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An examination of the ERP correlates of recognition memory using state-trace analysis.

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Abstract

There has been much debate in recent years as to whether recognition memory is best described using a single or dual process model. State-trace analysis provides an atheoretical approach to determining the number of underlying psychological variables, or processes, that mediate the effect of one or more independent variables on the measured dependent variables. Recently, state-trace analysis has shown strong support for a single process interpretation of the behavioral results from recognition memory experiments. In this paper, we demonstrate, using state-trace analysis, that both the behavioral and electrophysiological results from recognition memory experiments are also supportive of a single process interpretation.

Keywords: recognition memory; event-related potentials; single process models; dual process models

The study of recognition memory aims to determine the process(es) underlying how one recognizes something, or someone, as having been previously encountered (Mandler, 1980). In a typical recognition experiment, participants study a list of items, and at test are asked to discriminate between both studied (old) and unstudied (new) items. Two measures are obtained: the hit rate (proportion of old items correctly identified as being old) and the false alarm rate (the proportion of new items incorrectly identified as being old). The hit and false alarm rates can be combined to indicate an overall level of accuracy[1].

A number of mathematical models have been proposed attempting to describe the basis of recognition memory. These models can be grouped into two main frameworks: single and dual process models. This paper will attempt to assess the validity of these two classes of models by testing their basic assumptions using electrophysiological data from a recognition memory experiment. First these two frameworks will be described as well as some of the supporting behavioral, imaging and electrophysiological evidence. Next, an atheoretical method that can be used to test the basic assumptions of these two classes of models will be described. Following which, the results from an experiment, designed to test these underlying assumptions are presented.

Models of Recognition Memory

It has long been debated whether recognition memory decisions are performed on the basis of a single memory process, referred to as either strength, familiarity, or matching, or whether a recall-like component is also involved (Clark, 1999). The first dual process models were developed in the 1970s (e.g., Atkinson & Juola, 1974), but were overtaken in popularity when single process, global memory/matching models, were developed in the 1980s. Dual process models regained popularity in the early 1990s and as such the debate as to which type of model best describes memory is ongoing.

Single Process Models

Single process theories are based on the signal detection framework (Green & Swets, 1967). In its simplest form, signal detection theory considers two basic aspects of detection: the underlying representations, which are interpreted as psychological distributions, and a decision aspect, which involves the use of decision criteria to arrive at a response (DeCarlo, 2002). Signal detection theory can be applied in any task in which participants are required to discriminate between two or more classes of stimuli (Stanislaw & Todorov, 1999).

Signal detection memory models assume that when a participant is presented with a test stimulus it is directly matched to multiple memory representations in parallel and the fit of these matches is used to calculate a familiarity value (Clark, 1999). Familiarity is thought to be based on associative information and information about other items in memory, as well as on stored item-specific information about the test item. In a recognition memory experiment, stimuli presented in the study phase have familiarity values drawn from the ‘old’ normal distribution, while the familiarity values for new items are drawn from the ‘new’ normal distribution. The mean of the old distribution is assumed to be higher than the mean for the

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[1] For example, d’ is calculated by subtracting the z-transformed false alarm rate from the z-transformed hit rate.

new distribution. Each old and new condition has its own response distribution and the criterion is placed at a point chosen by the participant that determines whether an old or new response is made.

There are a number of specific single process theories that have been developed to account for findings in recognition memory. Although each of these models is considered to contain a single process, they vary quite substantially in their focus. For example, Attention-Likelihood Theory (ALT, Glanzer & Adams, 1990) is based on the idea of feature marking first proposed by Glanzer and Bowles (1976). Retrieving Effectively from Memory (REM, Shiffrin & Steyvers, 1997) is centered around item noise, while at the other end of the spectrum, the Bind Cue Decide Model of Episodic Memory (BCDMEM, Dennis & Humphreys, 2001) is focused on context noise.

Dual Process Models

Dual process models assume that recognition is based on two memory processes: familiarity and recollection, which are assumed to make independent contributions to recognition (Clark, 1999). Familiarity is assumed to be a fast process and is equivalent to the signal detection process described by single process theories. On the other hand, recollection is assumed to be a slow, deliberate, and relatively accurate search process whereby information about the study episode is retrieved (Arndt & Reder, 2002; Yonelinas, 1999). Generally, dual process theorists propose that the hit rate in a recognition experiment is driven by recollection and the false alarm rate is driven by familiarity (e.g., Joordens & Hockley, 2000).

