.e., 100 high-value trials; 100 low-value trials). Poorly functioning electrodes identified based on both high impedance values (above 20 kΩ) and visual inspection of the raw EEG signal were excluded from analysis (average 0.5 electrode for each younger adult and 1 electrode for each older adult). Eye blinks were corrected using spatial filtering in Neuroscan Edit. The data were epoched from 500 ms before stimulus onset to 1500 ms after stimulus offset. Epochs with peak signal amplitudes of ±75 μV were rejected. Of the total number of high-value epochs, 12.0% and 11.9% were rejected for younger and older adults, respectively. Of the total number of low-value epochs, 11.9% and 12.7% were rejected for younger and older adults, respectively. EEG data were re-referenced to the average potential over the entire scalp.

3.2.4. ERSP analysis

The EEG epochs from -500 to 1500 ms were used to generate ERSPs from -400 to 1400 ms. For the purpose of this paper, ERSPs were analyzed from 0 to 1000 ms (post-stimulus onset) with a non-overlapping baseline of -400 to -100 ms (pre-stimulus onset) using EEGLAB toolbox (Version 14.1.1b) (Delorme & Makeig, 2004) running under Matlab 2018b (MathWorks, Natick, MA, USA). Time-frequency decomposition was performed using short-time Fourier transform with Hanning window tapering as implemented in the EEGLAB function *newtimef.m*. Time-frequency data were obtained using a 256-ms sliding window with a step size of 10 ms and a pad ratio of 4, resulting in a frequency resolution of approximately 1 Hz from 4 to 30 Hz. Baseline correction was done in accordance with a gain model (Delorme & Makeig, 2004; Grandchamp &

Delorme, 2011), where each time-frequency time point was divided by the average pre-stimulus baseline power from -400 to -100 ms relative to stimulus onset at the same frequency.

3.2.5. ERSP power estimation

Mean power was estimated in the theta band (4-8 Hz) at frontal sites (average of Fz, F1, F2) and in the alpha band (8-12 Hz) at parietal sites (average of Pz, P1, P2). Changes in power will be described as synchronization or desynchronization, depending on whether there was an increase or decrease in power, respectively, relative to baseline. A priori defined alpha band was used, as opposed to bands derived from individual alpha frequency (IAF), as no significant between-group differences were observed for IAF values for either the high-value (p = .110) or low-value (p = .860) words. Additional details regarding IAF are provided in Supplementary Table 3.2 in Supplementary Material. The electrode sites were selected based on work demonstrating greater prominence of theta band at frontal sites and alpha at parietal/posterior sites (e.g., Cavanagh & Frank, 2014; Hanslmayr et al., 2012; Ishii et al., 1999; Kawasaki et al., 2010; Nguyen et al., 2019). Mean spectral power was computed for each group (younger/older adults), value (high-/low-value), and frequency band (theta, alpha) in 100-ms time windows from 0 ms to 1000 ms with no overlap, resulting in 10 time windows for analysis.

3.2.6. Statistical analysis

We first examined whether there were significant differences across the two versions based on the letter case (i.e., words in uppercase being assigned to high-value vs. words in lowercase being assigned to high-value) to guide the analysis of the behavioral and ERSP data. No significant differences were observed across versions for behavioral (p > .05 for all five lists) or ERSP data ($p > .05$ for all time windows), so the data was not separated by version. Task-related behavioral data, specifically the average number of high- and low-value words recalled, were analyzed using a general linear model (GLM) with group (younger/older adults) as a between-subject factor and value (high-/low-value) as a within-subject factor to assess whether participants engaged in strategic processing.

ERSP data were examined using separate GLMs for theta and alpha bands, with group (younger/older adults) as a between-subject factor and value (high-/low-value) as a within-subject factor, for each of the 10 time windows (100 ms time windows between 0 and 1000 ms post-stimulus onset). Significance values were corrected for multiple comparisons with the Bonferroni method at a threshold of $p < .05$. IBM SPSS Statistics 24 was used for analysis. The reported p-values were derived from F- and t-statistics, if not specified otherwise.

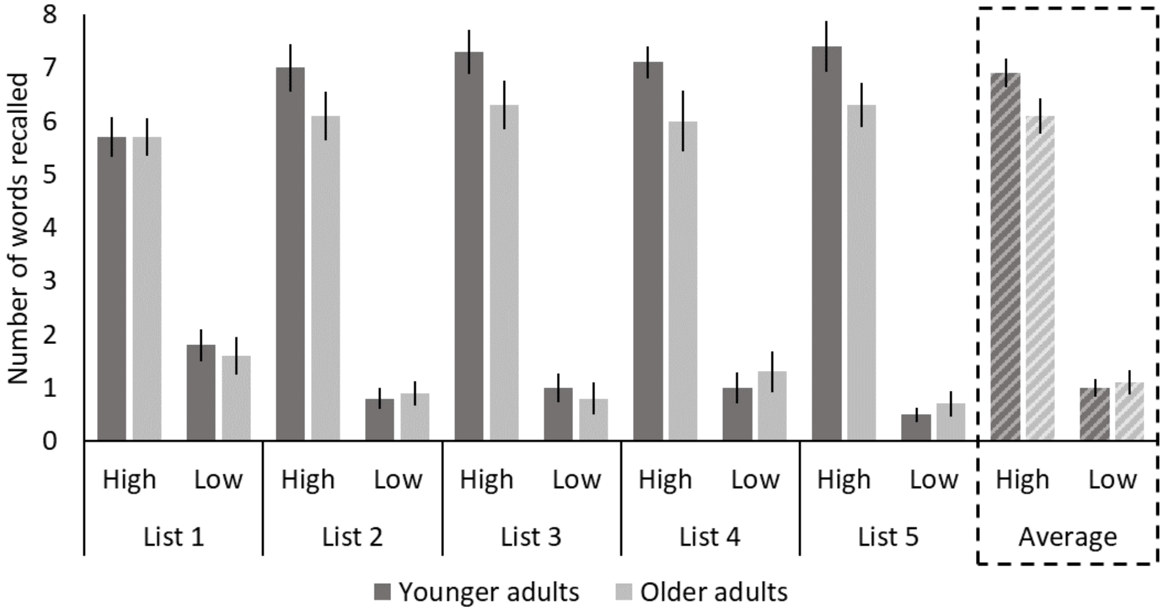
3.3. Results

3.3.1. Task-related behavioral data

Task-related behavioral data revealed main effects of value with greater recall for high- compared to low-value words for all five lists ($p < .001$; Figure 3.2). The main effects of group were not significant ($p > .05$) nor were the interaction effects between group and value ($p > .05$; see Supplementary Table 3.3 in Supplementary Material for detailed statistical results).

Figure 3.2

Task-related Behavioral Data



The number of high- and low-value words recalled across the five lists for both younger and older adults are shown. The average is the average number of words recalled across the five lists. Bars represent standard error. No significant differences were observed between the two groups in the number of words recalled.

3.3.2. Theta band (4-8 Hz) mean power

Significant main effects of value were observed from 700-1000 ms post-stimulus onset ($p < .05$), with greater frontal theta synchronization for low- compared to high-value words (Table 3.2; Figure 3.3). The main effects of group and the interaction effects between group and value were not significant at any of the 10 time windows ($p > .05$; Table 3.3; see Supplementary Table 3.4 in Supplementary Material for statistical results for the main effects of group). To examine if the significant effects extended beyond 1000 ms, a posteriori analysis was carried out from 1000-1300 ms. No significant main or interaction effects were observed for these extended time windows ($p > .05$).

3.3.3. Alpha (8-12 Hz) mean power

Significant main effects of value were observed from 500-1000 ms post-stimulus onset ($p < .001$), with greater parietal alpha desynchronization for high- compared to low-value words (Table 3.2; Figure 3.3). Significant interaction effects between group and value were observed from 800-1000 ms post-stimulus onset ($p < .05$; Table 3.3; Figure 3.4). While the post hoc analyses did not reveal any between-group differences ($p > .05$), there were within-group differences between high- and low-value words. These differences were seen from 800-900 ms for younger adults ($p = .006$) and from 800-1000 ms for older adults ($p < .001$), with both groups showing greater alpha desynchronization for high- compared to low-value words. The main effects of group were not significant at any of the 10 time windows ($p > .05$; see Supplementary Table 3.4 in Supplementary Material). A posteriori analysis was conducted from 1000-1300 ms to determine if the significant effects extended beyond 1000 ms. A main effect of value was seen from 1000-1100 ms post-stimulus onset ($p < .01$), with greater parietal alpha desynchronization for high- compared to low-value words, but these effects were not significant from 1100-1200 ms or 1200-1300 ms ($p > .05$). The main effects of group and the interaction effects between group and condition were not significant at any of these extended time windows ($p > .05$).

Table 3.2

Statistical Results for Main Effects of Value for Theta and Alpha Band Mean Power

	Time (ms)									
	0-100	**100-200**	**200-300**	**300-400**	**400-500**	**500-600**	**600-700**	**700-800**	**800-900**	**900-1000**
Theta	*F* = 0.40 *p* = .530	*F* = 0.89 *p* = .350	*F* = 0.68 *p* = .413	*F* = 0.27 *p* = .604	*F* = 0.07 *p* = .794	*F* = 1.75 *p* = .192	*F* = 3.03 *p* = .088	***F* = 6.73** ***p* = .013** **η_p^2 = .13**	***F* = 4.31** ***p* = .043** **η_p^2 = .09**	***F* = 6.33** ***p* = .015** **η_p^2 = .12**
Alpha	*F* = 0.10 *p* = .751	*F* = 0.44 *p* = .511	*F* = 0.00 *p* = .961	*F* = 0.13 *p* = .718	*F* = 0.89 *p* = .351	***F* = 17.29** ***p* < .001** **η_p^2 = .27**	***F* = 36.25** ***p* < .001** **η_p^2 = .44**	***F* = 48.99** ***p* < .001** **η_p^2 = .52**	***F* = 34.29** ***p* < .001** **η_p^2 = .43**	***F* = 29.72** ***p* < .001** **η_p^2 = .39**

Cells display statistics for the main effects of value (high-/low-value words) for mean power in theta (4-8 Hz) and alpha (8-12 Hz) bands across 10 time windows post-stimulus onset. For all *F*-values, degrees of freedom = (1, 46). Significant main effects of value are indicated by bolded values (*p* < .05, Bonferroni-corrected) and their effect sizes (η_p^2) are reported.

Table 3.3

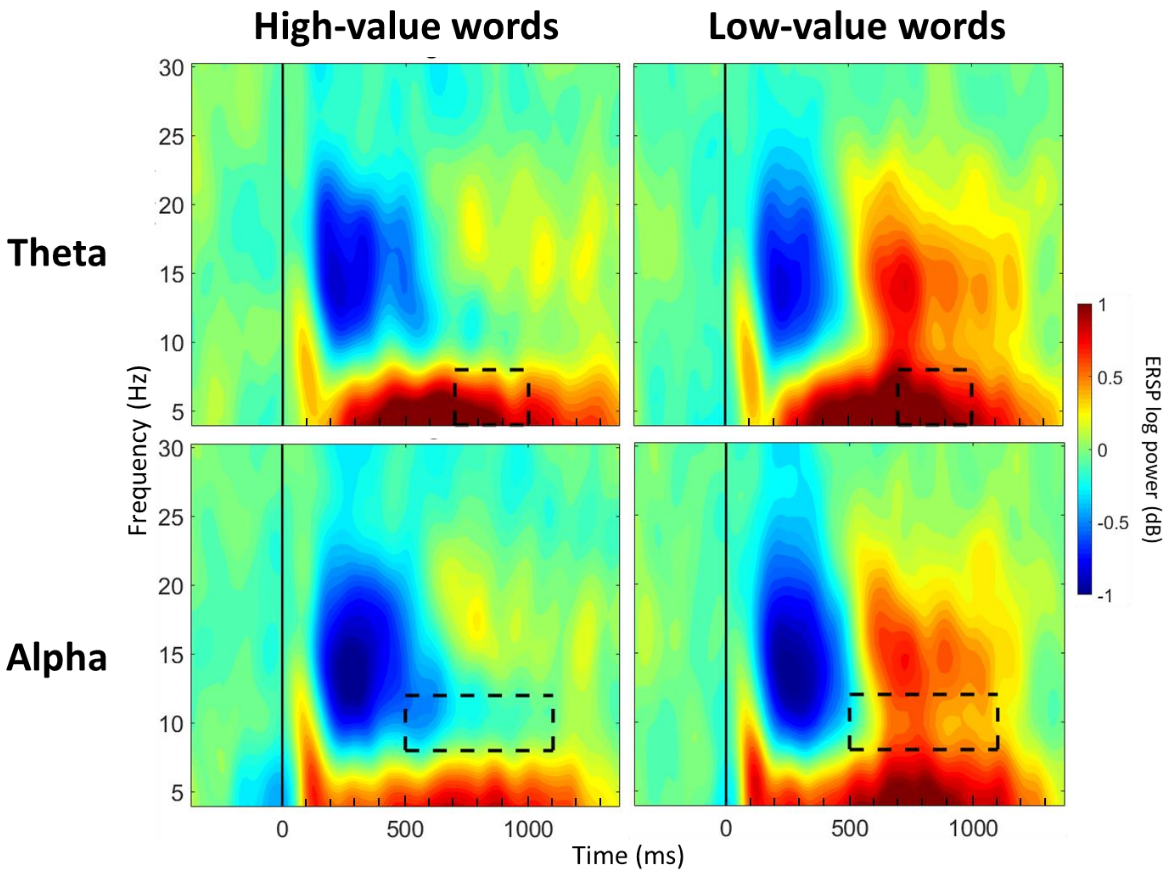
Statistical Results for the Group by Value Interactions for Theta and Alpha Band Mean Power

	Time (ms)									
	0-100	**100-200**	**200-300**	**300-400**	**400-500**	**500-600**	**600-700**	**700-800**	**800-900**	**900-1000**
Theta	*F* = 0.29 *p* = .596	*F* = 0.07 *p* = .794	*F* = 2.58 *p* = .115	*F* = 0.00 *p* = .953	*F* = 2.10 *p* = .154	*F* = 0.68 *p* = .414	*F* = 0.10 *p* = .752	*F* = 0.65 *p* = .425	*F* = 0.03 *p* = .860	*F* = 0.77 *p* = .385
Alpha	*F* = 0.02 *p* = .877	*F* = 0.80 *p* = .376	*F* = 1.40 *p* = .243	*F* = 0.78 *p* = .381	*F* = 0.09 *p* = .766	*F* = 3.02 *p* = .089	*F* = 0.20 *p* = .654	*F* = 3.72 *p* = .060	***F* = 4.37** ***p* = .042** **η_p^2 = .09**	***F* = 10.01** ***p* = .003** **η_p^2 = .18**

Cells display statistics for interaction effects between group (younger/older adults) and value (high-/low-value words) for mean power in theta (4-8 Hz) and alpha (8-12 Hz) bands across 10 time windows post-stimulus onset. For all *F*-values, degrees of freedom = (1, 46). Significant interaction effects between group and value are indicated by bolded values (*p* < .05, Bonferroni-corrected) and their effect sizes (η_p^2) are reported.

Figure 3.3

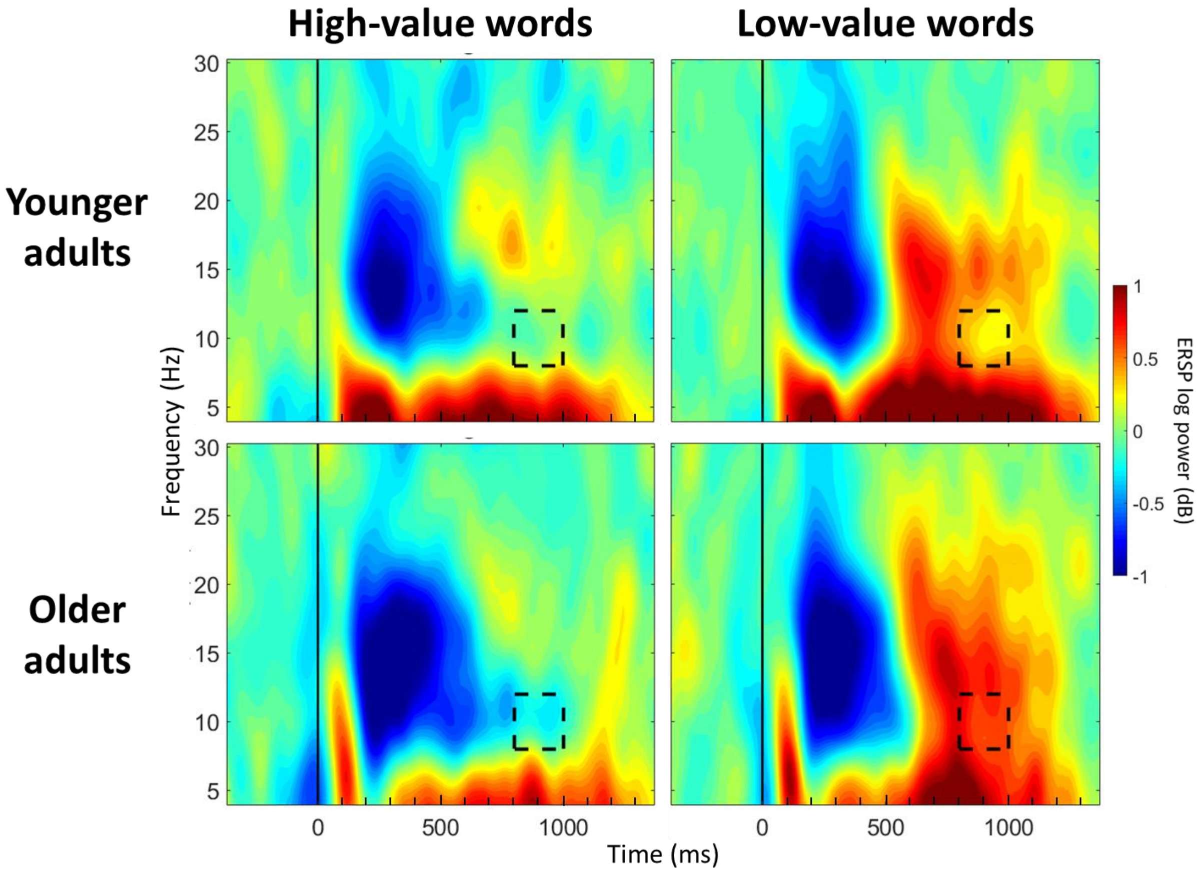
ERSP Comparisons for the Main Effects of Value



Spectrograms illustrate differences between value (high-/low-value) for theta band (4-8 Hz) at frontal sites (average of Fz, F1, F2) and alpha band (8-12 Hz) at parietal sites (average of Pz, P1, P2). The 0 ms time point (solid vertical line) represents stimulus onset. Dashed black rectangles indicate the time windows where significant main effects of value were observed, including the findings of the extended time window analysis (also see Table 2). An extended frequency spectrogram (1-50 Hz) of this data can be found in Supplementary Figure 3.1 in Supplementary Material.

Figure 3.4

ERSP Comparisons for Interaction Effects Between Group and Value



Spectrograms illustrate differences between group (younger/older adults) and value (high-/low-value) at parietal sites (average of Pz, P1, P2). The 0 ms time point (solid vertical line) represents stimulus onset. Dashed black rectangles indicate the alpha (8-12 Hz) band and time window (800-1000 ms) where significant interaction effects between group and value were observed (also see Table 3). An extended frequency spectrogram (1-50 Hz) of this data can be found in Supplementary Figure 3.2 in Supplementary Material.

3.4. Discussion

The current study examined oscillatory brain responses related to strategic processing as a function of age, a topic that has received limited investigation despite its relevance in understanding the neural mechanisms underlying potential age-related changes in strategic processing. Behavioral data are presented as evidence for preferential processing (i.e., greater recall of high- versus low-value words) consistent with the literature on value-directed strategic processing (Castel, 2007; Castel et al., 2002; Castel et al., 2007; Castel et al., 2011), while ERSP data describe the neurophysiological underpinnings related to strategic processing that are independent of subsequent recall. Similarities in value-directed strategic processing between younger and older adults were indexed by main effects of value (high-/low-value) for behavioral data, theta band activity (700-1000 ms), and alpha band activity (500-1100 ms). Age-related differences in value-directed strategic processing were noted by interactions between group (younger/older adults) and value (high-/low-value) in alpha band activity (800-1000 ms).

As hypothesized, younger and older adults exhibited comparable behavioral performance for value-directed strategic processing, with both groups recalling significantly more high-value words compared to low-value words. These findings are consistent with those of Castel and colleagues (Castel et al., 2002; Castel et al., 2007; Castel et al., 2011; Castel et al., 2013) who have shown that older adults have relatively preserved ability to strategically process information based on value. However, our findings differ somewhat from Castel and colleagues in that the older adults in our study recalled as many total number of words as the younger adults, whereas Castel and colleagues (Castel et al., 2002; Castel et al., 2007; Castel et al., 2011; Castel et al., 2013) found that older adults recalled fewer total words than younger adults. Several factors may have led to this difference in findings including differences in value assignment and age of the participants. Our study paradigm was simpler in that we used a binary value assignment of either high-value (10 points) or low-value (1 point) based on letter case, whereas Castel and colleagues used point value ranges in their studies where words were paired with various point value ranges (e.g., 1-12 points, -16-16 points) (Castel et al., 2002; Castel et al., 2007; Castel et al., 2011; Castel et al., 2013). Participants were told that this value represented how much the word was worth and that they should try to maximize their score. The added task complexity may have contributed to differences in findings between our studies. Additionally, on average, the older adults in our study were younger (average 63.2 years) than the older adults in the studies by Castel and colleagues (approximate average 71.3 years across studies; (Castel et al., 2002; Castel et al., 2007; Castel et al., 2011; Castel et al., 2013).

ERSP data also revealed some similarities between younger and older adults in processing high- versus low-value words within the theta and alpha bands. Both younger and older adults showed greater synchronization for low- compared to high-value words in frontal theta from 700-1000 ms post-stimulus onset (Figure 3.3), consistent with the findings of our previous study in young adults using the same task (Nguyen et al., 2019). Frontal theta synchronization has been associated with detecting and inhibiting conflicting information on tasks like Go/NoGo, flanker, Stroop, and Simon (Cavanagh & Frank, 2014; Cohen & Donner, 2013; Hanslmayr et al., 2008; Nigbur et al., 2011). Our theta band findings suggest that younger and older adults appear to have comparable levels of neural resources employed to strategically suppress the processing of less valuable information.

Both groups also had greater parietal alpha desynchronization for high- compared to low-value words from 500 to 1100 ms post-stimulus onset (Figure 3.3), similar to our previous study (Nguyen et al., 2019). Desynchronization in the alpha band has been shown to reflect engagement of selective attention in the context of visuo-spatial attention and selective attention paradigms (Foxe & Snyder, 2011; Klimesch, 2012; Klimesch et al., 2007), as well as being related to semantic processing within the context of semantic category and feature judgment tasks and the subsequent memory paradigm (Hanslmayr et al., 2009; Hanslmayr & Staudigl, 2014; Hanslmayr et al., 2012). Whether greater alpha desynchronization observed during processing of high-value words is a marker of selective attention or higher semantic-based processing, or both, cannot be parsed out using our paradigm. Interestingly though, 58% of all participants in the current study reported in their post-experiment interviews that they used semantic strategies to remember high-value words, including creating sentences and/or stories and categorizing words (e.g., animals), suggesting an inextricable interplay between selective attention and semantic processing of high-value words in the context of our paradigm for both younger and older adults. Our findings correspond well with the fMRI study of strategic processing by Cohen et al. (Cohen et al., 2016) who found that both younger and older adults had greater activity for high- compared to low-value words in the left inferior frontal gyrus, an area linked to semantic encoding strategies (Badre & Wagner, 2007; Miotto et al., 2014; Savage et al., 2001; Thompson-Schill et al., 1997). Overall, our findings demonstrate that both groups utilized comparable neural resources to preferentially process high-value information.

Alpha band data also revealed some age-related differences in strategic processing. Specifically, the greater alpha desynchronization for high- versus low-value words diverged with age in later stages of processing (800-1000 ms interval post-stimulus onset). We examined whether these findings continued beyond the 1000 ms timepoint by conducting a post hoc extended analysis from 1000-1300 ms. We did not find any significant effects beyond the 1000 ms timepoint. In both groups, there was greater alpha desynchronization for high- compared to low-value words, but older adults sustained this processing distinction longer than younger adults (i.e., 800-1000 ms for older adults vs. 800-900 ms for younger adults; see Figure 4). This could reflect more prolonged processing of high-value words in older adults to accomplish similar behavioral performance to younger adults. In fact, Castel, Murayama, Friedman, McGillivray, & Link (2013) found that older adults allocated more study time than younger adults to words paired with the highest point values effectively reducing age-related differences in recall of high-value words. Our finding can be interpreted as supporting the framework of CRUNCH (Reuter-Lorenz & Cappell, 2008; Reuter-Lorenz & Lustig, 2005), which states that older adults recruit additional neural resources to achieve a behavioral performance level similar to younger adults. Alternately, this finding might support the idea that, as a strategy to account for age-related cognitive changes, older adults selectively engage additional resources for certain tasks because they have metacognitive awareness of their reduced memory capacity (Hess, 2014; Hess et al., 2016; Siegel & Castel, 2019). The current study cannot definitively support whether the observed neurophysiological differences relate to neural compensation or selective cognitive engagement in older adults, but it highlights that neural processing linked to strategic processing differs between young and old.

The current study has a few limitations that could be addressed in future work. First, this study was not designed to allow for ERSP comparisons of successfully and unsuccessfully recalled words, as would be done in a subsequent memory paradigm (Paller & Wagner, 2002), because we did not have enough trials (i.e., accepted EEG epochs) to undertake such comparisons. Second, the current study did not examine spectral power in the beta band (12-30 Hz). Although beta band has been shown to be associated with semantic processing (Hanslmayr et al., 2012; Waldhauser et al., 2012), it has largely been related to successful episodic encoding and retrieval (Hanslmayr et al., 2012; Pfurtscheller & Lopes da Silva, 1999; Spitzer & Haegens, 2017), which this study was not designed to evaluate, as mentioned above. Future studies should consider how this task could be modified to collect ERSP data that can reveal possible associations between strategic processing, subsequent memory, and beta band power. Third, given that strategic processing ability may be influenced by metacognitive awareness (McGillivray & Castel, 2017; Siegel & Castel, 2019) and selective cognitive engagement (Hess, 2014), future study procedures should incorporate self-report measures of metacognitive awareness and level of engagement. This would allow for examinations of the relationship between these measures and the ERSP markers of strategic processing. Finally, the study procedures did not include recording the order of verbally recalled words. By examining participant's order of recall, patterns might emerge in their output that could potentially reveal strategies used during retrieval. For example, it may show that participants first only recalled high-value words and then recalled low-value words, demonstrating prioritization of the high-value information. It may also allow for analysis of semantic patterns such as clustering.

In summary, younger and older adults performed similarly on behavioral measures of recall coinciding with the findings of Castel and colleagues (Castel et al., 2002; Castel et al., 2007; Castel et al., 2011). The two groups also showed similarities in neural processing, namely in the theta and alpha bands, and these value-directed neural modulations align well with the findings of our previous study (Nguyen et al., 2019). Importantly, the current study revealed differences in alpha band between younger and older adults despite the comparable behavioral performance, suggesting that there were differences in the way neural resources were engaged to perform value-directed strategic processing. These ERSP markers may be valuable for characterizing early neural changes related to strategic processing in mild cognitive impairment and early stages of dementia. The prolonged processing observed in cognitively normal older adults in the current study may not be sustainable in disease states due to reduced capability in engaging compensatory mechanisms. Indeed, behavioral studies have shown altered strategic processing in older adults with dementia (Castel et al., 2009; Wong et al., 2019), but it is not clear what changes may occur in the underlying neurophysiological mechanisms.

Supplementary Material

There are three Supplementary Material sections. The first Supplementary Material section is a reprint of what can be found with the published article. The second Supplementary Material section includes beta band analysis and the third Supplementary Material section includes Principal Component Analysis, neither of which are part of the published article.

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3.5. Supplementary material for Chapter 3

Supplementary Table 3.1

Cognitive Assessment Performance for Older Adults

Measure	Mean (SD)
Montreal Cognitive Assessment	27.7 (1.5)
Trail Making Test - A	25.6 (6.8)
Trail Making Test - B	63.5 (19.6)
Letter fluency (F,A,S)	49.6 (11.9)
Category fluency (Animals)	21.5 (4)
Boston Naming Test (30 items)	28.4 (1.5)
DKEFS CWI - Color naming (sec)	26.5 (3.6)
DKEFS CWI - Word reading (sec)	21.2 (6.4)
DKEFS CWI - Inhibition (sec)	51.3 (9.2)
DKEFS CWI - Inhibition/Switching (sec)	56.7 (13.2)

DKEFS CWI: Delis-Kaplan Executive Function System Color-Word Interference.

3.5.1. Individual alpha frequency

For each participant, power was calculated for each electrode individually and then averaged across electrodes. The average of all the individual electrodes was used to calculate global power spectra for each condition (high-value/low-value). Individual alpha frequency **(**IAF) was determined by identifying the frequency that had peak power within the extended alpha range (7-14 Hz) in the global spectrum. IAF was calculated separately for each condition, resulting in two IAF values for each group. The IAF group means and *p*-values for the comparison of younger and older adults are reported in Supplementary Table 3.2.

Supplementary Table 3.2

Groups Means for Individual Alpha Frequency

	Younger adults	Older adults	*F, p*
High-value words	11.7 (2.2)	10.6 (2.6)	$F(1,47) = 2.65$, $p = .110$
Low-value words	10.9 (2.3)	11.0 (2.4)	$F(1,47) = 0.03$, $p = .860$

Each cell represents group mean (standard deviation) in Hz.

Supplementary Table 3.3

Statistical Results for Behavioral Data

	Main effect: Group	**Main effect: Value**	**Interaction: Group x Value**
List 1	$F = 0.17$ $p = .685$	$\boldsymbol{F = 93.36}$ $\boldsymbol{p < .001}$	$F = 0.06$ $p = .801$
List 2	$F = 1.99$ $p = .165$	$\boldsymbol{F = 211.63}$ $\boldsymbol{p < .001}$	$F = 1.75$ $p = .193$
List 3	$F = 2.83$ $p = .100$	$\boldsymbol{F = 255.27}$ $\boldsymbol{p < .001}$	$F = 1.30$ $p = .260$
List 4	$F = 1.61$ $p = .211$	$\boldsymbol{F = 147.12}$ $\boldsymbol{p < .001}$	$F = 2.23$ $p = .142$
List 5	$F = 1.71$ $p = .197$	$\boldsymbol{F = 305.49}$ $\boldsymbol{p < .001}$	$F = 3.28$ $p = .076$

Cells display statistics for main effects of group (younger/older adults), main effects of value (high-/low-value words), and interaction effects between group and value for the five word lists. For all *F*-values, degrees of freedom = (1, 46). Significant effects are indicated by bolded values.

Supplementary Table 3.4

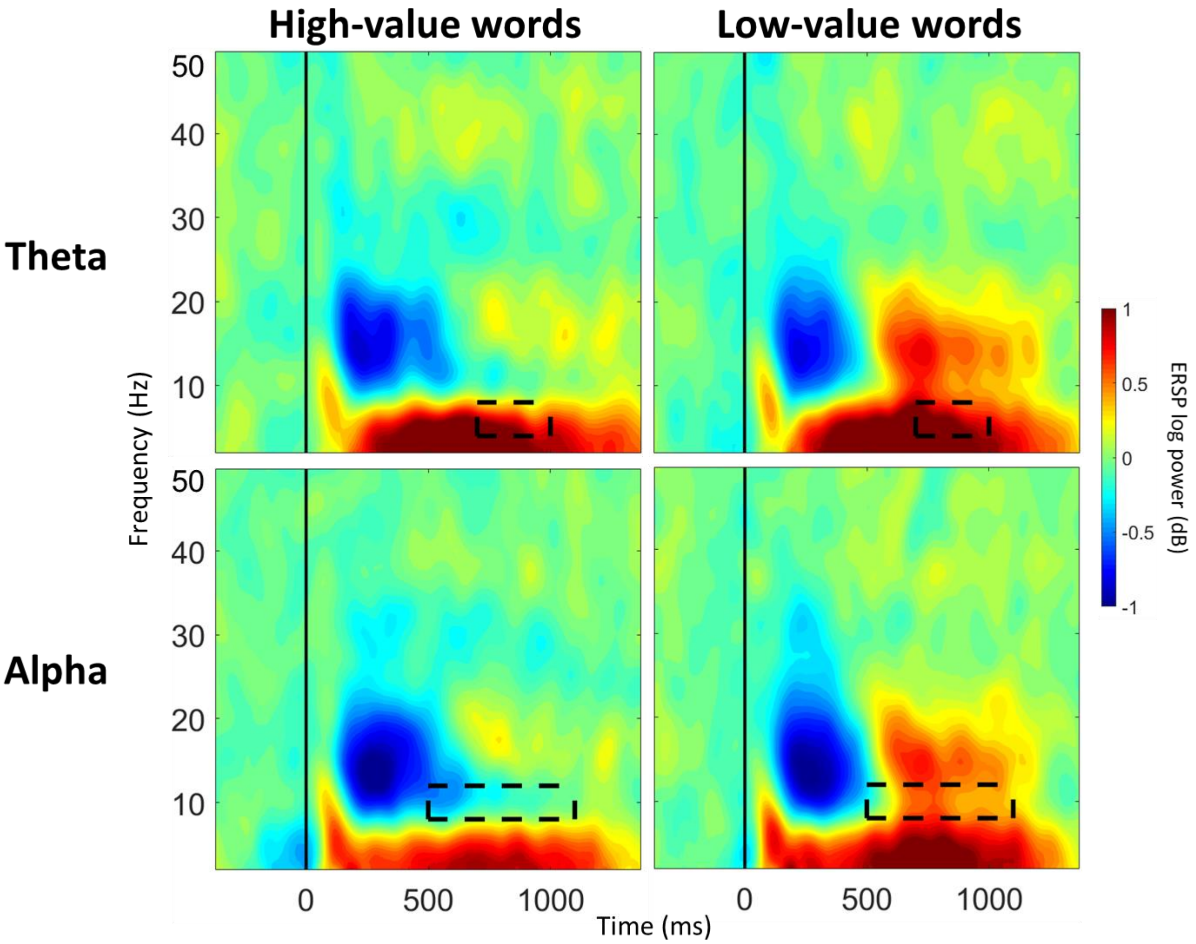
Statistical Results for Main Effects of Group for Theta and Alpha Band Mean Power

	Time (ms)									
	0-100	**100-200**	**200-300**	**300-400**	**400-500**	**500-600**	**600-700**	**700-800**	**800-900**	**900-1000**
Theta	$F = 0.03$ $p = .861$	$F = 0.03$ $p = .866$	$F = 3.80$ $p = .057$	$F = 0.31$ $p = .580$	$F = 0.00$ $p = .958$	$F = 0.01$ $p = .922$	$F = 0.08$ $p = .784$	$F = 0.03$ $p = .857$	$F = 0.04$ $p = .853$	$F = 0.30$ $p = .585$
Alpha	$F = 0.01$ $p = .913$	$F = 0.02$ $p = .897$	$F = 1.73$ $p = .194$	$F = 0.17$ $p = .681$	$F = 0.44$ $p = .510$	$F = 2.69$ $p = .108$	$F = 1.86$ $p = .179$	$F = 0.10$ $p = .755$	$F = 0.15$ $p = .698$	$F = 0.07$ $p = .799$

Cells display statistics for main effects of group (younger/older adults) for mean power in theta (4-8 Hz) and alpha (8-12 Hz) bands across 10 time windows post-stimulus onset. All *F*-values have 46 (denominator) degrees of freedom. No main effects of group were significant ($p > .05$, Bonferroni-corrected).

Supplementary Figure 3.1

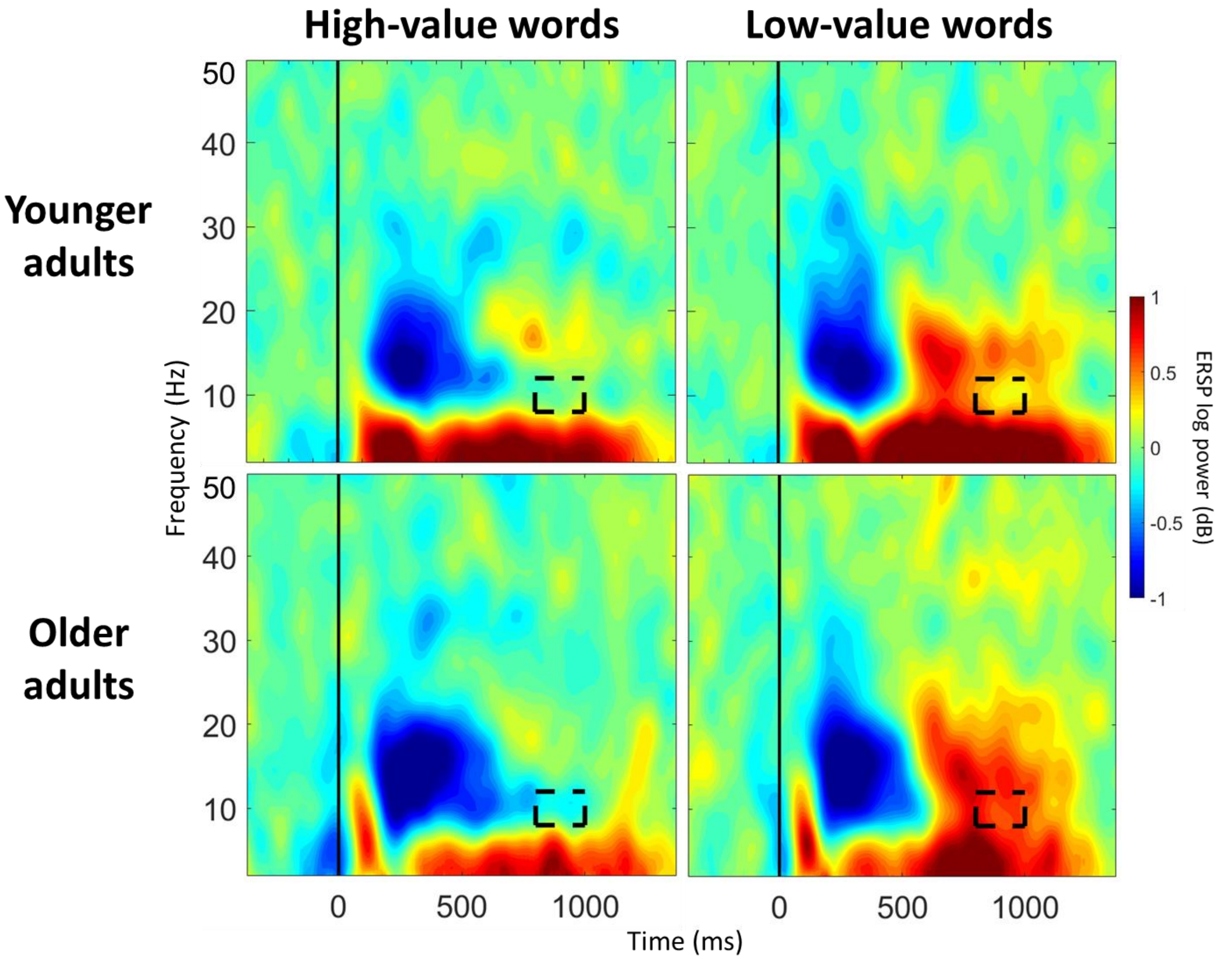
Extended Frequency ERSP Comparisons for Main Effects of Value



Spectrograms illustrate differences between value (high-/low-value) for theta band (4-8 Hz) at frontal sites (average of Fz, F1, F2) and for alpha band (8-12 Hz) at parietal sites (average of Pz, P1, P2). The 0 ms time point (solid vertical line) represents stimulus onset. Dashed black rectangles indicate the time windows where significant main effects of value were observed, including the findings of the extended time window analysis.

Supplementary Figure 3.2

Extended Frequency ERSP Comparisons for Interaction Effects Between Group and Value



Spectrograms illustrate differences between group (younger/older adults) and value (high-/low-value) at parietal sites (average of Pz, P1, P2). The 0 ms time point (solid vertical line) represents stimulus onset. Dashed black rectangles indicate the alpha (8-12 Hz) band and time window (800-1000 ms) where significant interaction effects between group and value were observed.

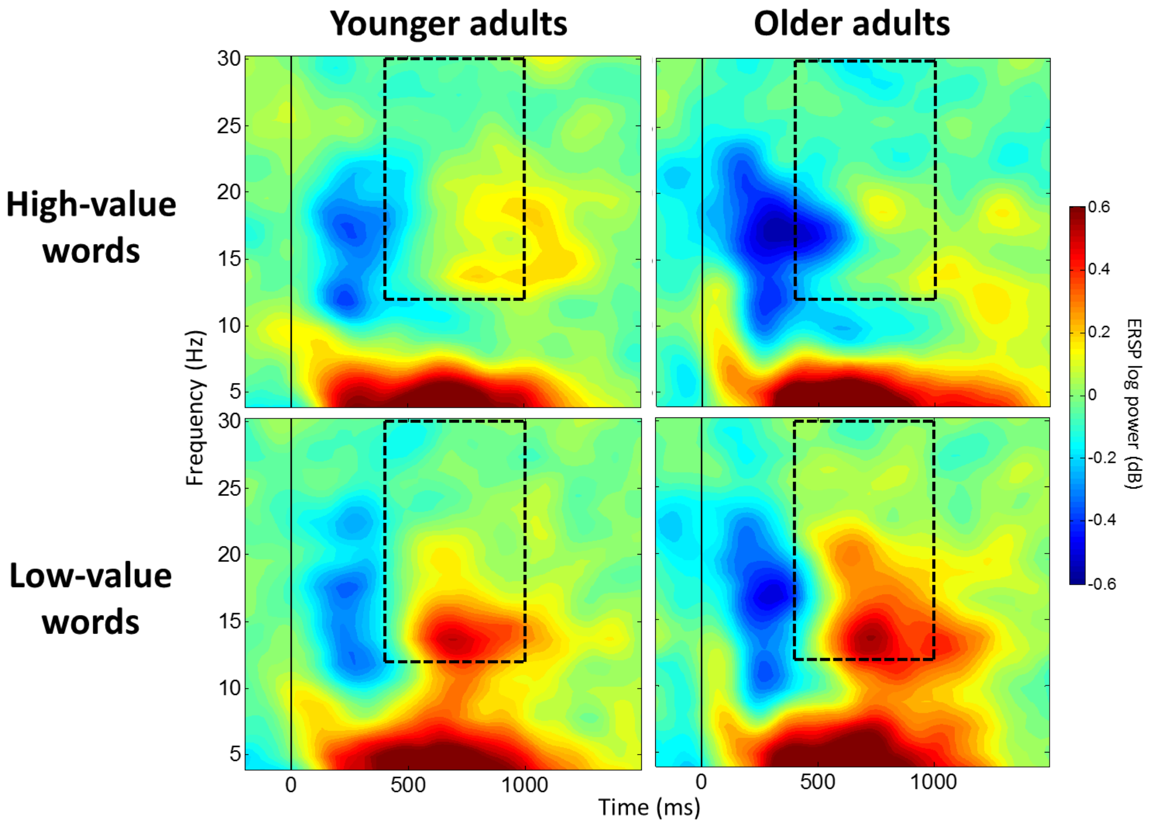
3.6. Supplementary material for Chapter 3: Beta band analysis

The primary ERSP analyses for Chapter 3 (see main text) were carried out to examine theta and alpha bands given their link to cognitive processes that are known to be involved in value-directed strategic processing. However, beta band (12-30 Hz) has also been linked to cognitive functions that relate to strategic processing (e.g., Hanslmayr et al., 2012) and is known to be affected by aging (for review see Ishii et al., 2017); thus this supplementary analysis was carried out. In particular, beta band synchronization has been linked to the inhibition of memory trace retrieval (Hanslmayr et al., 2012; Waldhauser et al., 2012), while beta band desynchronization has been associated with processing of semantic information (Hanslmayr et al., 2012; Waldhauser et al., 2012) and successful episodic encoding and retrieval (Hanslmayr et al., 2012; Pfurtscheller & Lopes da Silva, 1999; Spitzer & Haegens, 2017).

For this supplementary analysis, mean beta band (12-30 Hz) spectral power at frontal sites (average of Fz, F1, F2; Hanslmayr et al., 2012; Weiss & Mueller, 2012) was computed with group (younger/older adults) as a between-subject factor and value (high-/low-value) as a within-subject factor for 100 ms time windows from 0 ms to 1000 ms with no overlap, resulting in 10 time windows for analysis. The main effects of group were not significant at any of the 10 time windows ($p > .05$; see Supplementary Table 3.5). Significant main effects of value were observed from 400-1000 ms post-stimulus onset ($p < .05$; Supplementary Table 3.5), where the following differences in frontal beta power were observed: (i) greater desynchronization for high- compared to low-value words from 400-600 ms, and (ii) greater synchronization for low-compared to high-value words from 600-1000 ms. However, the main effects of value were qualified by significant interaction effects between group and value from 400-1000 ms post-stimulus onset ($p < .05$; Supplementary Table 3.5; Supplementary Figure 3.3). Post hoc analyses did not reveal between group differences (*p* > .05), however, significant within group differences emerged in the older adult group (*p* < .01), but not in the younger adult group (*p* > .05). Specifically, within-group differences between high- and low-value words were observed for older adults with greater beta desynchronization for high- compared to low-value words from 400-600 ms and greater synchronization for low- compared to high-value words from 600-1000 ms.

Supplementary Figure 3.3

ERSP Group Comparisons for High- and Low-Value Words at Frontal Electrodes



Spectrograms illustrate differences between groups (younger/older adults) and values (high-/low-value) at frontal sites (average of Fz, F1, F2). The 0 ms time point (solid vertical line) represents stimulus onset. Dashed black rectangles indicate the beta (12-30 Hz) band and time window (400-1000 ms) where significant interaction effects between group and value were observed.

Supplementary Table 3.5

Statistical Results for Beta Band Mean Power

		Time (ms)									
		0-100	**100-200**	**200-300**	**300-400**	**400-500**	**500-600**	**600-700**	**700-800**	**800-900**	**900-1000**
Group	*F(1,46)*	2.97	2.75	1.67	1.21	1.19	1.31	1.06	0.76	1.00	0.52
	p	.092	.104	.202	.278	.280	.259	.308	.388	.322	.475
Value	*F(1,46)*	0.31	0.04	0.17	0.63	**13.60**	**18.90**	**19.70**	**18.94**	**11.44**	**7.16**
	p	.580	.848	.685	.433	**.001**	**< .001**	**< .001**	**< .001**	**0.001**	**0.010**
Group x Value	*F(1,46)*	2.15	0.52	0.02	0.51	**4.03**	**6.61**	**6.43**	**6.14**	**5.81**	**4.58**
	p	.149	.473	.876	.479	**.050**	**.013**	**.015**	**.017**	**.020**	**.038**

Cells display statistics for main effects of group (younger/older adults), main effects of value (high-/low-value words), and interaction effects between group and value for mean power in beta band (12-30 Hz) across the 10 time windows post-stimulus onset. Bolded values correspond to significant effects (*p* < .05, Bonferroni-corrected).