Yonelinas (2002) presented a high-threshold dual process model of recognition memory. He proposed that recollection and familiarity are independent parallel processes that differ in the type of information they provide and the extent to which they influence a person's confidence. Familiarity reflects the assessment of quantitative memory strength information in the same manner as signal detection theory used in single process theories. The variable strength of familiarity leads to a wide range of confidence ratings. Recollection reflects a threshold retrieval process in which qualitative information about a previous event is retrieved, producing a high level of confidence.

A number of pieces of evidence have been put forward in support of the dual process models of recognition memory. The most dominant of these behavioral, imaging and electrophysiological findings are presented in the following section.

Behavioral, Imaging and Electrophysiological Evidence

The Remember-Know paradigm (Tulving, 1985) has been used to add support to the claim that recognition memory is best described using a dual process model. This procedure requires participants to indicate whether their 'old' responses in a recognition memory test are based upon familiarity alone (Know) or whether they recollect seeing the item in the study list (Remember). Some researchers (e.g., Gardiner & Java, 1990) have suggested that the mere finding that participants are able to distinguish between these two types of responses is evidence that both familiarity and recollection contribute to the recognition memory task. However, experiments finding dissociations between remember and know responses provide much more compelling arguments. For example, Gardiner (1988) reported a dissociation between remember and know responses such that deeper levels of processing at study led to more remember responses at test, but did not affect know responses. Since this early finding, numerous studies have been reported finding dissociations between remember and know responses (e.g., Gardiner & Java, 1990, 1991; Glanc & Greene, 2007; Joordens & Hockley, 2000; Park, Reder, & Dickison, 2005; Rajaram, 1993).

Although these dissociations between remember and know responses are often taken as evidence for dual process models (e.g., Jacoby, Yonelinas, & Jennings, 1997), a number of single process advocates have argued that remember and know responses are simply classifications of different levels of confidence, and as such can also be accounted for by single process models (e.g., Donaldson, 1996). Dunn (2004) put forward a compelling argument for remember and know responses representing higher and lower levels of confidence, respectively. In an analysis of 72 studies, Dunn showed that the arguments against remember-know data being described by a signal detection, single process framework could not be ruled out, and provided an equally plausible account of the data.

Since it appears that behavioral data can be well explained using single process models, researchers have recently started looking at the neurological basis of recognition memory, in order to determine if there is any biological evidence for familiarity and recollection playing a role in the decision process. Despite evidence that the remember-know procedure does not necessarily separate recollection and familiarity, it has been widely used in imaging and electrophysiological studies. Here the aim is to find either separate brain regions (in fMRI studies), or distinct event-related potentials (ERPs) related to remember and know responses, which are then interpreted as being related to recollection and familiarity, respectively.

Recently, Yonelinas, Otten, Shaw and Rugg (2005) suggested that they had found a neural signature of recollection that was distinct from familiarity. Because past researchers (e.g., Dunn, 2004) had suggested that remember responses simply reflect a subject's high level of confidence, Yonelinas et al. had their subjects respond 'remember' if they could remember something specific about the study episode, otherwise they were asked to give a confidence rating that the item was studied using a four-point scale (sure old / sure new). Yonelinas et al. found different neural signatures for remember and high confidence familiar responses, which led them to the conclusion that recollection and familiarity are two distinct processes (but see Dunn & Dennis, submitted, for a conflicting interpretation of these results).

Curran (1999, 2004) and colleagues (e.g., Curran & Dien, 2003; Curran, DeBuse, Woroch, & Hirshman, 2006; Curran, Tepe, & Piatt, 2006; Curran, DeBuse, & Leynes, 2007) have focused on differentiating recollection and familiarity using ERPs. Two time periods of interest have been identified. The first, occurring 300-500ms after stimulus onset is commonly referred to as the FN400 as it is a frontal negative peak. The second, occurring 400-800ms after stimulus onset has received numerous names, but the most common is the LPC, or late positive component, and is more dominant in the parietal brain region. Curran et al. have argued that the FN400 is an old/new decision component related to item familiarity, while the LPC is related to the recollection process. Evidence for this distinction also comes from studies using the remember-know procedure. Studies have shown that studied items produce a more negative FN400 than unstudied items, and that 'remembered' items produce a more positive LPC than 'known' items (e.g., Rugg et al., 1998; Rugg & Curran, 2007; Rugg & Yonelinas, 2003). However, as Finnigan, Humphreys, Dennis, and Geffen (2002) have demonstrated, these findings can be easily fit by a single process model whereby the FN400 reflects an individual's old/new decision, and the LPC reflects their confidence.

Obviously there is much controversy as to how both the behavioral and neurological data should be interpreted. The following section outlines a technique that can be used to determine the number of processes that are needed to account for a given data set, without making any assumptions about single or dual process models.