Beta differences between high- and low-value words were only observed within the older adult group and not within the younger adult group. This distinction in older adults started at 400 ms post-stimulus onset, with greater beta desynchronization for high-value words until 600 ms and greater synchronization for low-value words from 600-1000 ms post-stimulus onset (see Supplementary Figure 3.3). Beta desynchronization has been related to augmenting information processing (Sherman et al., 2016) and semantic processing, particularly in relation to the subsequent memory paradigm (Hanslmayr et al., 2009; Hanslmayr & Staudigl, 2014; Hanslmayr et al., 2012), while beta synchronization has been linked to inhibition (Engel & Fries, 2010; Sacchet et al., 2015; Sherman et al., 2016). This distinction suggests that older adults sustained more prolonged and deeper semantic processing for the high-value words, and greater inhibition of the low-value words. Age-related changes in beta band activity have been observed in previous studies, with greater desynchronization in older compared to younger adults in a variety of contexts, including during memory retrieval (Guran et al., 2019) and at rest (McEvoy, et al., 2001). Greater beta desynchronization for older adults compared to younger adults may reflect greater recruitment of neural resources to compensate for age-related changes (Ishii et al., 2017; Sebastián et al., 2011), in line with the Compensation-Related Utilization of Neural Circuits Hypothesis (Reuter-Lorenz & Cappell, 2008; Reuter-Lorenz & Lustig, 2005).

3.7. Supplementary material for Chapter 3: Principal component analysis

The primary ERSP analyses for Chapter 3 (see main text) were based on a priori hypotheses from previous literature using traditional GLM models. However, large EEG datasets are well-suited to data-driven dimension reduction approaches for analysis (e.g., Dien et al., 2003; Dien & Frishkoff, 2004; Spencer et al., 2001), such as principal component analysis (PCA). The current supplementary analysis utilized PCA for two purposes: (i) to determine if a data-driven approach would produce both spatial and temporal results that converged with our a priori hypothesis-based data analysis approach, and (ii) to explore if a data-driven approach would reveal additional spatial and temporal findings to advance this line of research.

This supplementary analysis used sequential spatial-temporal PCAs to first reduce the data in the spatial domain and then in the temporal domain. Conducting PCAs in this order is common practice with EEG data (e.g., Brier et al., 2008; Dien et al., 2003; Spencer et al., 2001). The specific methodology used for the current study was based largely on the work of Ferree et al. (2009), as well as Brier et al. (2008). Spatial-temporal PCAs were run separately for the groups (younger adults [YA] and older adults [OA]) and for the frequency bands (theta [4-8 Hz] and alpha [8-12 Hz] bands), resulting in four spatial-temporal PCAs (YA-theta, YA-alpha, OA-theta, OA-alpha). For each of the four PCAs, a spatial PCA was run first, followed by a temporal PCA, and then the resulting PCA scores were submitted to one-way ANOVAs to test for differences between value (low-value/high-value). Significant effects from the one-way ANOVAs will be discussed.

The data were first arranged in a matrix where columns indexed electrodes (62) and rows indexed the concatenation of subjects (24), conditions (2; high-value/low-value), and time points

(13; 100 ms windows from 0-1300 ms post-stimulus onset), resulting in a 62 by 624 (24 x 2 x 13) matrix (see Supplementary Figure 3.4).

Supplementary Figure 3.4

Spatial PCA Matrix Arrangement

62 columns

624 rows

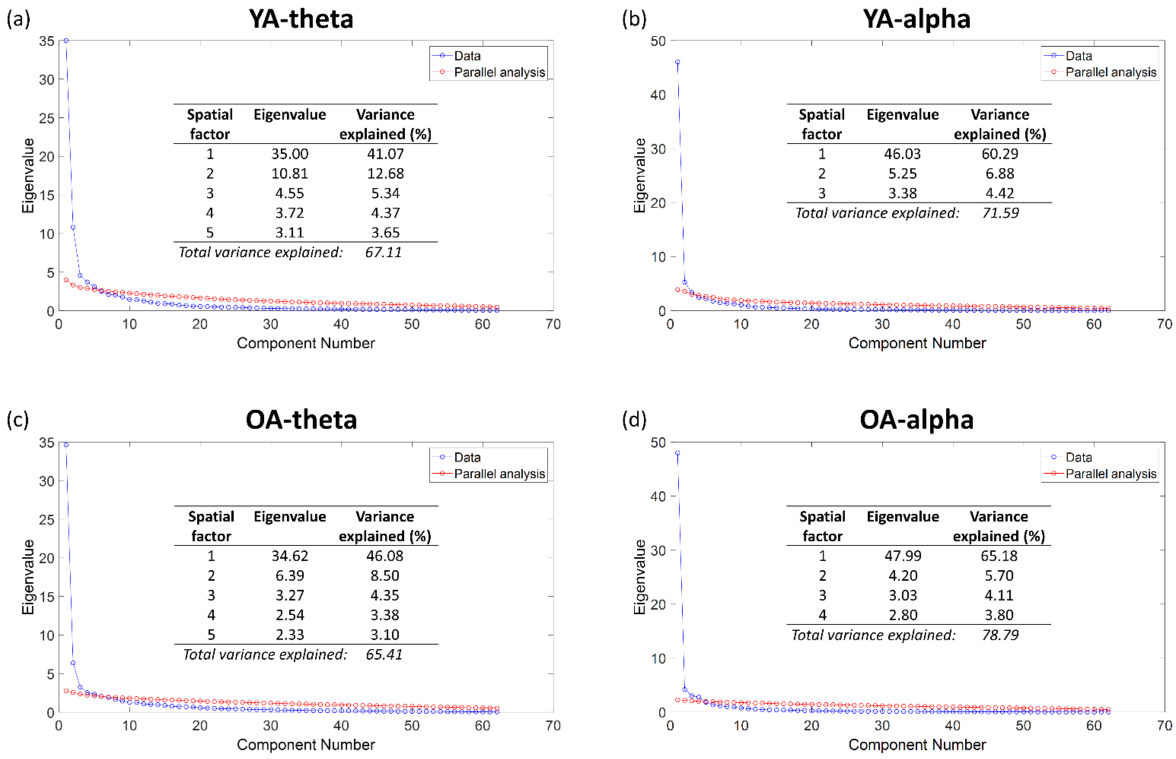
Condition	Time point	Subject	Electrode
1	1	1	1…62
1	1	2	1…62
1	1	3	1…62
…	…	…	1…62
1	1	24	1…62
…	…	…	1…62
1	13	24	1…62
2	1	1	1…62
…	…	…	1…62
2	13	24	1…62

Data for each of the spatial PCAs were arranged in a matrix where columns indexed electrodes (62) and rows indexed the concatenation of conditions (2; high-value/low-value), time points (13; 100 ms windows from 0-1300 ms post-stimulus onset), and subjects (24), resulting in a 62 by 624 (24 x 2 x 13) matrix.

Column means were subtracted, where for each column the mean across the rows was subtracted, and the covariance matrix was then computed. A spatial PCA was then conducted in order to obtain spatial factors, or principal components (consisting of eigenvectors and eigenvalues). To determine how many spatial factors to retain, parallel analysis (Horn, 1965) was used as it has been shown to be a reliable method for determining factor retention (Ferree et al., 2009; Hayton et al., 2004). This method works by creating a random matrix with the same dimensions as the original data matrix and running it through a PCA. The eigenvalues for both the original factors and the new parallel analysis factors are plotted on a scree plot (Cattell, 1966) and any original eigenvalue that is greater than its respective parallel analysis eigenvalue is retained. Supplementary Figure 3.5 shows the scree plots for the four PCAs (YA-theta, YA-alpha, OA-theta, OA-alpha) with both the original and parallel analysis eigenvalues, as well as table insets with information about the specific details on the eigenvalues and percent explained variance for each of the retained spatial factors.

Supplementary Figure 3.5

Parallel Analysis for Spatial PCAs



(a) YA-theta

Spatial factor	Eigenvalue	Variance explained (%)
1	35.00	41.07
2	10.81	12.68
3	4.55	5.34
4	3.72	4.37
5	3.11	3.65
Total variance explained:		*67.11*

(b) YA-alpha

Spatial factor	Eigenvalue	Variance explained (%)
1	46.03	60.29
2	5.25	6.88
3	3.38	4.42
Total variance explained:		*71.59*

(c) OA-theta

Spatial factor	Eigenvalue	Variance explained (%)
1	34.62	46.08
2	6.39	8.50
3	3.27	4.35
4	2.54	3.38
5	2.33	3.10
Total variance explained:		*65.41*

(d) OA-alpha

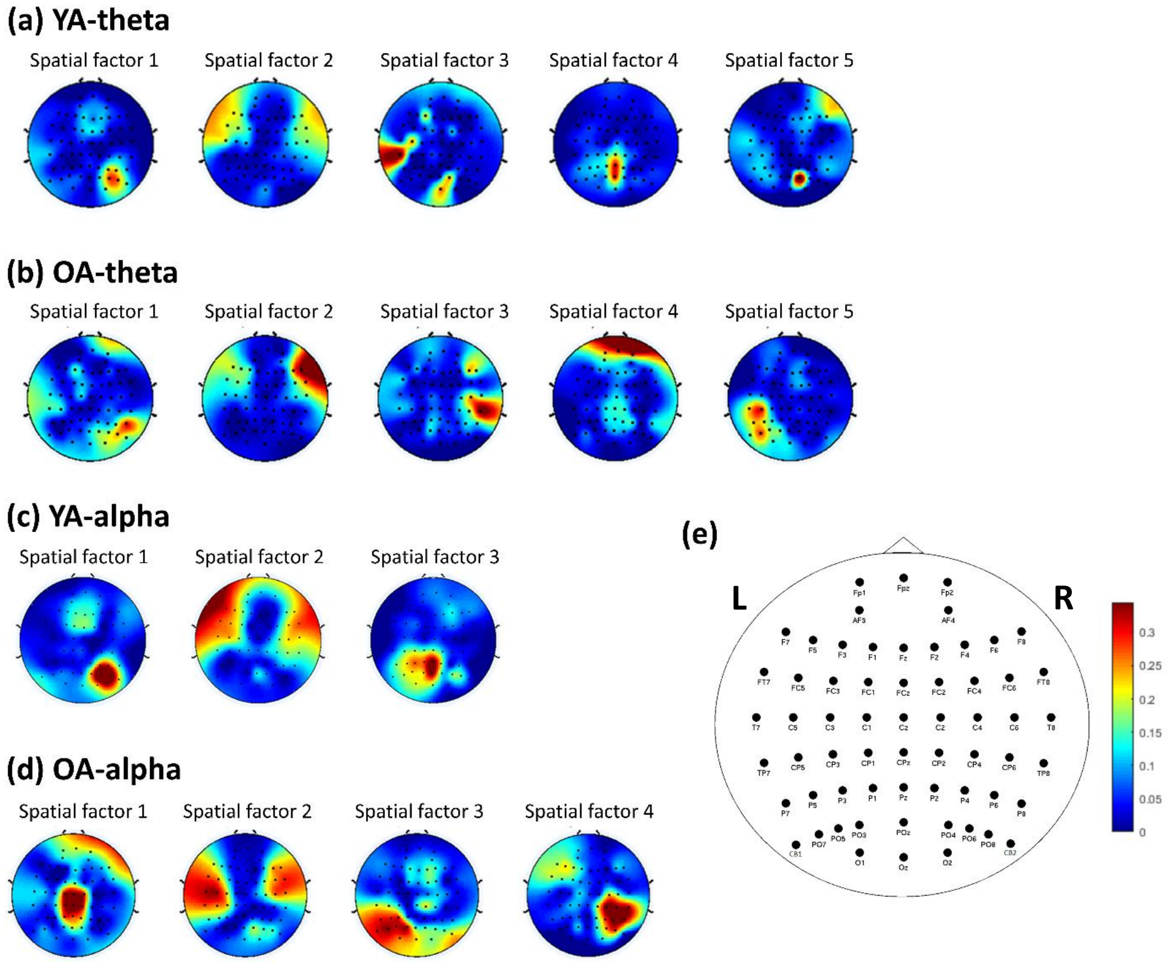
Spatial factor	Eigenvalue	Variance explained (%)
1	47.99	65.18
2	4.20	5.70
3	3.03	4.11
4	2.80	3.80
Total variance explained:		*78.79*

The figure depicts the scree plots for the four PCAs: (a) YA-theta, (b) YA-alpha, (c) OA-theta, and (d) OA-alpha with both the original and parallel analysis eigenvalues. Spatial factors are retained if the data eigenvalue is greater than the parallel analysis eigenvalue. Table insets provide specific details about the eigenvalues and percent variance explained for each of the retained spatial factors.

The retained spatial factors then underwent a Varimax rotation (Kaiser, 1958), which is an orthogonal transformation that rotates the principal components to maximize the variance of the factors, and has been suggested to help separate cognitive components in ERP work and improve interpretation of the data (Dien & Frishkoff, 2004). The retained and rotated spatial factors were plotted as topographic plots using absolute values, given that the signs are arbitrary (Ferree et al., 2009) and to promote ease of visualization (Supplementary Figure 3.6).

Supplementary Figure 3.6

Topographic Plots for the Retained Spatial Factors

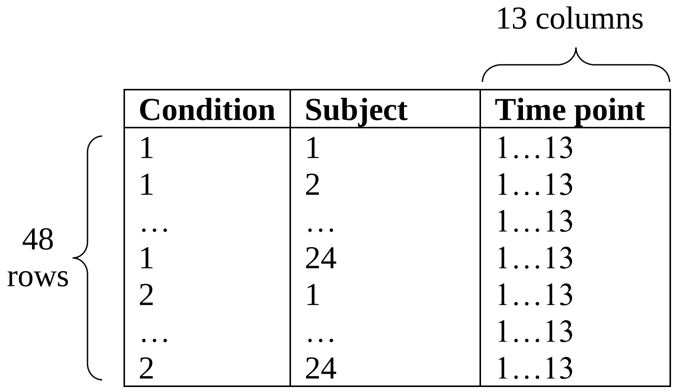


The figure depicts the topographic plots for each of the retained spatial factors for each of the four PCAs: (a) YA-theta, (b) YA-alpha, (c) OA-theta, and (d) OA-alpha. (e) depicts a general topographic plot with electrode names and the scale used for the topographic plots in (a-d).

For each of the retained spatial factors, corresponding factor scores were computed by projecting the original mean-centered data onto the retained and rotated factors (i.e., the original data was projected onto the new factor space). The corresponding factor scores for each retained spatial factor were reshaped into a matrix for the temporal PCA. Each of these matrices were arranged where columns indexed time points (13) and rows indexed the factor scores for each subject (24) and condition (2), resulting in a 13 by 48 (24 x 2) matrix for each of the retained spatial factors (see Supplementary Figure 3.7). A temporal PCA was then conducted for each of the retained spatial factors to obtain temporal factors, or principal components (consisting of eigenvectors and eigenvalues). The number of retained temporal factors for each PCA and each retained spatial factor are shown in Supplementary Table 3.6. For each of the retained temporal factors, corresponding factor scores were computed by projecting the original mean-centered data onto the retained and rotated factors (i.e., the original data was projected onto the new factor space).

Supplementary Figure 3.7

Temporal PCA Matrix Arrangement



Condition	Subject	Time point
1	1	1…13
1	2	1…13
…	…	1…13
1	24	1…13
2	1	1…13
…	…	1…13
2	24	1…13

Data for each of the temporal PCAs were arranged in a matrix where columns indexed time points (13) and rows indexed the factor scores for each subject (24) and condition (2), resulting in a 13 by 48 (24 x 2) matrix for each of the retained spatial factors.

Supplementary Table 3.6

Number of Temporal Factors Retained and Variance Explained for Each Spatial Factor

	Spatial factor	Number of temporal factors retained	Total variance explained (%)
YA-theta	1	3	81.46
	2	2	84.25
	3	2	83.92
	4	3	78.09
	5	2	79.46
OA-theta	1	3	83.45
	2	3	74.65
	3	3	75.49
	4	2	79.76
	5	3	79.59
YA-alpha	1	2	73.88
	2	2	79.97
	3	2	77.34
OA-alpha	1	3	85.96
	2	3	77.84
	3	2	74.87
	4	2	75.47

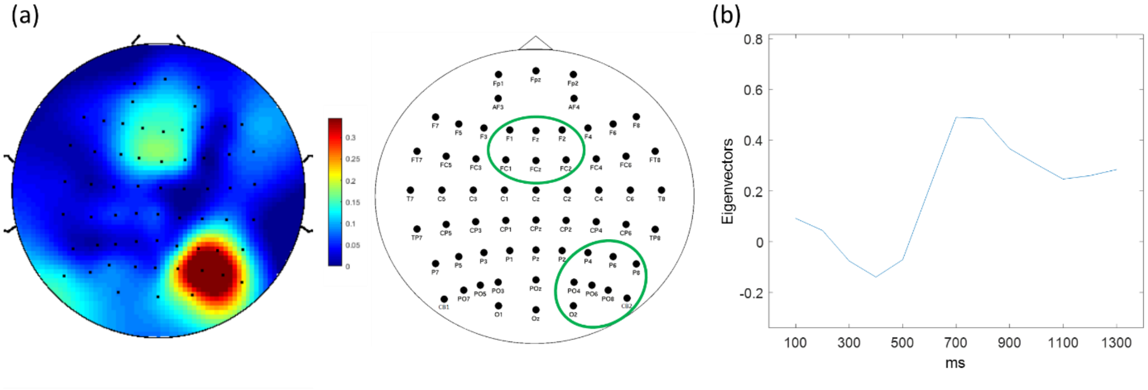
The table depicts the number of temporal factors retained and the total amount of variance explained by the retained temporal factors for each retained spatial factor for the four PCAs (YA-theta, YA-alpha, OA-theta, OA-alpha).

For each of the four PCAs (YA-theta, YA-alpha, OA-theta, OA-alpha), each of the retained temporal factor scores were submitted to one-way ANOVAs to test for differences between value (low-value/high-value). Bonferroni tests were used to control for multiple comparisons, resulting in the following Bonferroni corrected alpha thresholds: YA-theta (12 factors tested) = 0.0042; OA-theta (14 factors tested) = 0.0036; YA-alpha (6 factors tested) = 0.0083; and OA-alpha (10 factors tested) = 0.0050.

For both YA-theta and OA-theta, there were no significant differences between value for any of the tested factors. For YA-alpha, there were significant differences between value for two factors: (i) the second temporal factor of the first spatial factor (referred to henceforth as Spatial 1 Temporal 2), $F(1,47) = 8.09$, $p = .007$, $\eta_p^2 = .15$, and (ii) the first temporal factor of the third spatial factor (Spatial 3 Temporal 1), $F(1,47) = 8.99$, $p = .004$, $\eta_p^2 = .16$. The Spatial 1 Temporal 2 factor was spatially loaded in midline frontocentral and right parietal areas and was temporally loaded around 400 ms and 700-800 ms (Supplementary Figure 3.8). The Spatial 3 Temporal 1 factor was spatially loaded in left and midline parietal and parieto-occipital areas and was temporally loaded around 700 ms (Supplementary Figure 3.9).

Supplementary Figure 3.8

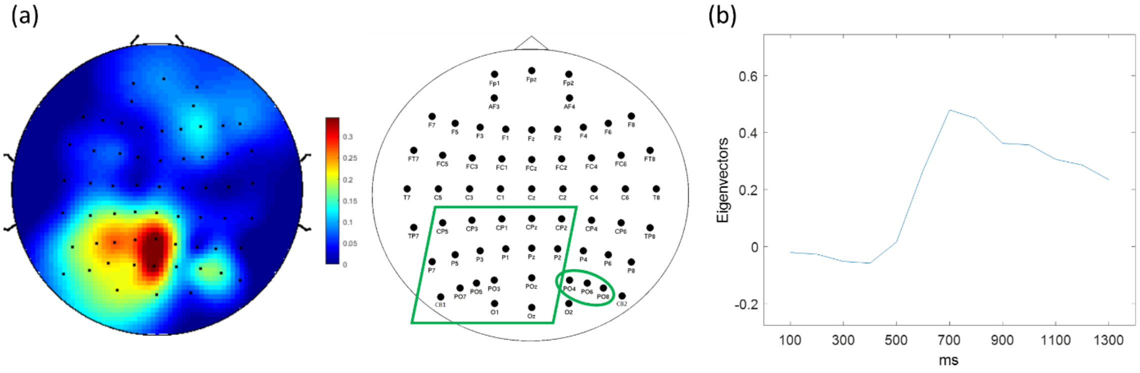
Visualization of YA-Alpha Spatial 1 Temporal 2



The figure depicts the (a) topographic plot for the first spatial factor and (b) temporal plot for the second temporal factor of the first spatial factor for YA-alpha.

Supplementary Figure 3.9

Visualization of YA-Alpha Spatial 3 Temporal 1

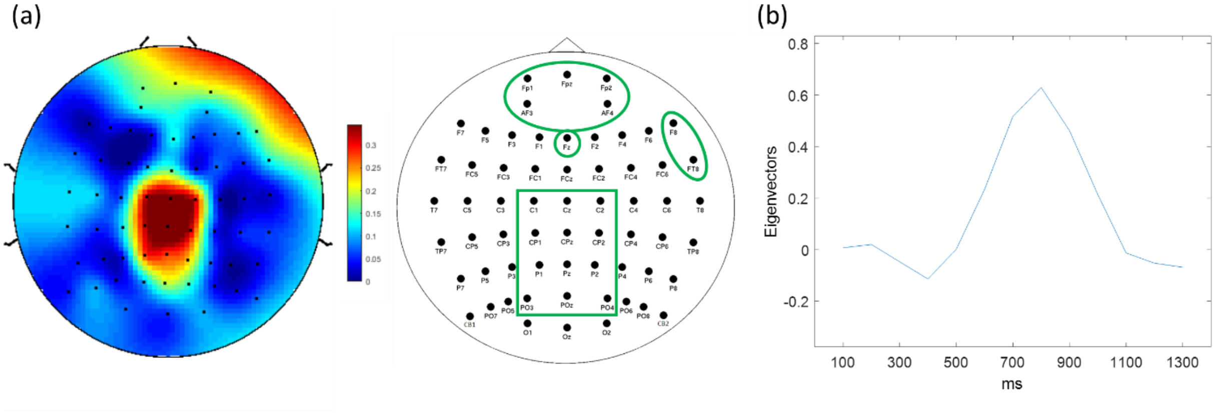


The figure depicts the (a) topographic plot for the third spatial factor and (b) temporal plot for the first temporal factor of the third spatial factor for YA-alpha.

For OA-alpha, there were significant differences between value for one factor: the first temporal factor of the first spatial factor (Spatial 1 Temporal 1), $F(1,47) = 15.36$, $p < .001$, $\eta_p^2 = .25$. The Spatial 1 Temporal 1 factor was spatially loaded in midline central and parietal areas and right frontal areas and was temporally loaded around 400 ms and 800 ms (Supplementary Figure 3.10).

Supplementary Figure 3.10

Visualization of OA-Alpha Spatial 1 Temporal 1



The figure depicts the (a) topographic plot for the first spatial factor and (b) temporal plot for the first temporal factor of the first spatial factor for OA-alpha.

Consistent with the first goal of this supplementary analysis, the spatial-temporal PCA analyses revealed some findings that converged with our a priori hypothesis-based approach that was used in the main text of Chapter 3. The PCA-ANOVAs did not reveal any significant findings for theta band for YA or OA. This aligns somewhat with our hypothesis-based findings in which significant main effects of value were observed for theta band, but the effect sizes were relatively small. It may be that theta band is a less reliable measure of value-based processing differences. The PCA analyses for alpha band indicated that later time periods, namely around 700 ms, may be valuable for differentiating between value, consistent with our hypothesis-based alpha findings, which also showed effects of value in later time periods. This could indicate that alpha band in later stages of processing is a strong and reliable measure of value-based strategic processing.

In regard to the second goal of this supplementary analysis, the PCA analysis did reveal new information. In particular, for alpha band for both YA and OA, the PCA revealed that frontocentral and central areas may be important to examine when differentiating between value, in addition to the parietal areas that were examined in our hypothesis-based approach. These new findings suggest that in the context of EEG, only using an a priori hypothesis-driven approach may not capture all of the effects, and that using data-driven approaches like PCA may help to identify electrodes of interest for analysis.

CHAPTER 4: EXAMINING VALUE-DIRECTED STRATEGIC PROCESSING IN MILD COGNITIVE IMPAIRMENT USING BEHAVIORAL AND EEG THETA AND ALPHA BAND MEASURES

ABSTRACT

Value-directed strategic processing involves attending to information of higher value, while inhibiting information of lower value. This preferential processing ability is relatively preserved in cognitively normal older adults, but is impaired in older adults with dementia. No studies have investigated whether value-directed strategic processing diminishes in earlier stages of cognitive decline. The current study examined differences between 16 older adults with mild cognitive impairment (MCI; mean age: 77.1 ± 4.3 years) and 16 cognitively normal older adults (CN; mean age: 74.5 ± 4.0 years) on behavioral and EEG measures linked to processing high- and low-value words in a value-directed strategic processing task. Behaviorally, MCI individuals recalled fewer total and high-value words compared to CN, but no group differences were observed in recall of low-value words. Neurally, MCI individuals had reduced overall theta synchronization relative to CN in the early time periods (100-400 ms post-stimulus), while this pattern was observed specifically for low-value words in the later time periods (700-800 ms). Greater alpha desynchronization for high- versus low-value words was observed in CN but not in MCI individuals (300-400 ms). Both groups showed some similarities in processing with greater theta synchronization for low-value words (800-900 ms) and greater alpha desynchronization for high-value words (500-1100 ms). Overall, value-directed strategic processing in MCI individuals was compromised both behaviorally and neurally compared to CN. These findings provide novel markers for early identification of MCI.

4.1. Introduction

We are surrounded by vast amounts of information at any given moment in our lives, but this information differs in its value, importance, or relevance. The ability to attend to information of higher value or importance, while inhibiting information of lower value or importance is referred to as value-directed strategic processing. This preferential processing ability is important for everyday activities as it can promote efficient processing by minimizing cognitive burden (for review see Castel, 2007). Value-directed strategic processing has been shown to be relatively well-preserved in normal cognitive aging across a number of studies (Castel et al., 2002, 2007, 2011; Nguyen et al., 2020); however, the impact of cognitive impairments on strategic processing in older adults is less well examined (Castel et al., 2009; Wong et al., 2018).

Two studies have examined value-directed strategic processing in older adults with cognitive impairments, both of which have focused on patients with dementia (Castel et al., 2009; Wong et al., 2018). Castel et al. (2009) used a value-directed remembering (VDR) task with patients with very mild and mild Alzheimer's disease (AD) and cognitively normal younger and older adults. The VDR task utilized eight word lists where the words were paired with different point values ranging between 1-12 points (e.g., Desk 12; Berry 1) and were presented sequentially. At the end of each list, participants were asked to recall as many words from the list as they could with the goal of scoring maximal points. Total word recall was poorer in individuals with AD compared to both cognitively normal younger and older adults across all word lists. Interestingly though, patients with AD did recall more high- than low-value words, suggesting that they had some retained value-directed strategic processing ability. However, the magnitude of the difference between high- and low-value word recall was significantly smaller in patients with AD when compared to cognitively normal younger and older adults.

Additionally, an estimation of selectivity (calculated by comparing a participants' actual score versus their ideal score based on the number of words they recalled) showed that the AD patients performed significantly worse than cognitively normal younger and older adults. Taken together, these findings demonstrate that patients with AD exhibit deficits in value-directed strategic processing relative to cognitively normal older adults.

In the second study of patients with dementia, Wong et al. (2018) contrasted the performance of patients with AD and behavioral variant frontotemporal dementia (bvFTD) with cognitively normal older adults. They used a simplified version of a VDR task in which the same word list was repeated three times, more similar to a typical episodic list learning task (e.g., California Verbal Learning Test). The words were either low- (1 point), medium- (5 points), or high-value (10 points). Both AD and bvFTD patients recalled fewer total words compared to cognitively normal older adults but performed comparably to one another. With regard to value-based recall, AD and bvFTD patients differed from cognitively normal older adults and one another. The cognitively normal older adults demonstrated ideal value-directed strategic processing (i.e., high- > medium- > low-value words recalled) across all lists. The AD patients showed some evidence for value-directed strategic processing in the third list (i.e., high- > medium- and low-value words recalled), but the bvFTD patients never demonstrated this ability in any of the three lists (i.e., similar recall for high-, medium-, and low-value words). The same pattern of effects was observed when using an estimation of selectivity. These findings were taken as evidence that AD patients were capable of improving value-directed strategic processing, but that the bvFTD patients were unable to strategically process information. A correlation between the selectivity measure and performance on an inhibition measure was observed in the bvFTD patients. Paired with the fact that bvFTD is characterized by prominent inhibitory deficits (Bozeat et al., 2000; Hornberger et al., 2008), the authors suggested that the lack of value-directed strategic processing in bvFTD patients was due to difficulty in selectively inhibiting lower value words. Collectively, the findings of both the Castel et al. (2009) and Wong et al. (2018) studies show that patients with dementia have significant impairments in value-directed strategic processing relative to cognitively normal older adults. However, the nature of the deficit differs across various types of dementia. To date, no studies have examined whether this ability begins to deteriorate in earlier stages of cognitive decline, namely mild cognitive impairment (MCI).

MCI is characterized by declines in cognitive abilities that are greater than expected given a person's age and education level, but are not severe enough to impair most activities of daily living or warrant a diagnosis of dementia (Albert et al., 2011; Petersen, 2011; Sperling et al., 2011). However, older adults with MCI are at greater risk of developing dementia compared to their cognitively normal peers. Many individuals with amnestic MCI, a common MCI subtype, present with predominant impairments in episodic learning and memory (e.g., de Jager et al., 2003; de Jager & Budge, 2005; Greenaway et al., 2006; Libon et al., 2010, 2011; Mistridis et al., 2015; Petersen et al., 1999; Ribeiro et al., 2007; Teng et al., 2009; for reviews see Arnáiz & Almkvist, 2003; Salmon, 2012). In addition to hallmark episodic memory deficits, individuals with multidomain amnestic MCI also experience impairments in other cognitive domains, including those relevant to value-directed strategic processing, namely attention and inhibition.

Studies have shown that individuals with amnestic MCI are impaired on a variety of attention-related tasks, including visual search tasks, and sustained, divided, and selective attention tasks (e.g., Belleville et al., 2007; McLaughlin et al., 2010, 2013; Okonkwo et al., 2008; Saunders & Summers, 2009; Saunders & Summers, 2011; Tales et al., 2005, 2011). Deficits in inhibition have also been observed in individuals with amnestic MCI across various tasks, including Stroop, Flanker, Hayling, Wisconsin Card Sorting Test, and stop-signal tasks (e.g., Bélanger et al., 2010; Bélanger & Belleville, 2009; Belleville et al., 2007; Traykov et al., 2007; Wylie et al., 2007; Zheng et al., 2012). Given these deficits in attention and inhibition, both of which are important for value-directed strategic processing, one would anticipate challenges with value-directed strategic processing in individuals with amnestic MCI.

To examine value-directed strategic processing in individuals with MCI, it is beneficial to use neurophysiological measures as they capture early neural changes that precede overt behavioral changes (Jack et al., 2013; Jack & Holtzman, 2013). Measures derived from electroencephalography (EEG) can help in this regard as they allow for examinations of the neurophysiological underpinnings and temporal unfolding of cognitive processes with millisecond-level precision. In particular, event-related spectral perturbations (ERSPs) provide spectral and temporal information about oscillatory brain responses in the EEG signal. ERSPs are typically discussed in terms of five different frequency bands, specifically delta (1-4 Hz), theta (4-8 Hz), alpha (8-12 Hz), beta (12-30 Hz), and gamma (>30 Hz) bands. ERSP power changes in a given frequency band are described as synchronization or desynchronization, which refer to increases or decreases in spectral power relative to a baseline period, respectively (Pfurtscheller & Lopes da Silva, 1999). Changes in theta and alpha band spectral power are particularly relevant to the current study, given that our previous studies have demonstrated the link between these oscillations and value-directed strategic processing in cognitively normal younger and older adults (Nguyen et al., 2019, 2020).

Our previous work showed greater synchronization in frontal theta for low- compared to high-value words (Nguyen et al., 2019, 2020), suggesting a link between theta band and inhibitory control of low-value words (Cavanagh & Frank, 2014; Cavanagh & Shackman, 2015; Nigbur et al., 2011). Additionally, greater desynchronization in parietal alpha was observed for high- compared to low-value words (Nguyen et al., 2019, 2020), indexing either greater selective attention to and/or semantic processing of high-value words (Hanslmayr et al., 2012; Klimesch, 1999; Klimesch et al., 2007; Klimesch, 2012; Pfurtscheller & Lopes da Silva, 1999). In our normal cognitive aging study, we found that cognitively normal older adults had similar behavioral performance to younger adults, but seemed to engage neural resources differently (Nguyen et al., 2020). Specifically, older adults engaged in more prolonged neural processing of high-value words compared to the younger adults, as indexed by the alpha band. We speculated that the decreased ability to recruit compensatory neural mechanisms in individuals with MCI would translate to alterations in value-directed strategic processing both behaviorally and neurally. Although there is limited work on task-related theta and alpha band power in MCI individuals, such studies have demonstrated differences in these bands between MCI individuals and cognitively normal older adults across a variety of tasks (e.g., *n*-back, Go/NoGo, Sternberg, simple attention (detection), attention orienting; Caravaglios et al., 2015; Cummins et al., 2008; Deiber et al., 2009, 2015; Fraga et al., 2018; Goodman et al., 2019; Nguyen et al., 2017). No studies have yet examined theta and alpha band in MCI individuals in the context of a value-directed strategic processing task.

As such, the purpose of the current study was to examine whether older adults with MCI show behavioral deficits and ERSP alterations in value-directed strategic processing when compared with cognitively normal older adults (CN). For the behavioral data, we hypothesized that MCI participants would recall fewer total words and fewer high-value words, but would recall more low-value words, as compared to CN participants. For theta band, we anticipated that there would be greater synchronization for low- compared to high-value words and that there would be a difference in this band between MCI and CN participants, but were uncertain of the direction of the effect. For alpha band, we predicted that there would be greater desynchronization for high- compared to low-value words and that MCI and CN participants would differ, but were again unsure about the direction of the effect.

4.2. Material and methods

4.2.1. Participants

Sixteen cognitively normal older adults (CN) and 16 older adults diagnosed with amnestic mild cognitive impairment (MCI) participated in the study (see Table 4.1 for demographics). All participants were native English speakers, right-handed, and had a minimum high school level education. Individuals of both sexes were included, and no exclusions were made based on racial or ethnic factors. Participants had no history of stroke, dementia, Parkinson's disease, traumatic brain injury, major psychiatric illness, epilepsy, alcohol or substance abuse, uncontrolled diabetes, autoimmune disease, learning disabilities, attention deficit hyperactivity disorder, or uncorrected vision or hearing loss.

The MCI participants had a clinical diagnosis of MCI from a neurologist at the Carle Neuroscience Institute. All MCI participants met the clinical MCI guidelines of the 2011 US National Institute on Aging and Alzheimer's Association workgroup (Albert et al., 2011), including: (a) cognitive concerns reported by the patient and/or corroborated by a reliable informant, (b) objectively verified impairments in one or more cognitive domains, (c) relative independence in activities of daily living, and (d) did not meet criteria for dementia. The pattern of cognitive impairments in the MCI participants showed predominant impairment in memory, with declines in other cognitive domains, falling into the multi-domain MCI definition (e.g., Petersen, 2004; Petersen et al., 2001, 2014). All participants in the MCI group completed the Clinical Dementia Rating (Morris, 1993) and received scores of 0.5. CN participants had no subjective memory or cognitive complaints and performed normally on the cognitive assessment.

All participants completed a global cognitive screening followed by a more detailed cognitive assessment (Table 4.1). Global cognitive screening was completed using either the Mini-Mental State Evaluation (MMSE; Folstein et al., 1975) or the Montreal Cognitive Assessment (MoCA; Nasreddine et al., 2005). All 16 CN participants completed the MoCA and had normal scores (26 or above). Twelve MCI participants completed the MoCA and four MCI participants completed the MMSE. The MMSE scores of the four MCI participants were converted to MoCA scores following the guidelines provided by Bergeron et al. (2017) to create group averages. After conversion, all MCI participants had impaired MoCA scores (below 26). Additionally, none of the participants reported elevated depressive symptoms (scored 5 or less on Geriatric Depression Scale - Short form [Sheikh & Yesavage, 1986] or scored 10 or less on Beck Depression Inventory [Beck et al., 1961]). Written informed consent was obtained from all participants in accordance with the protocols of both the University of Illinois at Urbana-Champaign and Carle Institutional Review Boards before completing the study.

Table 4.1

Participant Demographics and Cognitive Testing Performance

	CN **(N = 16)**	**MCI** **(N = 16)**	***p*-value**
Demographics			
Age	74.5 (4.0)	77.1 (4.3)	.092
Education	16.4 (2.9)	15.6 (3.4)	.473
Sex	13F/3M	13F/3M	1.00
Cognitive testing			
Montreal Cognitive Assessment	27.4 (1.4)	20.8 (3.8)	< .001**
LM – Immediate (Story A)	15.9 (3.2)[a]	7.7 (3.0)[b]	< .001**
LM – Delayed (Story A)	14.1 (4.2)[a]	3.8 (3.2)[b]	< .001**
LM – Immediate (Story A & B)	--	29.0[c]	--
LM – Delayed (Story A & B)	--	7.0[c]	--
RBANS Story memory – Immediate	--	10.3 (4.6)[d]	--
RBANS Story memory – Delayed	--	2.7 (1.5)[d]	--
Letter fluency (F, A, S)	49.1 (8.2)	36.2 (13.7)	.003**
Category fluency (Animals)	20.1 (4.1)	13.8 (5.1)	.001**
Boston Naming Test (30 items)	27.8 (1.7)	26.5 (2.7)[b]	.130
Boston Naming Test (60 items)	--	51.5 (5.8)[e]	--
Trail Making Test-A	26.8 (5.2)	35.0 (17.4)	.080
Trail Making Test-B	79.7 (29.9)	135.8 (60.4)	.002**
Digit span – forward	6.5 (1.5)[a]	6.8 (1.1)[b]	.642
Digit span – backward	5.1 (1.2)[a]	5.2 (1.2)[b]	.961

Cells represent mean (standard deviation). [a]n=14; [b]n=12; [c]n=1; [d]n=3; [e]n=4. The *p*-values were derived from one-way ANOVAs, except for sex which was derived from Pearson chi-square. *$p < .05$; **$p < .01$. CN: cognitively normal older adults; MCI: mild cognitive impairment; LM: Wechlser Memory Scale IV Logical Memory subtest; RBANS: Repeatable Battery for the Assessment of Neuropsychological Status.

4.2.2. Strategic processing task and procedures

All participants completed a strategic processing task, which was a value-directed word list learning task developed in-house. The word stimuli consisted of 200 single syllable four letter nouns from the MRC Psycholinguistic Database (Coltheart, 1981) and $\text{SUBTLEX}_{\text{US}}$ database (Brysbaert & New, 2009). Words were controlled for frequency (range: 1-96; mean: 25.3 ± 22.7), imageability (range: 439-659; mean: 571.1 ± 40.0), concreteness (range: 501-637; mean: 571.8 ± 40.7), and familiarity (range: 370-615; mean: 524.4 ± 51.7). The 200 word stimuli were divided into five lists of 40 words each. Given that the task was designed to evaluate strategic processing, each of the five lists contained a unique set of words, unlike typical episodic learning tasks (e.g., California Verbal Learning Test) which repeat the same words in each list. The words in the five lists were comparable in frequency, $F(4,195) = 0.32$, $p = .868$, imageability, $F(4,195) = 0.31$, $p = .874$, concreteness, $F(4,195) = 0.59$, $p = .668$, and familiarity, $F(4,195) = 0.58$, $p = .681$.

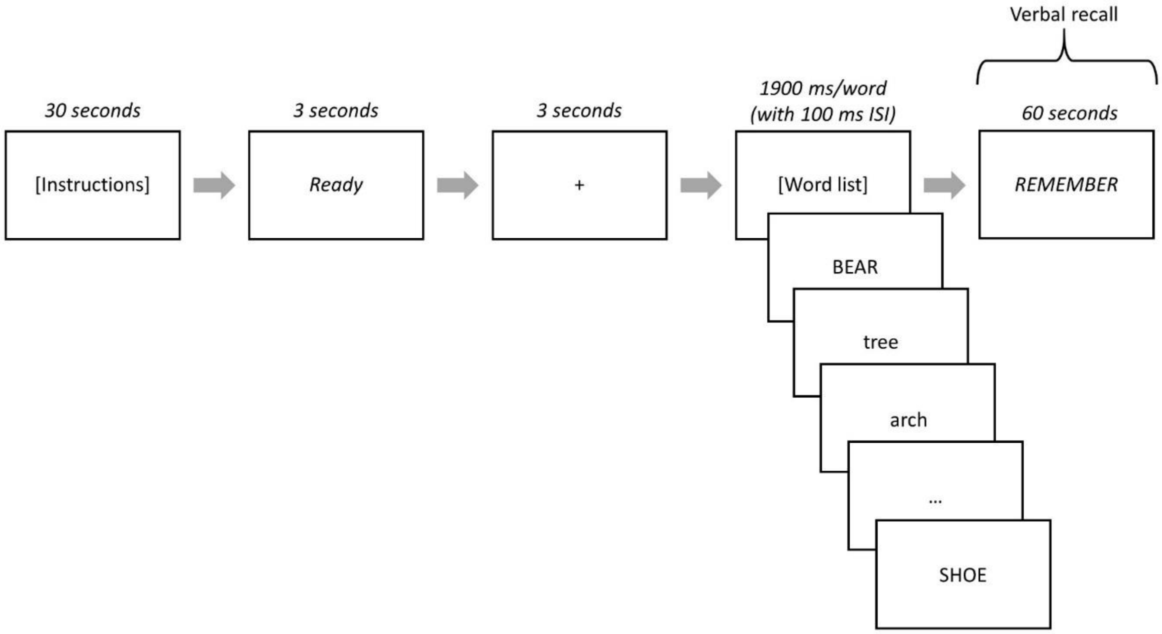
For each of the five lists, half of the words ($n = 20$) were assigned as high-value (worth 10 points) and half ($n = 20$) were assigned as low-value (worth 1 point). High- and low-value words were differentiated by letter case, i.e., words written in all uppercase letters (e.g., LAMB) were high-value and words written in all lowercase letters (e.g., lamb) were low-value, or vice-versa. The font size was controlled to ensure that uppercase and lowercase letters all appeared as the same size on the screen. Participants were randomly assigned to one of four versions of the task, and each version was counterbalanced for word value and letter case. In two versions, words in uppercase letters were assigned high-value and words in lowercase letters were assigned low-value. In the other two versions, words in lowercase letters were assigned high-value and words in uppercase letters were assigned low-value.

The following instructions were presented on screen to participants: “You will see words appear on the screen one at a time. Some words are in uppercase and some words are in lowercase. The uppercase words *[lowercase words]* are worth 10 points each (high-value words). The lowercase words *[uppercase words]* are worth 1 point each (low-value words). At the end of the list, you will see the word “REMEMBER” on the screen. Your task is to remember as many of the words from the list as possible with the goal of scoring the maximum number of points. This is similar to a game in which words are worth different amounts of money”. The research assistant conducting the experiment confirmed that participants understood the point values for the uppercase and lowercase words, which was dependent on their assigned version. Importantly though, the research assistant did not provide specific instructions on how to be strategic, such as only focusing on the high-value words.

Following the instructions, the word “Ready” was displayed at the center of the screen for 3000 ms followed by a fixation (+) for 3000 ms. The 40 words from one list were then displayed sequentially in the center of the screen for 1900 ms each with an inter-stimulus interval of 100 ms (blank screen). The word “REMEMBER” appeared at the end of each list at which point participants had 60 seconds to verbally recall words from that list while their responses were manually recorded on a score sheet (see Figure 4.1 for task schematic). Participants received immediate feedback from the research assistant about their score after each list and before the next list was presented. After all five lists were completed, participants completed a brief post-experiment interview about whether they used any strategies during the task, and if so, what types of strategies they used (e.g., categories; words that rhyme).

Figure 4.1

Strategic Processing Task Schematic



High- and low-value words were represented by lowercase or uppercase words depending on the task version. When the word "REMEMBER" was presented, participants verbally recalled words from the list, and their responses were recorded on paper and scored. This process was repeated for all five lists.

4.2.3. EEG data collection and preprocessing

Continuous EEG was recorded for each of the five lists using a 64-electrode elastic cap (Neuroscan Quikcap) using a Neuroscan SynRT amplifier and Scan v4.5 software (sampling rate: 1kHz, bandpass filter: DC-200Hz) with impedances typically below 10 kΩ. The reference electrode was located at the midline between Cz and CPz and vertical electrooculogram (VEOG) was recorded at sites above and below the left eye. EEG data were processed offline using Neuroscan Edit. Raw EEG data from each of the five lists (obtained during a single testing session) were appended together to have enough trials per value type for analysis (100 high-value trials; 100 low-value trials). Poorly functioning electrodes were identified based on both high impedance values (above 20 kΩ) and visual inspection of the raw EEG signal and were excluded from analysis (on average, 1.5 electrodes per CN participant were excluded and 1 electrode per MCI participant were excluded). Eye blinks were corrected using spatial filtering in Neuroscan Edit function. The data were epoched from 500 ms before stimulus onset to 1500 ms after stimulus offset. Epochs with peak signal amplitudes of ±75 μV were rejected. Of the total number of high-value epochs, 17% and 20% were rejected for CN and MCI, respectively, with no significant difference between the two groups, $F(1,31) = 1.38$, $p = .250$. Of the total number of low-value epochs, 17% and 21% were rejected for CN and MCI, respectively, with no significant difference between the two groups, $F(1,31) = 1.79$, $p = .191$. EEG data were re-referenced to the average potential over the entire scalp.

4.2.4. ERSP analysis

ERSPs were analyzed from 0 to 1300 ms (post-stimulus onset) with a non-overlapping baseline of -400 to -100 ms (pre-stimulus onset) using EEGLAB toolbox (Version 14.1.1b; Delorme & Makeig, 2004) running under Matlab 2018b (MathWorks, Natick, MA, USA). Time-frequency decomposition was performed using short-time Fourier transform with Hanning window tapering as implemented in the EEGLAB function *newtimef.m*. Time-frequency data were obtained using a 256-ms sliding window and a pad ratio of 4, resulting in a frequency resolution of approximately 1 Hz. Baseline correction was done following the gain model (Delorme & Makeig, 2004; Grandchamp & Delorme, 2011), where each time-frequency time point was divided by the average pre-stimulus baseline power from -400 to -100 ms relative to stimulus onset at the same frequency.

4.2.5. ERSP power estimation

Mean power was estimated in the theta band (4-8 Hz) at two separate frontal sites (Fz; FCz) and in the alpha band (8-12 Hz) at two separate parietal sites (CPz; Pz). Changes in power will be described as synchronization or desynchronization, depending on whether there was an increase or decrease in power, respectively, relative to baseline. A-priori defined alpha band was used, as opposed to bands derived from individual alpha frequency (IAF), as no significant between-group differences were observed for IAF values for either the high-value, $F(1,31) = 0.645$, $p = .428$, or low-value, $F(1,31) = 0.004$, $p = .948$, words. The electrode sites were selected based on work demonstrating greater prominence of theta band at frontal sites and alpha at parietal/posterior sites (e.g., Cavanagh & Frank, 2014; Hanslmayr et al., 2012; Ishii et al., 1999; Kawasaki et al., 2010) and based on our previous studies using the same task with younger and older adults (Nguyen et al., 2019, 2020). Individual midline electrodes were used to sample the data given the small sample size. Additionally, other studies that have examined theta and alpha bands in older adults with MCI have used individual electrodes, particularly midline electrodes including the ones selected for the current study (Deiber et al., 2009; Grunwald et al., 2002; Luckhaus et al., 2008; Mazaheri et al., 2018; Missonnier et al., 2006). Mean spectral power was computed for each group (CN/MCI), value (high-/low-value), and frequency band (theta, alpha) in 100 ms time windows from 0 ms to 1300 ms with no overlap, resulting in 13 time windows for analysis.