State-Trace Analysis

State-trace analysis (Bamber, 1979) is based on the premise that two dependent variables will covary with each other to the extent that they are affected by the same independent variable. By producing a plot of one dependent variable as a function of another dependent variable, one can determine the number of intervening psychological variables, or processes, that mediate the effect of one or more independent variables on the measured dependent variables. If the resulting scatter plot is one dimensional, that is all the data points lie on a single monotonically increasing (or decreasing) curve, then it can be assumed that the two dependent variables are functions of the same latent variable.

Dunn (2008) performed a state-trace analysis on the data from 37 remember-know studies. When the old/new hit rate was plotted as a function of the remember (or high confidence) hit rate, a predominately one dimensional curve was found, suggesting that the remember-know task is best described by a single process model. Further, when the z-transform of the state-trace was computed, a straight line with a slope of one was obtained. This finding is also in accordance with an unequal variance, signal detection, or single process model.

Experiment

The aim of the present research is to examine the ERP correlates of recognition memory. To do this, state-trace analyses will be applied to behavioral and ERP data obtained from an experiment that manipulates two independent variables identified by Yonelinas (2002) to affect either familiarity or recollection. The behavioral state-trace will plot the low confidence hit rate (LCHR) as a function of the high confidence hit rate (HCHR) and the ERP state-trace will plot the FN400 as a function of the LPC. If the HCHR/LPC reflects recollection, the state-trace plots should show two lines, separated on the dimension outlined by Yonelinas to reflect recollection. However, if the state-trace plots show a one dimensional curve, this will be indicative of a single process underlying recognition memory, and will provide strong evidence in favor of single process models.

Specifically, in our experiment the number of study repetitions (1/2/4) and attention at study (focused/divided) were manipulated. According to Yonelinas (2002), the attention manipulation should affect recollection, but not familiarity, and the study repetition manipulation should affect both familiarity and recollection. If the dual process interpretation of recognition memory is accurate, the state-trace plots should show two monotonic functions, separated by the attention manipulation. Specifically, the LCHR/FN400 should become more positive as the number of study repetitions increases, and the focused attention condition should be shifted to the right (i.e., a more positive HCHR/LPC) compared to the divided attention condition. However, if the resulting state-trace plot is one-dimensional, this will indicate that both the number of study repetitions, and attention at study are related to the same latent variable, or memory process, indicating that a single process interpretation of the data is accurate.

Method

Participants

54 students from the Ohio State University participated in return for course credit.

Stimuli

The stimuli consisted of 240 high frequency words with a mean frequency of 155 (ratings taken from the Celex database, Baayen, Piepenbrock, & van Rijn, 1993). Words were 4-8 letters in length (mean 4.6). Words were randomly divided into 5 lists for each participant and items within each list were randomly allocated to old/new, focused/divided attention, and repetition conditions.

Design

The experiment was a 2x3 design, with attention at study (focused/divided) and number of study repetitions (1/2/4) manipulated within-subjects.

Procedure

Participants were first briefed on the requirements of the study, signed a consent form and were fitted with the Geodesic Electrode Net.

Each study list consisted of 24 words. Half the words were presented alone on the screen (focused attention condition) while the other half were presented flanked by two numbers (divided attention condition). In the divided attention condition, the flankers appeared for 200ms and were then covered by a mask. The numbers differed in both their numerical value, and their font size. After the target word was removed from the screen, the participants were asked to report which number (left or right) was larger in either value or size by pressing the appropriate key on the keyboard. One third of the study items were presented once, one third were presented twice, and one third were presented four times during the study phase to give a total of 56 study trials. Repeated words were always repeated within the same attention condition. Words were presented for three seconds followed by a one second interstimulus interval (isi). Following the study phase, participants completed several math problems for a period of approximately three minutes.

The test lists consisted of 48 words, with an equal number of old and new items. Each word was presented for two seconds followed by a response cue, at which time the participant was required to give their response by pressing the appropriate key on the keyboard using a six-point confidence rating scale (sure old/sure new). Participants were instructed to wait for the cue before responding, to stay as still as possible, and to minimize eye blinks.

Each study/test cycle took approximately 20 minutes to complete. After each cycle, the Electrode Net was checked to ensure that impedances remained below 50kΩ. Participants completed as many study/test cycles as possible during the two hour time period, with most completing an average of four cycles.

EEG Recording

Scalp voltages were collected using a 128-channel Electrical Geodesics Sensor Net connected to a high impedance amplifier (300kΩ Net Amps^{TM}, Electrical Geodesics Inc, Eugene, OR, USA). Amplified analog voltages (0.1-100Hz bandpass, -3dB) were digitized at 500Hz. Individual sensors were adjusted until each reached an impedance of less than 50kΩ. The EEG was digitally low-pass filtered at 40Hz.