4.2.6. Statistical analysis

To guide the analysis of the behavioral and ERSP data, we first examined whether there were significant differences for the behavioral and ERSP data across the two version types based on the letter case (i.e., words in uppercase being assigned to high-value vs. words in lowercase being assigned to high-value). No significant differences were observed across versions for behavioral ($p > .05$ for all five lists; see Table 4.2 for exact *p*-values) or ERSP data ($p > .05$ for all time windows; see Table 4.3 for exact *p*-values), therefore we combined data from both version types. Task-related behavioral data, specifically the average number of high- and low-value words recalled, were analyzed using a general linear model (GLM) with group (CN/MCI) as a between-subject factor and value (high-/low-value) as a within-subject factor to assess whether participants engaged in strategic processing.

ERSP data were examined using separate GLMs for theta and alpha bands, with group (CN/MCI) as between-subject factor and value (high-/low-value) as within-subject factor, for each of the 13 time windows (100 ms time windows between 0 and 1300 ms post-stimulus onset). Significance values were corrected for multiple comparisons with the Bonferroni method at a threshold of $p < .05$. IBM SPSS Statistics 26 was used for analysis. The reported *p*-values, where not specified otherwise, are derived from *F*- and *t*-statistics.

Table 4.2

Statistical Results for the Effects of Version on Behavioral Data

		Version * Value
List 1	*F*(1,30)	0.92
	p	.345
List 2	*F*(1,30)	1.31
	p	.262
List 3	*F*(1,30)	0.68
	p	.417
List 4	*F*(1,30)	0.03
	p	.866
List 5	*F*(1,30)	0.14
	p	.714

Cells display statistics for interaction effects between version (words in uppercase being assigned to high-value/words in lowercase being assigned to high-value) and value (high-value/low-value) for each of the five lists. There were no significant differences observed across versions for the behavioral data.

Table 4.3

Statistical Results for the Effects of Version on ERSP data

		Time (ms)												
		0-100	**100-200**	**200-300**	**300-400**	**400-500**	**500-600**	**600-700**	**700-800**	**800-900**	**900-1000**	**1000-1100**	**1100-1200**	**1200-1300**
Theta (4-8 Hz)														
Fz	*F*(1,30)	0.05	0.97	0.17	0.63	1.44	0.94	0.24	0.15	3.15	3.16	0.27	1.17	0.08
	p	.829	.332	.682	.435	.240	.339	.627	.705	.086	.086	.609	.289	.780
FCz	*F*(1,30)	0.05	2.58	0.70	0.13	1.24	1.97	0.68	0.85	3.02	3.53	2.44	3.26	1.58
	p	.834	.119	.409	.723	.275	.172	.417	.364	.093	.070	.128	.081	.219
Alpha (8-12 Hz)														
CPz	*F*(1,30)	1.48	2.29	0.88	0.01	1.47	1.22	0.07	0.07	1.06	1.10	0.29	1.17	0.86
	p	.233	.142	.357	.935	.234	.278	.787	.799	.312	.298	.598	.289	.360
Pz	*F*(1,30)	2.93	2.68	0.14	0.34	0.06	0.08	0.04	0.20	0.35	0.63	0.15	1.11	0.01
	p	.097	.112	.708	.565	.803	.774	.842	.658	.556	.433	.700	.301	.923

Cells display statistics for interaction effects between version (words in uppercase being assigned to high-value/words in lowercase being assigned to high-value) and value (high-value/low-value) for mean power in theta band at Fz and FCz electrodes and in alpha band at CPz and Pz electrodes across 13 time windows post-stimulus onset. There were no significant differences observed across versions for the ERSP data.

4.3. Results

4.3.1. Task-related behavioral data

Task-related behavioral data showed significant main effects of group with more total words recalled for CN than MCI for all five lists ($p < .001$), as well as significant main effects of value with more high- than low-value words recalled for all five lists ($p < .001$; see Table 4.4 for exact p-values). These main effects were qualified by significant interaction effects between group and value for Lists 1, 2, 3, and 5 ($p < .001$) and trending for List 4 ($p = .055$; Table 4.4; Figure 4.2). Post hoc analyses revealed that for all five lists there were between group differences for the high-value words with more high-value words recalled by CN than MCI (List 1: $p < .001$; List 2: $p < .001$; List 3: $p < .001$; List 4: $p = .002$; List 5: $p < .001$), and there were no between group differences for low-value words (List 1: $p = .445$; List 2: $p = .758$; List 3: $p = .076$; List 4: $p = .319$; List 5: $p = .398$).

Table 4.4

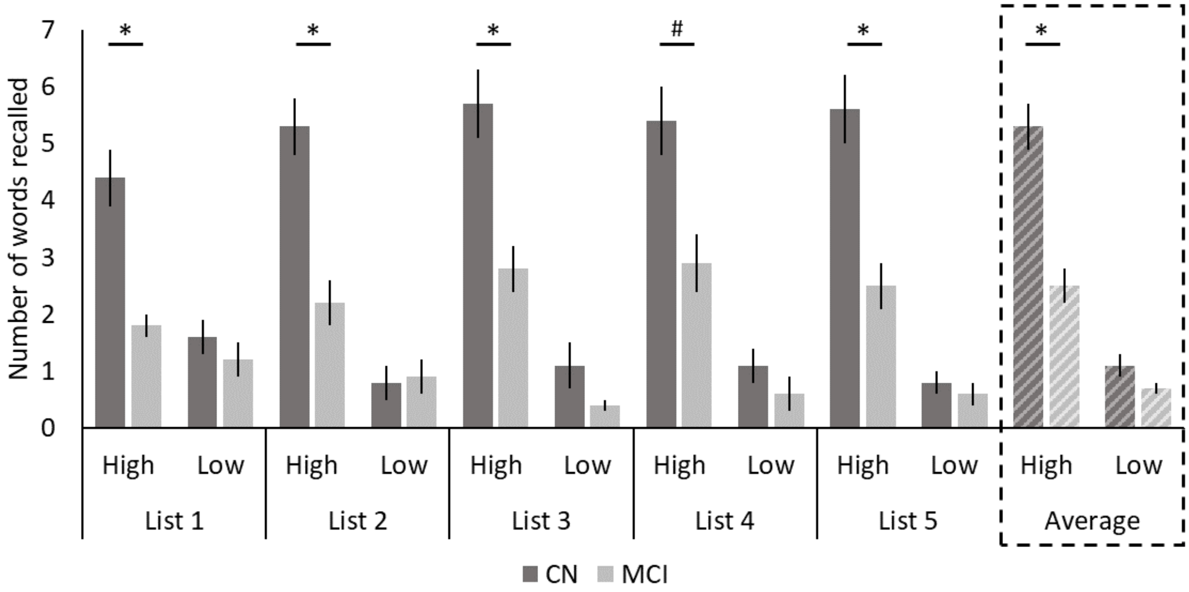
Statistical Results for Task-Related Behavioral Data

		Main effect: Group	**Main effect: Value**	**Interaction: Group x Value**
List 1	$F(1,30)$	30.94	14.31	5.80
	p	< .001**	.001**	0.022*
List 2	$F(1,30)$	30.94	42.80	12.87
	p	< .001**	< .001**	0.001**
List 3	$F(1,30)$	20.90	70.05	6.46
	p	< .001**	< .001**	0.016*
List 4	$F(1,30)$	21.15	41.73	3.97
	p	< .001**	< .001**	0.055
List 5	$F(1,30)$	31.47	60.29	10.94
	p	< .001**	< .001**	0.002**

Cells display statistics for main effects of group (CN/MCI), main effects of value (high-/low-value words), and interaction effects between group and value for the five word lists. *$p < .05$; **$p < .01$.

Figure 4.2

Task-related Behavioral Data



The number of high- and low-value words recalled across the five lists for both cognitively normal older adults (CN) and older adults with mild cognitive impairment (MCI) are shown. Average is the average number of words recalled across the five lists. Bars represent standard error. **p* < .05; #*p* = .055 (trending).

4.3.2. Theta band (4-8 Hz) mean power

For Fz, no significant main effects of group were observed for any of the 13 time windows (100 ms time windows between 0 and 1300 ms post-stimulus onset; *p* > .05; see Table 4.5 for exact *p*-values). Significant main effects of value were observed from 700-900 ms post-stimulus onset (*p* < .05), with greater theta synchronization for low- compared to high-value words (see Table 4.6 for exact *p*-values; Figure 4.3). A significant interaction effect between group and value was observed from 700-800 ms post-stimulus onset (*p* < .05; see Table 4.7 for exact *p*-values; Figure 4.4). Post hoc analyses revealed a between group difference for low-value words (*p* = .043), with greater theta synchronization for CN than MCI, but no between group difference for high-value words (*p* = .981). Additionally, a within group difference was observed for the CN group ($p < .001$), with greater theta synchronization for low- than high-value words, but not for the MCI group ($p = .118$).

For FCz, significant main effects of group were observed from 100-400 ms post-stimulus onset ($p < .05$; Table 4.5; Figure 4.5), with greater theta synchronization for CN than MCI. A significant main effect of value was observed from 700-800 ms post-stimulus onset ($p < .05$; Table 4.6; Figure 4.3), with greater theta synchronization for low- compared to high-value words. This main effect was qualified by a significant interaction effect between group and value and was observed from 700-800 ms post-stimulus onset ($p < .05$; Table 4.7; Figure 4.4). Post hoc analyses revealed a between group difference for low-value words ($p =.045$), with greater theta synchronization for CN than MCI, but no between group difference for high-value words ($p = .945$), similar to what was observed at Fz. Additionally, a within group difference was observed for the CN group ($p = .001$), with greater theta synchronization for low- than high-value words, but not for the MCI group ($p = .190$).

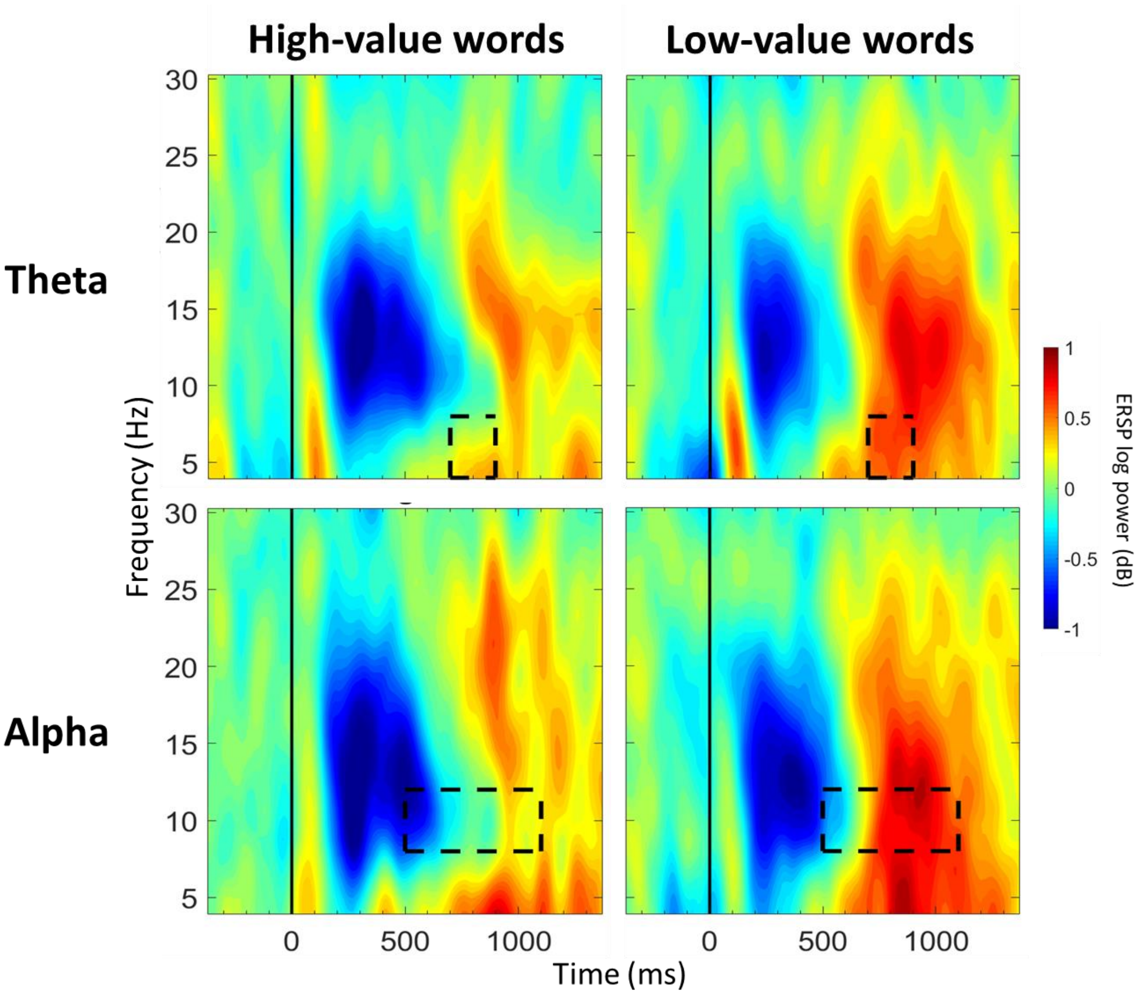
4.3.3. Alpha band (8-12 Hz) mean power

For CPz, no significant main effects of group were observed for any of the 13 time windows ($p > .05$; Table 4.5). Significant main effects of value were observed from 500-1000 ms post-stimulus onset ($p < .05$; Table 4.6; Figure 4.3), with greater alpha desynchronization for high- compared to low-value words. A significant interaction effect between group and value was observed from 300-400 ms post-stimulus onset ($p < .05$; Table 4.7; Figure 4.6). Post hoc analyses did not reveal any between group differences, but a within group difference was observed for the CN group ($p = .023$), with greater alpha desynchronization for high- than low-value words, but not for the MCI group ($p = .401$).

For Pz, no significant main effects of group were observed for any of the 13 time windows ($p > .05$; Table 4.5). Significant main effects of value were observed from 500-1100 ms post-stimulus onset ($p < .05$; Table 4.6; Figure 4.4), with greater alpha desynchronization for high- compared to low-value words. The interaction effects between group and value were not significant for any of the 13 time windows ($p > .05$; Table 4.7).

Figure 4.3

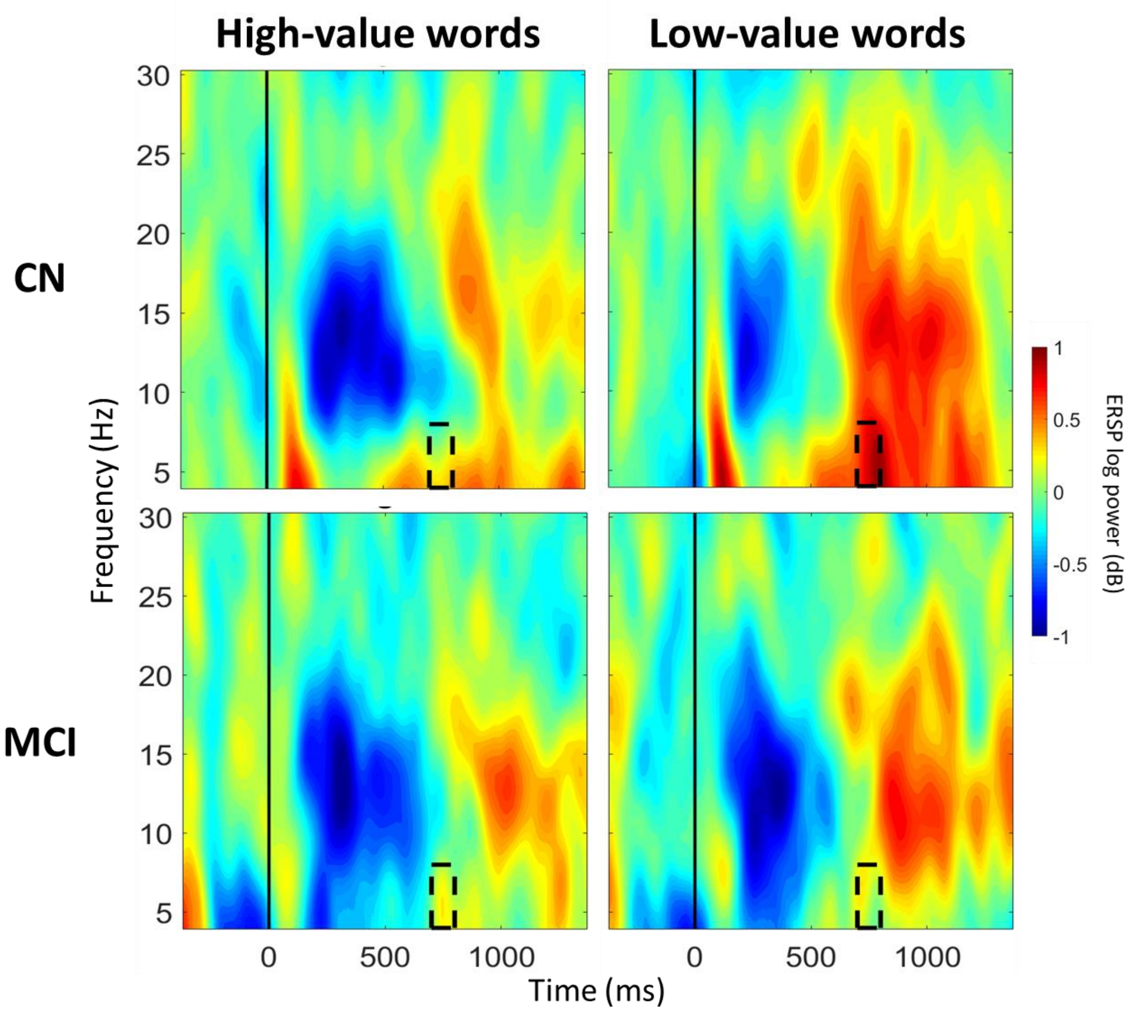
ERSP Comparisons for Main Effects of Value



Spectrograms illustrate differences between value (high-/low-value) for theta band (4-8 Hz) at Fz and alpha band (8-12 Hz) at Pz. The 0 ms time point (solid vertical line) represents stimulus onset. Dashed black rectangles indicate the time windows where significant main effects of value were observed (also see Table 4.3).

Figure 4.4

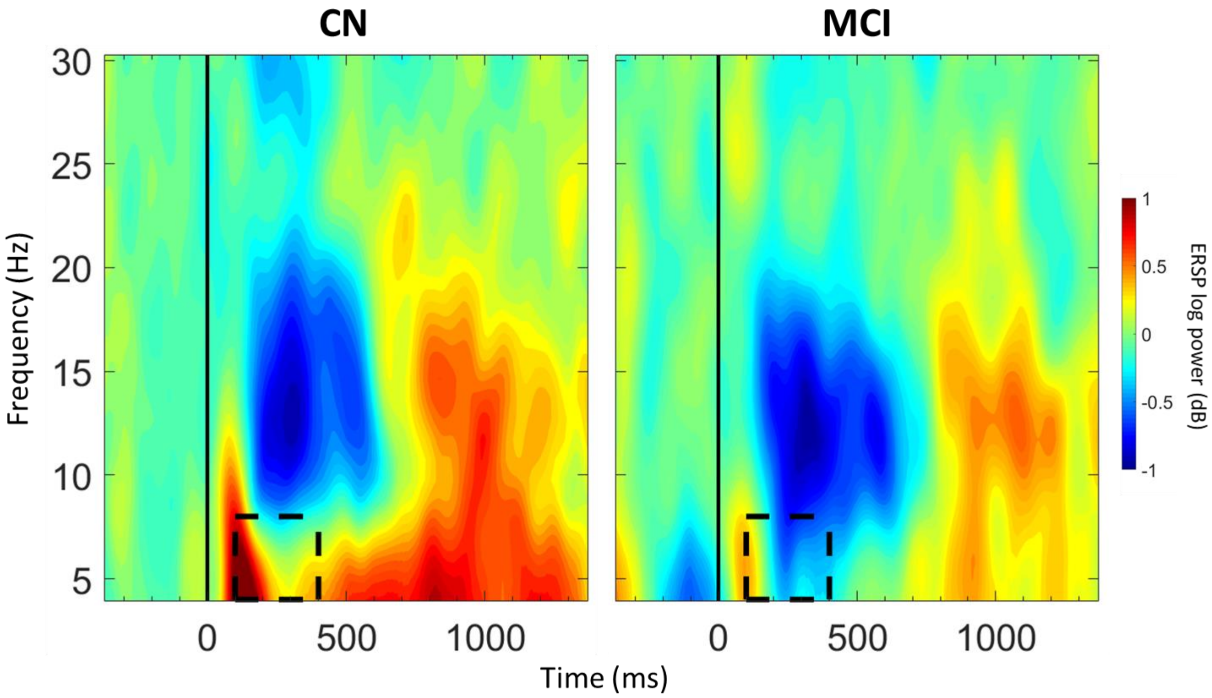
ERSP Comparisons for Theta Band for Interaction Effects Between Group and Value



Spectrograms illustrate differences between groups (CN/MCI) and value (high-/low-value) for theta band (4-8 Hz) at Fz. The 0 ms time point (solid vertical line) represents stimulus onset. Dashed black rectangles indicate the time windows where significant interaction effects between group and value were observed (also see Table 4.4). CN: Cognitively normal older adults; MCI: mild cognitive impairment.

Figure 4.5

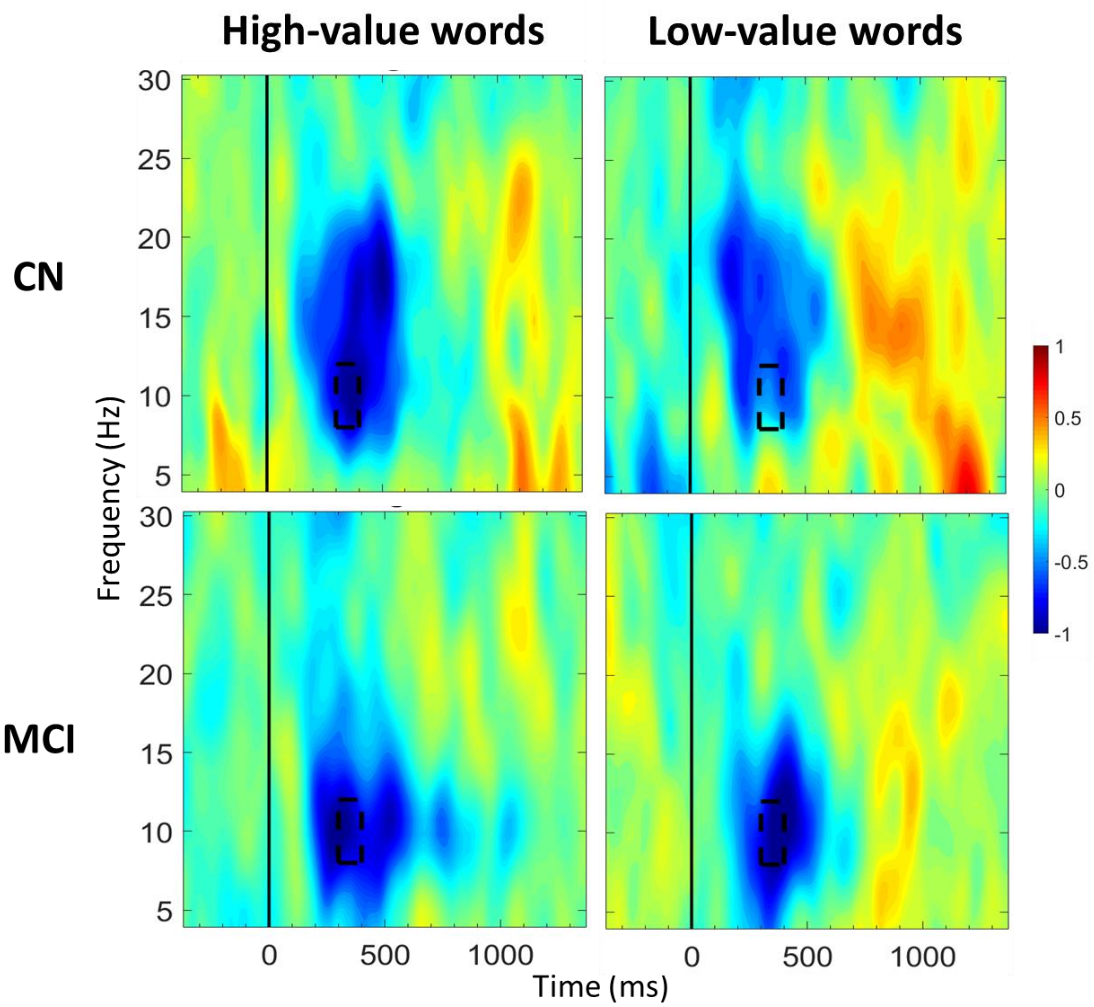
ERSP Comparisons for Main Effects of Group



Spectrograms illustrate differences between groups (CN/MCI) for theta band (4-8 Hz) at FCz. The 0 ms time point (solid vertical line) represents stimulus onset. Dashed black rectangles indicate the time windows where significant main effects of value were observed (also see Table 4.2). CN: Cognitively normal older adults; MCI: mild cognitive impairment.

Figure 4.6

ERSP Comparisons for Alpha Band for Interaction Effects Between Group and Value



Spectrograms illustrate differences between groups (CN/MCI) and value (high-/low-value) for alpha band (8-12 Hz) at CPz. The 0 ms time point (solid vertical line) represents stimulus onset. Dashed black rectangles indicate the time windows where significant interaction effects between group and value were observed (also see Table 4.4). CN: Cognitively normal older adults; MCI: mild cognitive impairment.

Table 4.5

Statistical Results for Main Effects of Group for Theta and Alpha Band Mean Power

		Time (ms)												
		0-100	**100-200**	**200-300**	**300-400**	**400-500**	**500-600**	**600-700**	**700-800**	**800-900**	**900-1000**	**1000-1100**	**1100-1200**	**1200-1300**
Theta (4-8 Hz)														
Fz	*F*(1,30)	0.23	3.33	1.67	1.65	0.84	0.84	1.85	1.30	1.36	1.38	1.87	1.77	0.44
	p	.635	.078	.206	.208	.367	.366	.184	.263	.253	.249	.182	.194	.514
FCz	*F*(1,30)	1.02	**8.14**	**6.65**	**5.16**	3.56	1.92	3.10	1.55	1.57	0.94	1.90	1.58	1.05
	p	.321	**.008**	**.015**	**.030**	.069	.176	.089	.223	.220	.339	.178	.219	.313
	η_p^2		**.21**	**.18**	**.15**									
Alpha (8-12 Hz)														
CPz	*F*(1,30)	0.15	0.46	0.23	0.49	0.33	2.01	0.79	1.16	0.09	0.19	3.63	1.67	0.93
	p	.700	.505	.637	.490	.571	.167	.380	.289	.765	.666	.066	.206	.342
Pz	*F*(1,30)	0.07	0.00	0.01	0.38	0.42	1.94	1.76	0.83	0.06	0.41	0.43	0.57	0.24
	p	.797	.973	.909	.545	.523	.174	.195	.371	.813	.527	.516	.455	.631

Cells display statistics for main effects of group (CN/MCI) for mean power in theta band (4-8 Hz) at Fz and FCz electrodes and in alpha band (8-12 Hz) at CPz and Pz electrodes across 13 time windows post-stimulus onset. Significant main effects of value ($p < .05$, Bonferroni-corrected) are indicated by bolded values and their effect sizes (η_p^2) are reported.

Table 4.6

Statistical Results for Main Effects of Value for Theta and Alpha Band Mean Power

		Time (ms)												
		0-100	**100-200**	**200-300**	**300-400**	**400-500**	**500-600**	**600-700**	**700-800**	**800-900**	**900-1000**	**1000-1100**	**1100-1200**	**1200-1300**
Theta (4-8 Hz)														
Fz	*F*(1,30)	0.50	0.45	0.00	0.41	0.5	3.03	3.51	**6.56**	**7.83**	3.21	1.76	1.55	0.06
	p	.486	.509	.954	.527	.485	.092	.071	**.016**	**.009**	.084	.195	.223	.813
	η_p^2								**.18**	**.21**				
FCz	*F*(1,30)	0.60	1.41	0.00	0.01	1.57	0.96	1.37	**8.83**	3.94	2.32	0.49	0.66	0.21
	p	.446	.245	.949	.931	.22	.334	.251	**.006**	.056	.138	.492	.424	.650
	η_p^2								**.23**					
Alpha (8-12 Hz)														
CPz	*F*(1,30)	0.11	0.00	1.46	3.14	0.27	**10.02**	**4.38**	**14.11**	**10.43**	**7.96**	3.97	0.66	0.52
	p	.741	.985	.236	.087	.608	**.004**	**.045**	**.001**	**.003**	**.008**	.055	.425	.478
	η_p^2						**.25**	**.13**	**.32**	**.26**	**.21**			
Pz	*F*(1,30)	0.44	0.18	0.68	0.09	0.00	**5.31**	**10.4**	**22.5**	**41.74**	**14.21**	**7.72**	1.30	0.38
	p	.510	.679	.416	.773	.966	**.028**	**.003**	**<.001**	**<.001**	**.001**	**.009**	.263	.544
	η_p^2						**.15**	**.26**	**.43**	**.58**	**.32**	**.21**		

Cells display statistics for main effects of value (high-/low-value words) for mean power in theta band at Fz and FCz electrodes and in alpha band at CPz and Pz electrodes across 13 time windows post-stimulus onset. Significant main effects of value ($p < .05$, Bonferroni-corrected) are indicated by bolded values and their effect sizes (η_p^2) are reported.

Table 4.7

Statistical Results for Group By Value Interactions for Theta and Alpha Band Mean Power

		Time (ms)												
		0-100	**100-200**	**200-300**	**300-400**	**400-500**	**500-600**	**600-700**	**700-800**	**800-900**	**900-1000**	**1000-1100**	**1100-1200**	**1200-1300**
Theta (4-8 Hz)														
Fz	*F*(1,30)	0.34	0.17	0.11	1.75	0.61	0.07	0.00	**5.77**	1.96	0.36	0.00	3.58	1.58
	p	.567	.682	.747	.195	.443	.793	.969	**.023**	.171	.551	.973	.068	.219
	η_p^2								**.16**					
FCz	*F*(1,30)	0.04	0.01	1.84	2.12	2.30	1.31	1.07	**4.33**	2.97	0.32	0.09	3.69	1.01
	p	.842	.922	.185	.156	.140	.262	.310	**.046**	.095	.578	.766	.060	.323
	η_p^2								**.13**					
Alpha (8-12 Hz)														
CPz	*F*(1,30)	0.04	0.24	1.35	**6.90**	2.24	0.63	0.22	0.09	0.03	0.31	0.47	0.00	0.03
	p	.846	.629	.255	**.013**	.145	.433	.646	.773	.857	.582	.500	.985	.855
	η_p^2				**.19**									
Pz	*F*(1,30)	1.27	0.02	0.00	2.63	3.02	1.87	1.37	1.69	1.31	0.26	0.08	0.30	0.11
	p	.268	.887	.975	.116	.093	.181	.251	.204	.261	.615	.781	.589	.742

Cells display statistics for interaction effects between group (CN/MCI) and value (high-/low-value words) for mean power in theta band at Fz and FCz electrodes and alpha band at CPz and Pz electrodes across 13 time windows post-stimulus onset. Significant interaction effects between group and value ($p < .05$, Bonferroni-corrected) are indicated by bolded values and their effect sizes (η_p^2) are reported.

4.4. Discussion

The purpose of the current study was to examine value-directed strategic processing in older adults with MCI. Behavioral data showed that MCI and CN participants differed in the total number of words recalled and the number of high-value words recalled, but not in the number of low-value words recalled. ERSP data revealed group differences in value-directed strategic processing in early time periods for theta band from 100-400 ms post-stimulus onset and alpha band from 300-400 ms. Group differences were also observed in the later periods of processing for theta band from 700-800 ms. Some similarities in value-directed strategic processing were also observed between the MCI and CN individuals in theta band power (800-900 ms) and alpha band power (500-1100 ms).

Behavioral data revealed group differences with the MCI participants performing worse than the CN participants across the five lists on total words (all lists combined, MCI = 15.9 words; CN = 31.7 words) and high-value words (all lists combined, MCI = 12.3 words; CN = 26.4 words). Poorer total recall in the MCI group was not surprising given the extensive literature from list learning tasks that show deficits in episodic learning and memory in individuals with MCI (e.g., de Jager et al., 2003; de Jager & Budge, 2005; Greenaway et al., 2006; Libon et al., 2010, 2011; Mistridis et al., 2015; Petersen et al., 1999; Ribeiro et al., 2007; Teng et al., 2009; for reviews see Arnáiz & Almkvist, 2003; Salmon, 2012). While the impaired recall of high-value words in MCI compared to CN participants may also be related to deficits in episodic memory, it could potentially be due to impairments in value-directed strategic processing. This latter possibility is supported, to some extent, by data from the exit interviews in which participants were asked whether they used a strategy to complete the task. Only 57% of MCI participants reported using a strategy to perform the task compared to 81% of CN participants. This is consistent with list learning studies that have shown reduced strategy use in MCI compared to CN individuals (Malek-Ahmadi et al., 2011; McLaughlin et al., 2014; Price et al., 2010; Ribeiro et al., 2007). The relative lack of strategy use in the MCI compared to the CN participants may have hindered their behavioral performance for high-value words. Interestingly, although the groups differed in the recall of total words and high-value words, there were no group differences in the number of low-value words recalled (all lists combined, MCI = 3.6 words; CN = 5.3 words). This could suggest some retained ability to ignore low-value words in the MCI individuals. However, both groups exhibited floor effects for low-value word recall (i.e., very few low-value words were recalled), so our task may have lacked the power to delineate group differences effectively. Although the behavioral data provide some indication of value-directed strategic processing, this data is confounded by memory processes (i.e., encoding, storage, and retrieval). Data from real-time online processing measured using ERSPs provided additional information about group differences.

ERSP differences between CN and MCI participants were observed for both theta and alpha bands beginning in early stages of stimulus processing. Reduced frontal theta synchronization was observed in MCI participants compared to CN participants between 100-400 ms (FCz) post-stimulus onset (main effects of group). The current findings seem consistent with a handful of studies that have observed reduced theta synchronization in MCI participants compared to CN participants across various tasks (i.e., Go/NoGo, *n*-back, and Sternberg tasks; Cummins et al., 2008; Deiber et al., 2009, 2015; Goodman et al., 2019; Nguyen et al., 2017). Given that frontal theta synchronization is related to inhibitory processes (Cavanagh & Frank, 2014; Cavanagh & Shackman, 2015; Nigbur et al., 2011), the MCI participants may not have been able to engage early inhibitory processes that were as robust as the CN participants, aligning with studies that have shown inhibitory deficits in MCI individuals (e.g., Bélanger et al., 2010; Bélanger & Belleville, 2009; Belleville et al., 2007; Traykov et al., 2007; Wylie et al., 2007; Zheng et al., 2012). Given that the observed group differences occurred in early stages of stimulus processing, it may be that less robust inhibitory processes in the MCI individuals made it more difficult for them to effectively filter information early on. As such, during subsequent processing, the MCI individuals may have engaged in more similar processing for both high- and low-value words.

Alpha band group differences lend some support to the notion that MCI individuals may process high- and low-value words more similarly compared to CN individuals. Processing differences between CN and MCI participants for high- versus low-value information were observed from 300-400 ms (CPz) post-stimulus onset (interaction effect between group and value). While within group differences between high- and low-value words were not observed in the MCI participants, the CN participants demonstrated greater alpha desynchronization for high- compared to low-value words. This suggests a lack of early value-based neural differentiation (i.e., more similar processing between high- and low-value words) in the MCI participants relative to the CN participants, which may have contributed to their poorer recall of high-value words. This compromised ability to differentially modulate processing high- versus low-value words in MCI individuals is somewhat similar to what has been noted in AD pathology. In particular, animal studies of AD have shown alterations in EEG measures that are suggestive of impaired neural modulation (e.g., Kim et al., 2020; Mugantseva & Podolski, 2009; Schneider et al., 2014; for review see Hamm et al., 2015). For instance, using an auditory oddball task, Kim et al. (2020) found that amyloid-beta injected mice did not show EEG amplitude differences between standard and deviant tones, but the control mice did show a difference between the two tone types. This finding is similar to the pattern observed in the current study.

Additional group differences in processing of high- versus low-value information were observed in theta band in later time periods, specifically from 700-800 ms (Fz; FCz) post-stimulus onset (interaction effect between group and value). In particular, reduced theta synchronization was noted in the MCI participants compared to the CN participants for low-value words, but not for high-value words. In the absence of behavioral group differences for low-value word recall, this theta finding may reflect neural alterations that precede behavioral alterations in MCI individuals. This possibility aligns with the pathological cascade model of AD in which various pathophysiological changes appear years before any obvious cognitive changes (Jack et al., 2013; Jack & Holtzman, 2013). In light of biomarker studies which utilize early neural changes to try to identify those at greater risk of AD before any overt behavioral manifestations of the disease, these findings will be important to explore further. For example, examining individuals with early AD may reveal more pronounced neural changes that are also accompanied by behavioral impairments in low-value word recall. Such a finding could implicate that the neural changes observed in the current study may be early markers of neural deterioration. Future studies could also try utilizing more complex tasks and/or making the study conditions or environment less optimal (e.g., environments with distractions) to better elicit behavioral group differences.

Similarities between MCI and CN participants in processing high- versus low-value words were also seen in theta and alpha bands but were subsequent to the initial group differences. Both groups showed greater theta synchronization for low- compared to high-value words from 800-900 ms (Fz) post-stimulus onset (main effect of value, which was not qualified by an interaction), and greater alpha desynchronization for high- compared to low-value words from 500-1000 ms (CPz) and 500-1100 ms (Pz) post-stimulus onset (main effects of value). These findings are similar to our previous studies that utilized the same task with both cognitively normal younger and older adults (Nguyen et al., 2019, 2020). The consistency in the distinct neural patterns observed for high- and low-value words across ages and cognitive status suggests that theta and alpha bands are robust neural measures of value-directed strategic processing. It was not completely unexpected to find some similarities between the groups for processing high- and low-value information as there is evidence that individuals with MCI retain some ability to extract important information, although they are still impaired relative to CN individuals (e.g., Coutinho et al., 2015; de Simone et al., 2017; Kavé & Heinik, 2004; Tremont et al., 2010). Additionally, Castel et al. (2009) found that very mild and mild AD patients recalled more high- than low-value words. Although this ability was significantly impaired compared to cognitively normal younger and older adults, this would suggest that value-directed strategic processing is retained to some degree in individuals with MCI. It will be important for future studies to directly compare CN with MCI and AD individuals to better understand how value-directed strategic processing is affected by disease progression.

Despite some promising findings in the current study, there are certain limitations related to the analysis and task, and potential future directions that can help address these limitations. First, the analysis utilized individual electrodes, as opposed to average electrode clusters like our two previous studies (Nguyen et al., 2019, 2020), due to the small sample size. It will be important to increase the sample size and examine ERSPs in electrode clusters to validate these findings. Additionally, it may be useful to use data reduction techniques, such as principal component analysis, to identify electrodes of interest through more data-driven (as opposed to hypothesis-driven) approaches. Second, the current task was a passive task and was not designed to examine how subsequent recall may relate to value-directed strategic processing. Specifically, the task design does not allow us to examine how ERSP data during stimulus processing differs between words that were subsequently successfully versus unsuccessfully recalled, as is typical in subsequent memory paradigms (for reviews see Paller & Wagner, 2002; Wagner et al., 1999; Werkle-Bergner et al., 2006). Such a comparison might provide more clarity as to whether lower recall of high-value words in MCI individuals relative to CN individuals was due to impairments in episodic memory or value-directed strategic processing. For instance, if similar neural patterns were observed for both successfully and unsuccessfully recalled high-value words, that might be indicative of episodic memory deficits. Third, the limited number of low-value words recalled in both groups might be addressed in future studies by using a task that burdens the cognitive system more, such as using different distributions of low- and high-value words (e.g., 80% low-value words, 20% high-value words). Another possibility would be to use a task with a similar format to the work of Castel and colleagues in which words are paired with a range of values (e.g., ranging between 1-12 points; Castel et al., 2002, 2011). In these types of tasks, multiple point values are considered low-value (e.g., words worth 1, 2, or 3 points), which may help in creating a greater range of recall performance for low-value words that may reveal behavioral group differences. Lastly, studies that have used list learning tasks have shown reductions in spontaneous strategy use in cognitively normal older adults (Dunlosky & Hertzog, 2001; Taconnat et al., 2009; Witte et al., 1993) and in individuals with MCI (Malek-Ahmadi et al., 2011; McLaughlin et al., 2014; Price et al., 2010; Ribeiro et al., 2007). Providing explicit instructions to use such strategies has been shown to improve recall in both cognitively normal older adults (Kuhlmann & Touron, 2016; Naveh-Benjamin et al., 2007) and individuals with

MCI (Ribeiro et al., 2007). As such, it would be interesting to examine the effects of explicitly defining value based on conceptual information, such as categories (e.g., animals are high-value words), on value-directed strategic processing in both CN and MCI individuals in future studies.

In conclusion, the current study showed that value-directed strategic processing is compromised both behaviorally and neurally in MCI individuals as compared to CN individuals. The group differences in theta and alpha bands in earlier time periods of stimulus processing suggest that MCI and CN participants regulate strategic processing differently, which may have contributed to impaired recall of high-value words by MCI participants relative to CN participants. The theta alterations linked to processing of low-value information in MCI participants relative to CN participants may be an early marker of neural deterioration that precedes overt behavioral changes. The similarities between MCI and CN participants for theta and alpha bands showed that there are distinct neural processes for high- and low-value words. These distinct neural processes are consistent with our previous studies (Nguyen et al., 2019, 2020), demonstrating the utility of ERSPs as measures of the neurophysiological underpinnings of value-directed strategic processing across normal cognitive aging and clinically significant cognitive decline. The findings of the current study may be clinically applicable by providing targets for cognitive training programs that are aimed at maintaining cognitive abilities in MCI, such as teaching individuals with MCI to better attend to and process the most valuable information.

CHAPTER 5: THE EFFECTS OF PERCEPTUALLY VERSUS CONCEPTUALLY DEFINED VALUE ON VALUE-DIRECTED STRATEGIC PROCESSING IN COGNITIVELY NORMAL YOUNGER AND OLDER ADULTS

ABSTRACT

The current study investigated whether behavioral measures of value-directed strategic processing are differentially affected when value is defined by perceptual versus conceptual features, and how normal cognitive aging impacts processing. Cognitively normal younger (N = 16; mean age: 22.1 ± 2.9 years) and older adults (N = 16; mean age: 66.9 ± 7.3 years) completed two value-directed strategic processing tasks, where value was defined by either perceptual (i.e., uppercase and lowercase letters; Letter Case task) or conceptual (i.e., animals and household items; Categories task) features. Both groups had higher recall on the Categories task compared to the Letter Case task, and higher recall for high- than low-value words. However, older adults recalled fewer total words than younger adults. These findings indicate that manipulating perceptual and/or conceptual features to define value can be used to study value-directed strategic processing in younger and older adults.

5.1. Introduction

When presented with large amounts of information, we often selectively attend to and process a subset of the information while ignoring or inhibiting the rest of the information. In the real world, what we selectively attend to can be driven by the value we ascribe to the information, often based on factors such as perceptual features that make the information stand out (e.g., bolded text), or conceptual features that make it easy to group information (e.g., categories). The selective attention to and inhibition of information based on value is referred to as value-directed strategic processing. Studies of value-directed strategic processing have largely used a value-directed remembering task in which participants are presented with word lists where each word is paired with a different numerical point value (e.g., point values ranging between 1-12 points; TABLE 10). At the end of a word list, participants are instructed to recall as many words as they can with the goal of maximizing their score (e.g., Castel et al., 2002, 2007, 2011; for review see Castel, 2007). These studies have elucidated how value-directed strategic processing is engaged when explicit numerical values are assigned to information. This line of work can be advanced by examining the effects of defining value by perceptual and conceptual features, as is more common in daily life.

The studies presented in the current dissertation (Chapters 2-4) have examined value-directed strategic processing using a variation of the value-directed remembering task where value was based on perceptual features, namely letter case. In this task, participants saw multiple unique word lists in which half of the words were presented in uppercase letters (e.g., LAMB) and half were presented in lowercase letters (e.g., lamb). Counterbalancing across participants, some were told that the uppercase letters were high-value words (worth 10 points) and the lowercase letters were low-value words (worth 1 point), and vice versa. At the end of each word list, participants were asked to verbally recall as many words as they could with the goal of maximizing their score. Broadly speaking, these studies have shown that value can be effectively manipulated by perceptual features (i.e., letter case), which is more representative of what we commonly encounter in daily life as opposed to assigning a numerical value to each individual word, across cognitively normal younger and older adults and older adults with mild cognitive impairment.

In addition to perceptual features, value or salience in everyday settings is also determined based on conceptual features, such as how things are conceptually associated with one another or how information can be categorized based on shared features. One of the most common ways to study how information is categorized is to examine object categorization. Object categorization is a process by which we sort information that we encounter into sets, or categories, allowing us to process that information more meaningfully and efficiently (e.g., Mervis & Rosch, 1981; Rosch et al., 1976). Categories can be used to cluster information to allow for more efficient encoding, storage, and recall of information. For example, when making a mental list of grocery items to purchase, one might group all of the fruits together, vegetables, frozen items, snacks, etc. to make it easier to remember the whole list. Clustering information based on categories has been commonly examined experimentally in list learning tasks that elicit free recall (e.g., Bousfield, 1953; Bousfield & Sedgewick, 1944; Cofer et al., 1966). In these studies, participants study word lists and subsequently are asked to recall words from a given list. Examination of the order in which the words are recalled has shown that categorizing the information conceptually and clustering the words together results in better recall in both younger and older adults (e.g., Bäckman & Wahlin, 1995; Bousfield, 1953; Bousfield & Sedgewick, 1944; Cofer et al., 1966; Kuhlmann & Touron, 2016; Olofsson & Bäckman, 1993; Tulving, 1968; Wingfield et al., 1998). The use of categorization strategies has also been observed within the context of value-directed strategic processing tasks. Using a value-directed remembering paradigm, Ariel, Price, and Hertzog (2015) showed that younger and older adults who employed strategies that included consideration of how words were conceptually related and how they could be categorized, had better recall than those who attempted to just use rote memorization (Ariel et al., 2015). Additionally, our previous study on value-directed strategic processing with younger and older adults using perceptually defined value showed that approximately 60% of participants utilized conceptual strategies such as categorizing words to aid recall (Nguyen et al., 2020).

Interestingly, list learning studies have shown that older adults are typically less effective at spontaneously using conceptual strategies compared to younger adults, as they create fewer total categories and fewer items within the categories during free recall (Haut et al., 1999; Taconnat et al., 2009; Witte et al., 1993). However, providing cues that direct participants to use a conceptual categorization strategy has been shown to aid recall in older adults, as well as younger adults (Bäckman & Larsson, 1992; Ceci & Tabor, 1981; Kuhlmann & Touron, 2016). For example, providing participants with cues that the words are derived from various superordinate categories (e.g., animals) could benefit recall as superordinate categories encompass a broad range of items and within-category clusters can be created (e.g., animals can be further organized into the categories of pets, aquatic animals, and farm animals). Collectively, list learning and value-directed strategic processing studies suggest that defining value based on superordinate categories may also facilitate strategic processing and recall.