Results

Trials were discarded from the analysis if they contained eye movements (EOG over 70μV), or more than 20% of channels were bad (average amplitude over 200μV or transit amplitude over 100ms). Individual bad channels were replaced on a trial-by-trial basis with a spherical spline algorithm (Srinivasan, Nunez, Silberstein, Tucker, & Cadusch, 1996). Consistently bad channels for a given subject were replaced throughout that subject's entire dataset (bad channels per subject: median = mode = 1, range = 0 - 3). EEG was measured with respect to a vertex reference (Cz), but an average-reference transformation was used to minimize the effects of reference-site activity and accurately estimate the scalp topography of the measured electrical fields (Dien, 1998; Picton, Lins, & Scherg, 1995). Average-reference ERPs were computed for each channel as the voltage difference between that channel and the average of all channels. The average reference was corrected for the polar average reference effect (Junghofer, Elbert, Tucker, & Braun, 1999). ERPs were baseline-corrected with respect to a 100ms prestimulus recording interval.

Figure one shows the state-trace plot obtained by plotting the mean LPC against the mean FN400 for each attention by repetition condition. Both the FN400 and the LPC were found to increase (i.e., become more positive) with increasing study repetitions. Additionally, there is no significant differentiation between the focused and divided attention conditions.

The behavioral state-trace plot, also shown in Figure one, shows that both high and low confidence hit rates increase with increasing study repetitions. Further, there is no differentiation between the attention conditions.

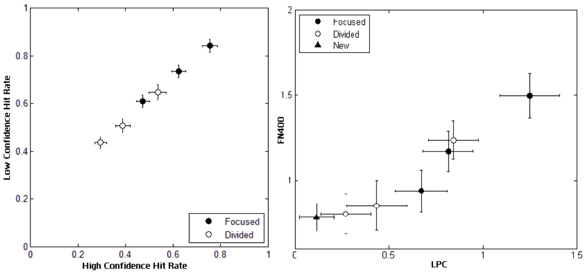

Figure 1: State-trace plots of the behavioral (left) and ERP (right) results for each of the attention by repetition conditions.

Discussion

The state-trace plots produced from the analysis of our experiment are clearly one-dimensional and thus provide very little evidence in support of the dual process interpretation of recognition memory. Rather, our findings show strong support for a single process interpretation of recognition memory.

Numerous previous recognition memory studies looking at ERPs have assumed that the LPC is reflective of recollection (e.g. Curran, 2004; Curran, Tepe, & Piatt, 2006). These studies have rejected a single process interpretation of the FN400 and LPC because it “does not explain the double-dissociation between mid-frontal and parietal effects observed by Woodruff et al.” (Rugg & Curran, 2007, p.264). In the study which Rugg and Curran (2007) refer to, participants we asked to respond using a variation of the remember-know procedure, in which they either made a graded, confidence-based familiarity judgment on a 4-point scale, or a remember/recollection response. The authors report differing ERP patterns for the FN400 and the LPC and suggest that the ordering of the waveforms (1<2<3<4=R and 1=2=3=4<R, respectively) are evidence that the FN400 represents familiarity, and the LPC represents recollection. However, as explained by Dunn and Kirsner (2003), this is actually a classic non-double-association. The error is that the authors implicitly assume that changes in volts (a physical variable) are linearly related to memory strength (a psychological variable). If on the other hand, one assumes that this relationship is at best monotonic and different for frontal and parietal, the underlying assumption of state-trace analysis, then there is no dissociation. At both sites, the underlying pattern of memory strength is 1<2<3<4<R but mapped onto frontal and parietal volts by different functions. By using state-trace analysis to interpret our research findings, we have not only avoided this common error, but have also shown strong support for a single, rather than dual, process interpretation of ERP results.

Additionally, the results from our experiment add weight to the suggestion by Finnigan et al. (2002) that the LPC is not reflective of recollection. Finnigan et al. suggested that the LPC may instead be related to confidence. Although not specifically addressed in this analysis, our research methods provided an opportunity for testing this idea in the future.

Yonelinas (2002) suggested that dividing attention at study would affect recollection at test, such that items in the focused attention condition would have higher levels of recollection than items in the divided attention condition. The analysis of our behavioral data produced a single monotonic state-trace curve (see also Dunn, Heathcote, Dennis, & deZubicary, in preparation). Our ERP findings extend these behavioral findings, supporting a single process interpretation of recognition memory.

Combined, these findings suggest that not only is the LPC not reflective of recollection as suggested by Curran and colleagues, but they also suggest that the notion of recollection itself may be flawed, further supporting the predictions of single process models of recognition memory.

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