In an attempt to better understand potential differences in value-directed strategic processing when value is defined by perceptual versus conceptual features, the current study compared two value-directed strategic processing tasks: one in which value was defined by letter case (specifically uppercase and lowercase letters) and one in which value was defined by superordinate categories (specifically animals and household items). This study aimed to address two questions: (i) what are the similarities and differences in behavioral measures of value-directed strategic processing when value is defined by perceptual (Letter Case task) versus conceptual (Categories task) features for YA and OA separately, and (ii) does normal cognitive aging affect behavioral measures of value-directed strategic processing when value is defined by perceptual (Letter Case task) versus conceptual (Categories task) features, and if so, how? Addressing the first question, we hypothesized that there would be greater recall of total words and high-value words, and no difference for low-value words, for the Categories task compared to the Letter Case task in both younger and older adults. In regard to the second question, we hypothesized that there would be (i) greater recall of total words and high-value words, but similar recall of low-value words, for younger compared to older adults in the Categories task, and (ii) no difference in recall of total words, high-value words, or low-value words between younger and older adults in the Letter Case task given the findings of our previous study (Nguyen et al., 2020).

5.2. Materials and method

5.2.1. Participants

Sixteen cognitively normal younger adults (*M* = 22.1, *SD* = 2.9) and 16 cognitively normal older adults (*M* = 66.9, *SD* = 7.3) participated in the study (see Table 5.1 for full demographics). All participants were native English speakers, right-handed, had a minimum of high school education, and did not report a history of neurological disorders, traumatic brain injury/head injury, communication disorders, psychiatric disorders, learning disabilities, uncontrolled diabetes, or uncorrected visual or auditory impairments. Written informed consent was obtained from all participants in accordance with the University of Illinois at Urbana-Champaign Institutional Review Board protocols before completing the study.

All participants completed a cognitive assessment that evaluated various domains including episodic learning and memory, executive function, attention, and working memory. All had normal global cognitive screening scores on the Montreal Cognitive Assessment (score of 26 or higher; Nasreddine et al., 2005) and none had elevated depressive symptoms (all younger adults scored 10 or below on the Beck Depression Inventory [Beck et al., 1961]; all older adults scored 5 or below on the Geriatric Depression Scale [Almeida & Almeida, 1999]).

Table 5.1

Participant Demographics

	YA (N = 16)	**OA (N = 16)**	**Statistic**
Age (yrs)	22.1 (2.9)	66.9 (7.3)	$F(1, 31) = 521.56$, $p < .001$**
Education (yrs)	15.1 (1.6)	16.3 (4.6)	$F(1, 31) = 0.85$, $p = .364$
Sex	11F/5M	12F/4M	$\chi^2(1, N = 32) = 0.16$, $p = .694$

Cells represent mean (standard deviation). The *p*-values for age and education were derived from one-way ANOVAs and the *p*-value for sex was derived from Pearson chi-square. YA: younger adults; OA: older adults. $^{**}p < .01$.

5.2.2. Study procedures

All participants completed two value-directed strategic processing tasks for this study: the Letter Case task and the Categories task. The Letter Case task was adapted from our previous studies (Nguyen et al., 2019, 2020; Chapter 4) and the Categories task was developed for this dissertation project. Both tasks will be described below and additional details about task development are provided in the Supplementary Material.

Letter Case Task: The stimuli for the Letter Case task consisted of 90 monosyllabic, four-letter nouns that were divided into three word lists of 30 unique words each. The word lists did not differ on frequency, concreteness, imageability, or familiarity measures (see Supplementary Table 5.1). For each of the three lists, half (*n* = 15) of the words were designated as high-value (worth 10 points) and half (*n* = 15) were designated as low-value (worth 1 point). High- and low-value words were differentiated by **letter case** (i.e., uppercase and lowercase letters). Four versions of the task were developed. In two versions of the task, uppercase letters were designated as high-value (10 points) and lowercase letters were designated as low-value (1 point). In the other two versions, lowercase letters were designated as high-value and uppercase letters as low-value. Word order was pseudorandomized in each list. The font size was controlled for the height of the words. This ensured that uppercase and lowercase words, all of which were four-letter words, appeared to have comparable sizes on the screen.

Categories Task: The stimuli for this task consisted of 90 monosyllabic, three to five letter nouns belonging to two superordinate categories, where half (*n* = 45) were animals and half (*n* = 45) were household items. Three word lists were created with 30 unique words in each list, with 15 words from each category. The words from the two categories did not differ on frequency, concreteness, imageability, or familiarity measures across the three lists (see Supplementary Table 5.4). For each of the three lists, half (*n* = 15) of the words were designated as high-value (worth 10 points) and half (*n* = 15) were designated as low-value (worth 1 point). High- and low-value words were differentiated by **superordinate category**, namely animals and household items. Four versions of the task were developed. In two versions of the task, animals were designated as high-value (10 points) and household items as low-value (1 point). In the other two versions of the task, household items were designated as high-value and animals as low-value. Word order was pseudorandomized for each list.

Practice Lists: A practice list was developed for each of the two tasks to familiarize participants with the tasks. The two practice lists each included a set of 20 words (10 high-value, 10 low-value) that were not used in the three test lists of each task.

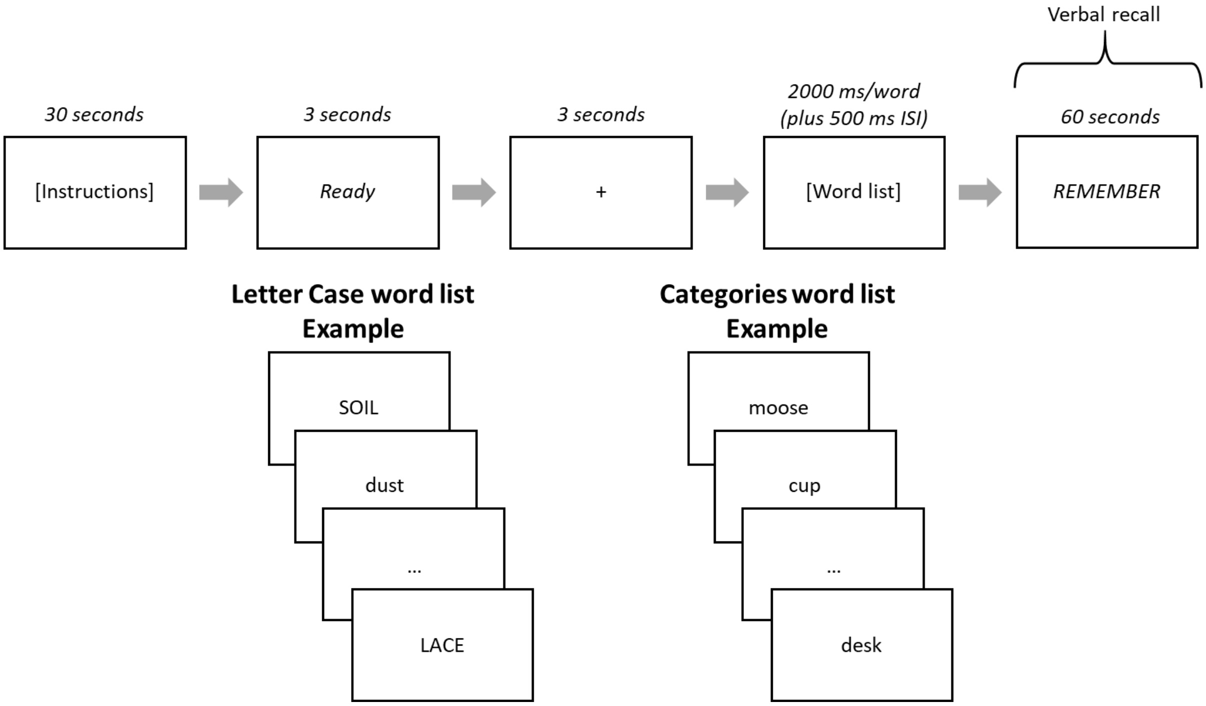
Instructions and Task Procedures: Participants first read printed instructions on paper. For the Letter Case task, they read one of the following depending on their assigned version: "You will see words appear on the screen one at a time. Some words are in uppercase letters and some words are in lowercase letters. The uppercase words *[lowercase words]* are worth 10 points each (high-value words). The lowercase words *[uppercase words]* are worth 1 point each (low-value words). At the end of the list you will see the word "REMEMBER" on the screen. Your job is to remember as many of the words from the list as possible with the goal of scoring maximum number of points".

For the Categories task, they read one of the following depending on their assigned version: "You will see words appear on the screen one at a time. Some of these words are types of animals and some of these words are household items. The animals *[household items]* are worth 10 points each (high-value words). The household items *[animals]* are worth 1 point each (low-value words). At the end of the list you will see the word "REMEMBER" on the screen. Your job is to remember as many of the words from the list as possible with the goal of scoring maximum number of points".

The researcher then confirmed that the participant understood the directions. Importantly, the research assistant did not provide specific instructions on how to be strategic, such as only focusing on the high-value words. The participants then saw the same instructions on the screen in front of them (presented for 30 seconds) at the beginning of the practice list and each of the three test lists. Following the instructions, the word "Ready" was displayed on the center of the screen for 3000 ms followed by a fixation (+) for 3000 ms. The 30 words from a list were then displayed sequentially in the center of the screen for 2000 ms each with an inter-stimulus interval of 500 ms (blank screen). The word "REMEMBER" appeared at the end of each list at which point participants had 60 seconds to verbally recall words from that list while their responses were manually recorded on a score sheet (see Figure 5.1 for task schematic). Participants received immediate feedback from the research assistant about their score after each list and before the next list was presented.

Figure 5.1

Value-directed Strategic Processing Task Schematic



Participants saw a list of 30 words presented sequentially. When the word "REMEMBER" was presented, participants verbally recalled words from the list, and their responses were recorded on paper and scored. This process was repeated for the practice list and the subsequent three lists. For the Letter Case task, the high- and low-value words were represented by lowercase and uppercase words. For the Categories task, the high- and low-value words were represented by animals or household items.

Task order for the Letter Case and Categories tasks was counterbalanced so that approximately half of the participants completed the Letter Case task first. Version order was counterbalanced so that approximately an equal number of participants received each version. The Letter Case and Categories tasks were always separated by a simple reaction time task, where participants pressed a button as fast as possible when a plus sign (+) appeared on the screen, which served as a distractor task to provide an active break for participants between the Letter Case and Categories tasks. After completing both tasks, participants completed a post-experiment survey that asked about whether they used strategies during each of the two tasks, and if so, what types of strategies they used for each (e.g., repeating words over and over; sorting them into categories). The survey also had them state whether the Letter Case or Categories task was easier and why.

5.2.3. Statistical analysis

To guide the analysis of the behavioral data, we first examined whether there were significant differences in the task-related behavioral data depending on what was designated as high- and low-value (i.e., uppercase/lowercase letters; animals/household items) in the different versions. No significant differences were observed across versions for the Letter Case or Categories task ($p > .05$ for all three lists; see Table 5.2 for exact *p*-values), so the data were not analyzed separately for the different versions.

Table 5.2

Statistical Results for the Effects of Version on Behavioral Data

	Letter Case	**Categories**
List 1	*F*(1,30) = 0.99, *p* = .328	*F*(1,30) = 1.46, *p* = .237
List 2	*F*(1,30) = 0.96, *p* = .336	*F*(1,30) = 0.92, *p* = .346
List 3	*F*(1,30) = 0.94, *p* = .340	*F*(1,30) = 0.07, *p* = .793

Cells display statistics for interaction effects between version (words in uppercase being assigned to high-value/words in lowercase being assigned to high-value) and value (high-value/low-value) for each of the three lists. There were no significant differences observed across versions for the behavioral data.

Task-related behavioral data, specifically high- and low-value word recall for both the Letter Case task and the Categories task were analyzed using IBM SPSS Statistics 26. The data were examined using two different approaches to best answer the two research questions. In Model 1, general linear models (GLMs) were run separately for younger and older adults for the number of high- and low-value words recalled in each list with the task (Letter case/Categories), list (1/2/3), and value (high-/low-value) as within-subject factors. This design allowed us to evaluate if and how value-directed strategic processing differs when value is defined by perceptual (i.e., letter case) versus conceptual (i.e., categories) features for each group independently. In Model 2, the average number of high-value words and low-value words recalled were computed for each subject, and each task by taking the mean across the three lists. A GLM was then run for the average number of high- and low-value words recalled with group (younger/older adult) as a between-subject factor and the task (Letter case/Categories) and value (high-/low-value) as within-subject factors. This design allowed us to evaluate potential differential effects of normal cognitive aging on value-directed strategic processing when value is defined by perceptual (i.e., letter case) versus conceptual (i.e., categories) features.

5.3. Results

5.3.1. Cognitive assessment performance

Group differences were observed on some cognitive assessment measures, particularly measures related to episodic memory and executive function. Older adults performed significantly worse than younger adults on (i) Rey Auditory Verbal Learning Test – short delay recall and long delay recall, (ii) Craft Story 21 – immediate verbatim recall, (iii) Trail Making Test B, (iv) Delis-Kaplan Executive Function System (DKEFS) Verbal fluency – Animals, Fruits/Furniture, and Fruits/Furniture switching accuracy, and (v) DKEFS Color-Word Interference – Inhibition trial and Inhibition/Switching trial (Table 5.3).

Table 5.3

Cognitive Assessment Performance

Measure	**YA**	**OA**	***p*-value**
Montreal Cognitive Assessment (MoCA)	29.1 (1.5)	28.4 (1.6)	.218
MoCA-Memory Index Score	14.8 (0.5)	14 (1.7)	.075
Trail Making Test-A (sec)	18.7 (6.9)	22.1 (5.5)	.135
Trail Making Test-B (sec)	43.9 (19.9)	60.4 (21.2)	.031*
Number span – Forward	6.8 (0.9)	6.6 (1.0)	.580
Number span – Backward	5.4 (1.4)	5.4 (1.0)	1
Boston Naming Test (30 items)	27.8 (2.3)	28.9 (1.0)	.070
Rey Auditory Verbal Learning Test			
Trial 1	7.9 (1.5)	6.9 (2.7)	.196
Trial 5	14.1 (1.1)	12.9 (2.2)	.063
Interference list	7.0 (1.6)	6.1 (2.2)	.214
Short delay	13.3 (1.1)	11.2 (3.3)	.023*
Long delay	13.4 (1.3)	10.7 (3.8)	.010*
Recognition list	13.6 (1.4)	12.4 (2.8)	.114
Craft 21 Story			
Immediate, Verbatim	28.4 (6.7)	23.4 (5.5)	.028*
Immediate, Paraphrase	19.2 (3.5)	17.9 (3.1)	.275
Delayed, Verbatim	25.6 (7.7)	21.5 (5.0)	.087
Delayed, Paraphrase	18.7 (4.0)	16.9 (3.2)	.181
Benson Complex Figure Copy			
Immediate	16.5 (0.9)	16.7 (0.9)	.553
Delayed	14.6 (1.8)	13.8 (2.5)	.297
DKEFS Verbal fluency			
Letter fluency – F, A, S	48.2 (11.7)	49.2 (6.8)	.769
Category fluency – Animals	26.1 (4.8)	22.8 (4.3)	.047*
Category fluency – Boys' names	22.1 (4.4)	21.4 (5.8)	.708
Category switching – Fruits & Furniture	16.9 (2.4)	14.3 (3.0)	.011*
Category switching – Fruits & Furniture, switching accuracy	16.3 (2.2)	13.4 (3.0)	.004**
DKEFS Color-Word Interference			
Color Naming (sec)	26.0 (5.0)	27.1 (4.2)	.519
Word reading (sec)	20.1 (4.4)	20.6 (2.9)	.706
Inhibition (sec)	42.9 (9.8)	53.4 (10.8)	.008**
Inhibition/Switching (sec)	48.5 (7.7)	56.3 (12.1)	.038*

Cells represent mean (standard deviation). The *p*-values were derived from one-way ANOVAs. *$p < .05$; **$p < .01$. YA: younger adults; OA: older adults; DKEFS: Delis-Kaplan Executive Function System.

5.3.2. Task-related behavioral data

5.3.2.1. Model 1: Perceptually vs. conceptually defined value for YA and OA independently

For younger adults, there was a significant main effect of task, $F(1,15) = 6.12$, $p = .026$, $\eta_p^2 = .29$, with greater recall in the Categories task compared to the Letter Case task (5.8 vs. 5.2 words). There was a significant main effect of value, $F(1,15) = 60.69$, $p < .001$, $\eta_p^2 = .80$, with greater recall of high- compared to low-value words (8.3 vs. 2.7 words). There was not a significant main effect of list, $F(2,30) = 2.11$, $p = .139$ (5.7 vs. 5.6 vs. 5.3 words). No significant interaction effects were observed for task by list, $F(2,30) = 0.76$, $p = .476$, task by value, $F(1,15) = 0.01$, $p = .913$, list by value, $F(2,30) = 0.25$, $p = .781$, or task by list by value, $F(2,30) = 1.19$, $p = .318$. See Table 5.4 and Figure 5.2 for task-related behavioral data.

For older adults, there was a significant main effect of task, $F(1,15) = 12.00$, $p = .003$, $\eta_p^2 = .44$, with greater recall in the Categories task compared to the Letter Case task (4.3 vs. 3.8 words). There was a significant main effect of value, $F(1,15) = 119.35$, $p < .001$, $\eta_p^2 = .89$, with greater recall of high- compared to low-value words (7.0 vs. 1.1 words). There was not a significant main effect of list, $F(2,30) = 1.03$, $p = .370$ (4.2 vs. 3.9 vs. 4.0 words). No significant interaction effects were observed for task by list, $F(2,30) = 0.89$, $p = .420$, task by value, $F(1,15) = 1.04$, $p = .324$, list by value, $F(2,30) = 3.12$, $p = .059$, or task by list by value, $F(2,30) = 0.61$, $p = .548$. See Table 5.4 and Figure 5.2 for task-related behavioral data.

Table 5.4

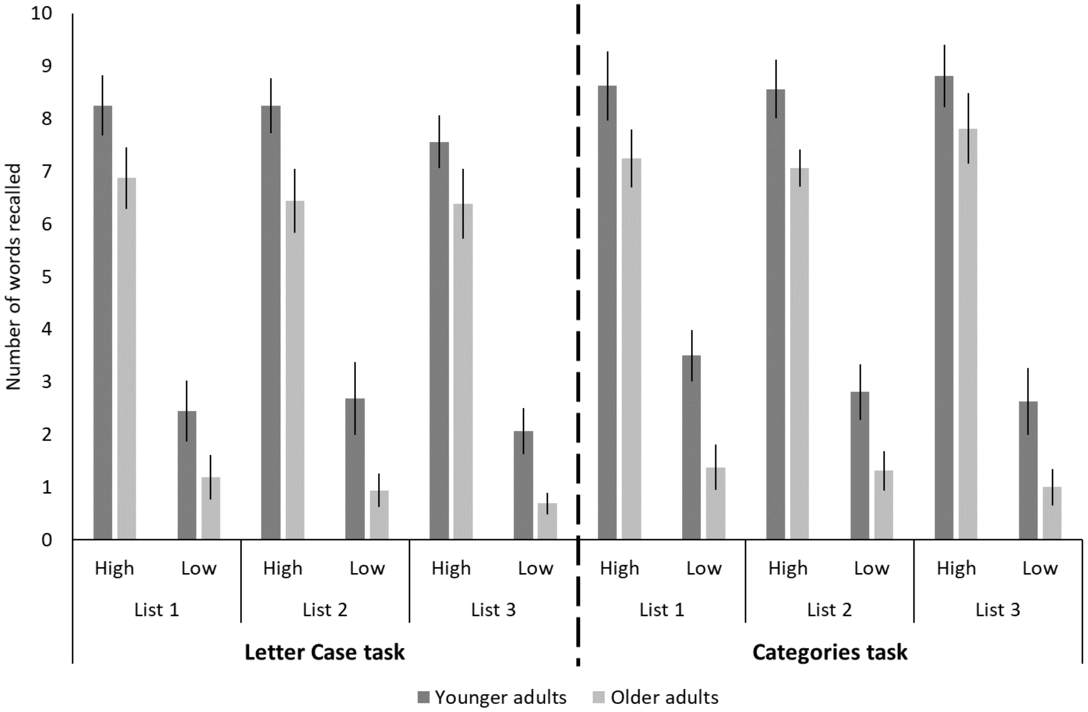
Task-related Behavioral Data

	Letter Case task		Categories task	
	YA	**OA**	**YA**	**OA**
List 1				
High-value	8.3 (2.3)	6.9 (2.3)	8.6 (2.7)	7.3 (2.2)
Low-value	2.4 (2.3)	1.2 (1.7)	3.5 (2.0)	1.4 (1.7)
List 2				
High-value	8.3 (2.1)	6.4 (2.4)	8.6 (2.2)	7.1 (1.4)
Low-value	2.7 (2.8)	0.9 (1.3)	2.8 (2.1)	1.3 (1.5)
List 3				
High-value	7.6 (2.0)	6.4 (2.6)	8.8 (2.4)	7.8 (2.7)
Low-value	2.1 (1.8)	0.7 (0.8)	2.6 (2.6)	1.0 (1.4)
Average				
High-value	8.0 (1.8)	6.6 (2.3)	8.7 (2.2)	7.4 (1.9)
Low-value	2.4 (2.0)	0.9 (1.1)	3.0 (1.9)	1.2 (1.2)

Cells represent mean (standard deviation).

Figure 5.2

Number of High-Value and Low-Value Words Recalled Per List for Younger and Older Adults



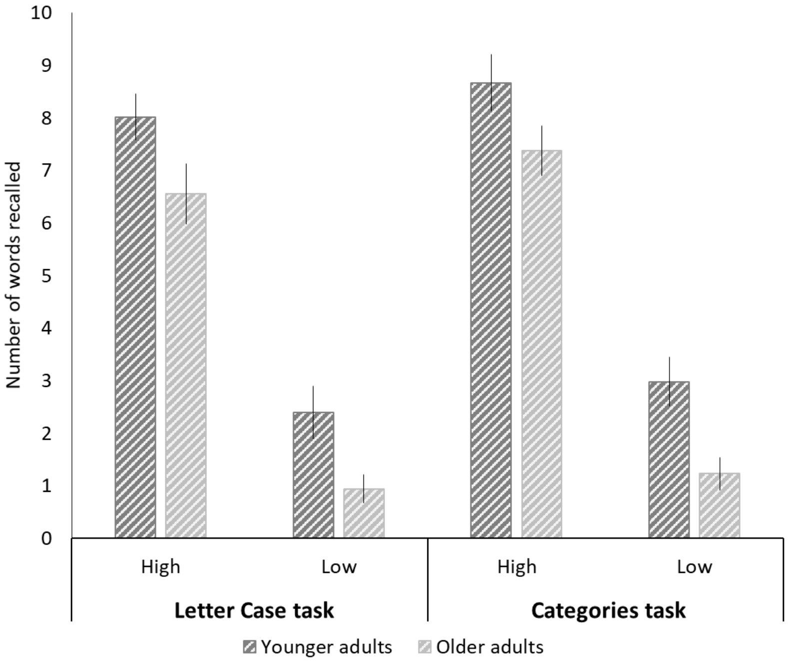
The number of high- and low-value words recalled for each of the three lists for both younger and older adults are shown. Bars represent standard error.

5.3.2.2. Model 2: Perceptually vs. conceptually defined value in normal cognitive aging

There was a significant main effect of group, $F(1,30) = 14.04$, $p = .001$, $\eta_p^2 = .32$, with greater recall in the younger adults compared to the older adults (5.5 vs. 4.0 words). There was a significant main effect of task, $F(1,30) = 15.62$, $p < .001$, $\eta_p^2 = .34$, with greater recall in the Categories task compared to the Letter Case task (5.0 vs. 4.5 words). There was a significant main effect of value, $F(1,30) = 162.97$, $p < .001$, $\eta_p^2 = .85$, with greater recall of high- compared to low-value words (7.7 vs. 1.9 words). No significant two-way interaction effects were observed for group by task, $F(1,30) = 0.05$, $p = .834$, group by value, $F(1,30) = 0.06$, $p = .802$, or task by value, $F(1,30) = 0.59$, $p = .450$. The three-way interaction effect for group by task by value was not significant, $F(1,30) = 0.36$, $p = .552$. See Table 5.4 and Figure 5.3 for task-related behavioral data.

Figure 5.3

Average Number of High-Value and Low-Value Words Recalled for Younger and Older Adults



The average number of high- and low-value words recalled across the three lists for both younger and older adults are shown. Bars represent standard error.

5.4. Discussion

The current study investigated how behavioral measures of value-directed strategic processing were differentially affected when value was defined by perceptual (Letter Case task) versus conceptual (Categories task) features in cognitively normal younger and older adults. In particular, this study first compared the Letter Case and Categories tasks for younger and older adults independently to better understand the effects of defining value by different features (i.e., perceptual and conceptual; Model 1). The Letter Case and Categories tasks were then compared between younger and older adults to determine how value-directed strategic processing may be affected by normal cognitive aging (Model 2). The findings from Model 1 and Model 2 were similar, with both showing greater total recall for the Categories task compared to the Letter Case task, as well as greater recall of high- compared to low-value words in younger and older adults. Additionally, Model 2 revealed group differences with greater recall in younger compared to older adults irrespective of task or value.

Differences between the Letter Case and Categories tasks were observed, with more total words recalled in the Categories task compared to the Letter Case task in both younger and older adults (indexed by main effects of task in Models 1 and 2). As hypothesized, this finding indicates that defining value based on categories supports greater recall for both younger and older adults compared to defining value based on letter case. Exit interview data from the current study revealed that 69% of YA and 79% of OA participants reported that the Categories task was easier than the Letter Case task. These findings align nicely with a significant body of literature that has shown that providing category cues improves recall performance when compared to free recall (i.e., without category cues; e.g., Bäckman & Larsson, 1992; Davis & Friedrich, 1983; Sanders et al., 1980; Smith, 1977). Furthermore, the participants who stated that the Categories task was easier, reported using strategies such as making stories and sentences and creating subcategories (e.g., predators; kitchen items) to remember the words during the task, consistent with studies that have shown that clustering and/or categorizing information aids recall (e.g., Bäckman & Larsson, 1992; Bousfield, 1953; Bousfield & Sedgewick, 1944; Cofer et al., 1966; Craik et al., 2007; Kuhlmann & Touron, 2016; Tulving, 1968). Collectively, these findings suggest that using conceptual features (i.e., categories) to denote value leads to more robust value-directed strategic processing, and thus better recall, as compared to denoting value by perceptual features (i.e., letter case).

Across the two tasks, younger and older adults recalled more high- than low-value words (indexed by main effects of value in Models 1 and 2). These findings are consistent with our previous studies (Nguyen et al., 2019, 2020), indicating that both younger and older adults can differentially regulate processing based on value defined both by perceptual (i.e., letter case) and conceptual (i.e., categories) features. Interestingly, although we had anticipated that both groups would recall more high-value words in the Categories task than the Letter Case task, the current study did not reveal any differential effects between the tasks for the number of high- and low-value words recalled, as no significant interaction effects were observed between task and value or group, task, and value. Future work comparing these two task types should increase the sample size for both the younger and older adult groups to investigate whether the lack of findings was due to a power issue.

Although younger and older adults did demonstrate some similarities as discussed above, group differences were also observed, where the older adults recalled significantly fewer words overall compared to younger adults (indexed by a main effect of group in Model 2). These findings align with the cognitive assessments that showed poorer performance on memory measures in the older adults compared to younger adults, and the vast literature on cognitive aging that has shown age-related declines in episodic memory (for reviews see Balota et al., 2000; Brickman & Stern, 2009; Glisky, 2007; Harada et al., 2013; Hedden & Gabrieli, 2004; Luo & Craik, 2008; Luszcz, 2011; Zacks et al., 2000). Moreover, Castel and colleagues have also shown lower recall for older compared to younger adults when using a value-directed remembering task where value was denoted by a different numerical value for each word (Castel et al., 2002, 2007, 2011). However, in our previous study on cognitively normal younger and older adults using a task that was similar to the Letter Case task, we did not find any group differences for the number of words recalled (Nguyen et al., 2020). The discrepancy between these two studies might be due to variations in the task procedures and/or the use of practice lists in the current study, each of which will be discussed in more detail below.

Perhaps the biggest difference between the two study procedures is the inclusion of the Categories task in the current study. Although there was better recall for the Categories task than the Letter Case task in both groups, it may be that the older adults did not benefit from the categories to a similar extent as the younger adults, allowing for group differences to be revealed. Some support for this comes from a study showing that provision of explicit instructions to cluster information showed some benefits in recall for older adults, but younger adults benefitted to a greater extent (Kuhlmann & Touron, 2016). Furthermore, the Letter Case and Categories tasks in the current study each used three lists of 30 words each (a total of 180 words), whereas our previous study that used the Letter Case task (Nguyen et al., 2020) had five lists of 40 words each (a total of 200 words). The differences between the two studies might be attributed to the number of word lists and/or the number of words in each list. Having more lists in the previous study may have given older adults more opportunities to improve their selectivity across trials leading to overall recall that was more comparable to younger adults (Nguyen et al., 2020). Additionally, having fewer words per list in the current study may have been more beneficial to younger adults, and less so to older adults due to limitations in resource capacity (e.g., Craik & Byrd, 1982; Rabinowitz et al., 1982).

The current study also used a practice list for each of the two tasks, whereas the previous study did not include a practice list. It is possible that younger adults may have benefited more from the practice lists, resulting in better overall recall. To address this possibility, a posteriori analyses were conducted using separate paired sample *t*-tests for younger and older adults to compare practice list and List 1 recall. Paired sample *t*-tests revealed significant differences between practice and List 1 for both younger, $t(15) = 3.61$, $p = .003$, and older adults, $t(15) = 2.59$, $p = .021$, with more words recalled in List 1. Interestingly, effect size calculations (Cohen's *d*) showed that this difference was stronger for younger adults, $d = 0.93$, than older adults, $d = 0.64$, suggesting that while practice lists may have aided both groups, younger adults benefitted more than older adults.

In conclusion, this study provides preliminary behavioral evidence on how value-directed strategic processing, inferred based on recall measures, is differentially affected when value is defined by perceptual versus conceptual features in cognitively normal younger and older adults. In particular, using conceptual features to define value, specifically superordinate categories, improved recall performance in both younger and older adults when compared to perceptually defined value. Interestingly, although younger and older adults differed in overall recall, this study did not find evidence for specific age-related differences in recall between perceptually versus conceptually defined value. This could indicate that while older adults have poorer overall recall compared to younger adults, they seem to be effectively engaging in value-directed strategic processing both when value is defined by perceptual or conceptual features. To get a better sense of processing that is independent of recall performance, it will be critical to examine neurophysiological measures, namely EEG-derived event-related spectral perturbations, that can reveal millisecond-level neural processing differences related to value-directed strategic processing when value is cued by different feature types. Furthermore, event-related spectral perturbation measures may help to clarify the lack of age-related differences between perceptually and conceptually defined value.

5.5. Supplementary material for Chapter 5: Task development

5.5.1. Task development: Letter Case task

The Letter Case task was adapted from a previous task developed in-house that was used in Chapters 2-4 of this dissertation (Nguyen et al., 2019, 2020). The stimuli were comprised of four-letter, monosyllabic nouns from the MRC Psycholinguistic Database and SUBTLEX$_{US}$ database. The 90 stimuli were divided into three lists of 30 words each. The word lists were tested to determine if they differed in frequency, concreteness, imageability, and familiarity, and no significant differences were observed between the lists (see Supplementary Table 5.1).

Supplementary Table 5.1

Statistics of Word Dimensions for the Word Lists

	List 1	**List 2**	**List 3**	***p*-value**
Total N	30	30	30	--
Frequency				
Mean (SD)	32.5 (22.8)	32.6 (22.3)	28.4 (22.1)	.708
Median	28.5	29.5	22.5.0	
Range	6.0-80.0	4.0-96.0	5.0-97.0	
Concreteness				
Mean (SD)	563.9 (41.2)	569.3 (42.3)	578.7 (40.0)	.373
Median	573.5	573.0	589.5	
Range	451.0-637.0	492.0-637.0	472.0-624.0	
Imageability				
Mean (SD)	565.7 (35.6)	573.1 (40.5)	569.9 (36.6)	.746
Median	566.5	574.0	577.5	
Range	497.0-631.0	486.0-638.0	439.0-624.0	
Familiarity				
Mean (SD)	538.5 (46.6)	539.2 (51.7)	534.3 (38.8)	.904
Median	539.5	547.0	539.0	
Range	443.0-613.0	430.0-615.0	442.0-603.0	

The *p*-values were derived from one-way ANOVAs.

5.5.2. Task development: Categories task

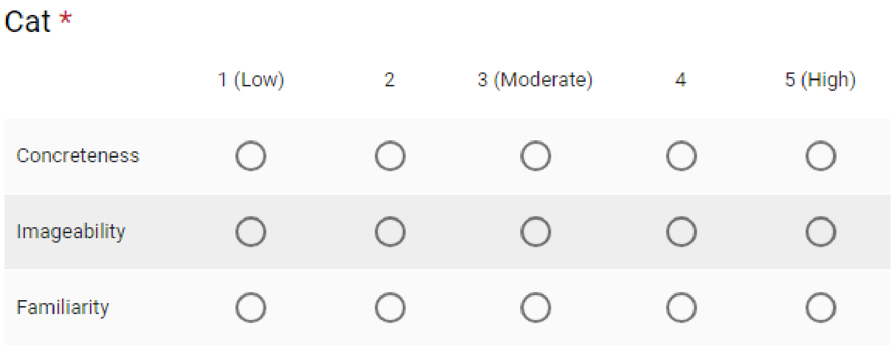
For the Categories task, stimulus selection began with compilation of nouns that were monosyllabic and three to five letters in length from previous task stimulus lists, the MRC Psycholinguistic Database (Coltheart, 1981), and other online resources. This search yielded 1,237 words. From this list, words that belonged to the category of animals and household items were selected, yielding 91 animals and 73 household items. The MRC Psycholinguistic Database (Coltheart, 1981), $\text{SUBTLEX}_{\text{US}}$ database (Brysbaert & New, 2009), and Corpus of Contemporary American English (Davies, 2009) were used to obtain values related to word frequency, concreteness, imageability, and familiarity for each word. Words were excluded if they did not have (i) a frequency value of at least one occurrence per one million words and/or (ii) a concreteness, imageability, or familiarity score within ± two standard deviations from the mean of the normative data provided in the MRC Psycholinguistic Database. This process yielded 61 animals and 47 household items.

A simple word rating survey was developed to obtain initial ratings on the dimensions of concreteness, imageability, and familiarity from four undergraduate students (aged 20-21 years with 14-15 years of education) at the University of Illinois at Urbana-Champaign. The survey was administered online using Google Forms. The survey consisted of 108 words (61 animals, 47 household items). Participants rated each of these words on the three dimensions (concreteness, imageability, and familiarity) using a rating scale from 1-5, with 1 being the lowest rating and 5 being the highest rating. Supplementary Figure 5.1 shows an example of the online word rating survey with the three dimensions being evaluated. The survey had the following instructions:

> *“In this survey, you will be rating a set of words on 3 different scales – concreteness, imageability, and familiarity. These scales assess different aspects of word meanings. Please rate these words according to your first impression. When making your ratings, try to be as accurate as possible, but do not spend too much time on any one word.*
>
> *Concreteness is a measure of how concrete or abstract something is. A word would have a HIGH concreteness rating if it represents something that exists in a definite physical form in the real world. In contrast, a word would have a low concreteness rating if it represents more of a concept or idea (e.g., happiness). Please indicate how concrete you think each word is on a scale of LOW to HIGH concreteness, with the midpoint being moderately concrete.*
>
> *Imageability is a measure of how easy or difficult something is to imagine. A word would have a HIGH imageability rating if it represents something that is very easy to imagine or picture. In contrast, a word would have a LOW imageability rating if it represents something that is very difficult to imagine or picture. Please indicate how imageable you think each word is on a scale of LOW to HIGH imageability, with the midpoint being moderately imageable.*
>
> *Familiarity is a measure of how familiar something is. A word would have a HIGH familiarity rating if you see/hear it often and it is easily recognizable. In contrast, a word would have a LOW familiarity rating if you rarely see/hear it and it is relatively unrecognizable. Please indicate how familiar you think each word is on a scale of LOW to HIGH familiarity, with the midpoint being moderately familiar”.*

Supplementary Figure 5.1

Example of the Online Word Rating Survey



Cat *

	1 (Low)	2	3 (Moderate)	4	5 (High)
Concreteness	○	○	○	○	○
Imageability	○	○	○	○	○
Familiarity	○	○	○	○	○

Using the survey data, words that received an average score of 2 or less on any of the three scales were removed, which only resulted in the removal of one word. Examination of the data revealed that any words with an average score of 4 or less could be removed, meaning that only the highest rated words remained. This process resulted in an equal number of stimuli in each category, with 45 words in each (see Supplementary Table 5.2 for a list of the stimuli).

Supplementary Table 5.2

Word Stimuli for the Categories of Animals and Household Items

		Animals		
ant	cow	fox	moth	sloth
ape	crab	frog	mouse	snail
bear	crow	goat	mule	snake
bee	deer	goose	owl	squid
boar	dog	hawk	pig	swan
bull	duck	hen	rat	toad
cat	eel	horse	shark	whale
chimp	elk	lamb	sheep	wolf
clam	fish	moose	skunk	worm

		Household items		
bath	clock	fork	mug	sink
bed	comb	glass	pan	soap
bench	cot	grill	pen	spoon
book	couch	hose	phone	stool
bowl	crib	jar	plate	stove
broom	cup	knife	pot	tongs
brush	desk	lamp	rug	tray
cart	door	lock	seat	vase
chair	flag	mop	shelf	whisk

Comparisons between the two categories were subsequently conducted to determine if they differed on the frequency, concreteness, imageability, and familiarity dimensions obtained from the MRC Psycholinguistic Database (Coltheart, 1981), SUBTLEX$_{US}$ database (Brysbaert & New, 2009), and Corpus of Contemporary American English. A Mann-Whitney U test with category (animals/household items) as the between-group factor was used for the factor of frequency, as it had a non-normal distribution. One-way ANOVAs were computed using IBM SPSS Statistics with category (animals/household items) as the between-group factor for the following factors: concreteness, imageability, and familiarity. Results showed that the two categories did not differ on the median values of frequency. However, the two categories did differ on the dimensions of concreteness, imageability, and familiarity. The category of animals had more concrete and imageable items, whereas the category of household items had more familiar items. The descriptive data and *p*-values are reported in Supplementary Table 5.3. Although the two categories differed on three of the word dimensions, the three word lists were carefully selected so that each list did not differ in frequency, concreteness, imageability, and familiarity between the two categories (Supplementary Table 5.4).

Supplementary Table 5.3

Statistics of Word Dimensions for Animals and Household Items

	Animals	**Household items**	***p*-value**
Total N	45	45	--
Frequency			
Mean (SD)	20.9 (33.4)	38.6 (65.6)	.110
Median	10.4	12.9	
Range	1.4-192.8	1.0-292.1	
Concreteness			
Mean (SD)	608.9 (23.3)	595.0 (19.6)	.006
Median	613.0	595.0	
Range	550.0-654.0	539.0-635.0	
Imageability			
Mean (SD)	602.1 (26.7)	581.9 (26.0)	.001
Median	607.0	584.0	
Range	524.0-652.0	527.0-635.0	
Familiarity			
Mean (SD)	507.1 (38.6)	557.1 (57.4)	.001
Median	509.0	566.0	
Range	421.0-598.0	391.0-643.0	

The *p*-values are derived from a Mann-Whitney *U* test for frequency, and from *F*-statistics of one-way ANOVAs for concreteness, imageability, and familiarity.

Supplementary Table 5.4

Statistics of Word Dimensions for Animals and Household Items by List

	List 1		List 2		List 3		*p*-value
	Animals	**Household items**	**Animals**	**Household items**	**Animals**	**Household items**	_List * Category_
Total N	15	15	15	15	15	15	--
Frequency							
Mean (SD)	12.3 (9.7)	28.1 (24.4)	19.1 (20.1)	59.0 (100.6)	31.4 (53.0)	28.8 (46)	.313
Median	10.4	12.3	13.0	8.0	9.7	15.2	
Range	3-32.6	1.0-78.8	1.4-66.3	1.0-292.1	1.8-192.8	3.5-187.1	
Concreteness							
Mean (SD)	611.5 (20.0)	586.7 (21.0)	604.7 (26.3)	600.4 (15.6)	610.5 (24.5)	598.9 (19.6)	.243
Median	614.0	591.0	611.0	601.0	613.0	595.0	
Range	568.0-648.0	539.0-614.0	550.0-636.0	571.0-624.0	558.0-654.0	575.0-635.0	
Imageability							
Mean (SD)	612.1 (20.5)	579.0 (30.0)	595.4 (28.2)	588.0 (18.8)	598.7 (29.5)	580.3 (27.5)	.240
Median	614.0	574.0	603.0	589.0	597.0	581.5	
Range	578.0-652.0	532.0-633.0	541.0-635.0	550.0-614.0	524.0-636.0	527.0-635.0	
Familiarity							
Mean (SD)	514.5 (21.2)	564.1 (47.3)	500.4 (42.3)	547.6 (80.1)	506.5 (48.5)	558.6 (44.6)	.760
Median	516.0	583.0	509.0	556.0	504.0	557.0	
Range	477.0-554.0	454.0-617.0	421.0-582.0	391.0-643.0	433.0-598.0	452.0-636.0	

The reported *p*-values reflect List (1, 2, 3) by Category (animals/household items) interaction effects for each of the word dimension.

CHAPTER 6: GENERAL CONCLUSIONS AND FUTURE DIRECTIONS

This dissertation investigated value-directed strategic processing, where value was defined by perceptual or conceptual features, using behavioral measures and EEG-derived event-related spectral perturbations (ERSPs) in cognitively normal younger adults, cognitively normal older adults, and older adults with mild cognitive impairment (MCI). This final chapter will discuss the major contributions of the dissertation in advancing knowledge about (i) the use of perceptually and conceptually defined value to examine value-directed strategic processing, (ii) neurophysiological markers linked to value-directed strategic processing, and (iii) effects of age and MCI on value-directed strategic processing. This final chapter will conclude with a brief discussion of the overall limitations of this work.

Previous work on value-directed strategic processing was advanced in this dissertation by examining whether value can be manipulated by perceptual and conceptual features, which is more analogous to how we process information in daily life as compared to attaching unique numerical values to individual words. The dissertation work showed that both perceptual (Chapters 2-4) and conceptual (Chapter 5) manipulations of value could be successfully utilized to examine value-directed strategic processing. Using conceptual features to define value appeared to be particularly beneficial for value-directed strategic recall, likely due to the provision of conceptual context or support. This dissertation also demonstrated the ubiquitous nature of value-directed strategic processing, as selectivity to high-value information and suppression of low-value information was observed in cognitively normal younger and older adults (Chapters 2, 3, and 5), and in older adults with MCI to some extent (Chapter 4). The consistent findings across the studies suggest that value-directed strategic processing can be effectively studied using various manipulations of stimulus features or characteristics across different age groups and cognitive status. While a binary approach for defining value was used in this dissertation (i.e., high-value [10 points] vs. low-value [1 point]), future studies could experiment with using more value manipulations, such as low-, medium-, and high-values (e.g., 1, 5, and 10 points). For example, perceptual feature manipulations could include regular font, **bold font**, and <u>underline font</u> (e.g., lamb, **desk**, <u>pear</u>), while conceptual feature manipulations could include animals, household items, and food. This could help to elucidate the extent to which value-directed strategic processing manipulated by perceptual and conceptual features is granular.

The underlying neurophysiological markers linked to value-directed strategic processing independent of recall were established in this dissertation. The findings revealed ERSP markers linked to both selective attention and inhibitory processes during value-directed strategic processing. In particular, high-value information was robustly indexed by alpha band, which is often tied to selective attention, and low-value information was consistently indexed by theta band, which is typically linked to inhibition. Additionally, ERSPs revealed age-related alterations in processing high-value information, but not low-value information, despite behavioral data suggesting that value-directed strategic processing is relatively preserved in normal cognitive aging. ERSPs also helped to clarify how neural processing related to value-directed strategic processing, where value was defined by perceptual features, unfolds temporally. The most consistent findings showed that differences in processing high- versus low-value information emerged in intermediate stages of stimulus processing, with a brief theta activity “burst” related to low-value information, and a prolonged period of alpha activity related to high-value information. Whether the observed neural differences related to value-directed strategic processing were related to the specific type of value manipulation, namely the perceptual manipulation of letter case, or would be observed for other types of value manipulation, such as conceptual feature manipulations, was not parsed out in this dissertation. Future studies should examine ERSPs in relation to both perceptual and conceptual manipulations of value using tasks similar to the ones used in Chapter 5 to determine whether these findings are specific to perceptually defined value or are present across different value manipulations. The ERSP findings inform some of the selective attention theories discussed in Chapter 1. Theta and alpha bands revealed that selectivity involves a combination of processes related to attention and inhibition that differentially unfolds in both early and later stages of processing.

Value-directed strategic processing was shown to be compromised in older adults with MCI, with impairments being observed both in their ability to attend to high-value information and to inhibit low-value information. Importantly, older adults with MCI could be differentiated from cognitively normal older adults on ERSP measures, particularly in early time periods of neural processing. These findings indicate the need for future studies to validate the utility of ERSP measures related to value-directed strategic processing for identifying individuals in early stages of cognitive decline. Additionally, future studies could examine how these markers change in individuals with a clinical diagnosis of dementia due to Alzheimer’s disease in comparison to individuals with MCI to better understand the progression of decline. The ERSP markers may also be beneficial to study neural outcomes of pharmacological or non-pharmacological interventions that impact attention and inhibition.

Limitations of the dissertation studies have been discussed within each individual chapter, but there are some additional limitations that span across the studies that need to be addressed. In regard to the EEG analyses (Chapter 2-4), ERSP frequency bands, electrode sites, and 100 ms time windows were selected a priori. This dissertation only focused on theta and alpha bands given their relationship to inhibition and attention, respectively, both of which are involved in value-directed strategic processing. An emerging body of work, particularly from subsequent memory studies, suggests that beta band may be critical for better understanding memory-related processes within the context of value-directed strategic processing. However, because this dissertation focused on processing independent of retrieval/recall, beta band was not examined with an exception (see Chapter 3 supplementary material for a preliminary beta band analysis for exception). The electrode sites were chosen based on previous literature showing that theta activity is prominent in frontal regions and alpha activity is prominent in parietal regions. The 100 ms time windows were utilized to better capture the temporal unfolding of the neural processes related to value-directed strategic processing. Although these a priori selections revealed important findings in this dissertation, it could be argued that the electrode selection was limited and that the time windows were either too big or too small to best capture the neural unfolding of value-directed strategic processing. One potential solution would be to use data-driven approaches, such as principal component analysis (similar to the Chapter 3 supplementary material) or permutation-based cluster analysis, to select electrodes and time periods of interest.

Another limitation of this dissertation work relates to the connection between the behavioral data and the ERSP data. The behavioral data reflects participant recall of high- and low-value words, meaning that it also reflects encoding and storage processes, while the ERSP data reflects neural processing related to high- and low-value words that is independent of whether a given word is later recalled or forgotten. Although this dissertation makes interpretations about the relationship between behavioral and ERSP findings, it is difficult to truly make direct connections between the two. An example of how the two could be more directly connected would be to examine ERSP data specifically for words that were later recalled versus words that were later forgotten to determine if there are neural processing differences between the two. Future studies will need to redesign the task to allow for such comparisons in order to better connect the behavioral and ERSP data.

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