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# The N400 in a semantic categorization task across 6 decades

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**Abstract**

**Objectives**: To characterize the effects of normal aging on the amplitude, latency and scalp distribution of the N400 congruity effect.
**Methods**: Event-related brain potentials (ERPs) were recorded from 72 adults (half of them men) between the ages of 20 and 80 years (12/decade) as they performed a semantic categorization task. Participants listened to spoken phrases (e.g. ‘a type of fruit’ or ‘the opposite of black’) followed about 1 s later by a visually-presented word that either did or did not fit with the sense of the preceding phrase; they reported the word read and whether or not it was appropriate. ERP measurements (mean amplitudes, peak amplitudes, peak latencies) were subjected to analysis of variance and linear regression analyses.
**Results**: All participants, regardless of age, produced larger N400s to words that did not fit than to those that did. The N400 congruity effect (no-fit ERPs − fit ERPs) showed a reliable linear decrease in the amplitude (0.05–0.09 $\mu$V per year, $r = 0.40$) and a reliable linear increase peak latency (1.5–2.1 ms/year, $r = 0.60$) with age.
**Conclusions**: In sum, the N400 semantic congruity effect at the scalp gets smaller, slower and more variable with age, consistent with a quantitative rather than qualitative change in semantic processing (integration) with normal aging. 

*Keywords:* Semantic categorization; N400 semantic congruity effect; Aging; Event-related potential

## 1. Introduction

Since development and aging span a lifetime, there is good reason to look at every brain and psychological function through the perspective of age. Indeed we believe this is unavoidable if our ultimate goal is to understand the mind–brain link. In this report we examine the effects of normal aging on semantic memory use. By semantic memory we refer to the repository of knowledge that one has about words, objects and events in the world, knowledge that supports categorization, inference and aspects of natural-language processing. It is generally believed that semantic memory is relatively unaffected by normal aging, in contrast to the age-related decline in retrieval of memories for particular episodes in an individual’s life. And, in fact, when the integrity of semantic knowledge is inferred from performance on vocabulary tests, there is not only little evidence of age-related decline but even occasional reports of an age-related increase in vocabulary size (e.g. O’Dowd, 1984; Bowles and Poon, 1985). However, this apparent equivalence in vocabulary scores across the ages may at times mask qualitative differences in the nature of the definitions that younger and older subjects provide. For example, younger adults tend to define a word with a single good synonym whereas older adults are more likely to give a less specific and more verbose description (e.g. Botwinick et al., 1975).

Other estimates of whether or not and, if so, how semantic memory organization and access might change with age have been based on variants of so-called semantic-priming paradigms. The most common among these are the lexical decision, word and picture naming, and semantic categorization tasks. Methodological differences notwithstanding, these paradigms are similar in showing that context[1] can have a facilitatory effect on task performance; the accuracy,

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[1] Although we are using the term ‘context’ in a general sense, in most cases, context is embodied in a single priming word or a sentence fragment that occurs prior to the ‘target’ word.


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the speed, or both, of a task decision are generally improved when a (target) word is preceded by a semantically or associatively related (prime) word or a congruent sentence fragment as opposed to an unrelated word or an incongruent sentence fragment (see Neely (1991) for a review). This facilitatory effect (priming) of reaction times (RTs) by an appropriate context is the norm whether a subject is 20 or 70. However, there is some question as to whether the size of the semantic-priming effect remains constant across the adult lifespan; the results are inconsistent. Most investigators have found that semantic priming[2] remains stable across the adult lifespan, even in the presence of deficits in explicit memory (Byrd, 1984; Cerella and Fozard, 1984; Bowles and Poon, 1985; Rabinowitz, 1986; Burke et al., 1987; Balota et al., 1992; Mueller et al., 1997). Others, however, have observed significant age-related changes in the size of semantic-priming effects, in some cases smaller and in other cases larger than normal (e.g. Petros et al., 1983; Howard et al., 1986; Chapman et al., 1994; for meta-analysis see Laver and Burke, 1993; Nyberg et al., 1996). These discrepancies are difficult to tease apart, as a number of factors, such as the duration of the interval between the context (prime) and target stimuli, the proportion of related to unrelated items, and the strength of the relationship between the prime and target modulate the automatic and attentional contributions to the overall priming effect.

On the one hand, it is generally assumed that semantic information remains largely intact across the lifespan, i.e. that the structure of the semantic network is not qualitatively altered by normal aging. On the other hand, the literature also suggests that the speed with which semantic information is utilized (including access and integration), whether consciously or unconsciously, is significantly slowed with advancing age. Elderly volunteers typically show slower response times in lexical decision, naming, categorization, and various verbal fluency tasks (e.g. Birren and Fisher, 1995). In fact, some researchers have suggested that the disproportionately greater than normal amount of semantic priming sometimes observed in elderly populations is an artifact of the slower response times and that it vanishes when overall slowing is factored out (see Milberg and Blumstein (1981) for a similar argument in aphasic patients). In any case, to date there is no consensus as to whether this effect is merely a consequence of general, domain non-specific cognitive and motoric slowing or specific to semantic or verbal processing.

We decided to examine aspects of this issue using a measure of both brain activity and cognitive processing that is sensitive to semantic relations and does not require a motor response. Specifically, we chose to measure the electrical activity recorded from the human scalp synchronized to target events that need to be categorized relative to a semantic context. These time-locked recordings known as event-related brain potentials (ERPs) provide a multidimensional (amplitude, latency, topography) measure of the difference between two or more experimental conditions – in this case, a word that has been semantically primed and one that has not.

A number of investigators have recorded ERPs from college undergraduates as they rendered decisions about category membership (e.g. Fischler et al., 1983, 1985; Boddy, 1986; Neville et al., 1986; Kounios and Holcomb, 1992; Heinze et al., 1998). A finding common to all these studies is the pattern of ERPs for words that are actually category members versus those that are not. Regardless of the type of response required (including none), ERPs elicited by a category non-member are more negative between 200 and 600 ms than those elicited by a category member. This negative difference, termed the N400 effect, typically has a posterior (centro-parietal) maximum, and shows a slight amplitude and durational asymmetry favoring the right hemisphere.[3]

The N400 component of the ERP was first described in response to semantically-anomalous words within isolated sentences or within written text (Kutas and Hillyard, 1980; Kutas and Hillyard, 1983). Subsequent experiments demonstrated an N400 to every word in a sentence, as well as in response to letter strings (words and pseudowords) in word lists or wordpairs (for review see Kutas and Van Petten, 1994). N400 amplitudes have been found to vary with a number of factors: (1) more predictable words elicit smaller N400s than less predictable words, (2) open class words elicit larger N400s than closed class words, (3) low-frequency words elicit larger N400s than high-frequency words, especially for words occurring for the first time, (4) words occurring at the beginnings of sentences elicit larger N400s than those occurring near the ends of sentences, (5) words occurring for the first time in an experiment have larger N400s than upon repetition, although this effect interacts with the similarity of the context within which the various presentations occur and the interval

[2] Here we use the term semantic-priming effect in its most general sense; that is, the beneficial effect of semantic context, be it a word or a sentence, without commitment to whether the effect reflects activity of automatic or controlled processes.

[3] It is likely that the N400 effect reflects the activity of a set of different neural generators, i.e. consists of different subcomponents. For instance based on an extensive mapping study, Nobre and McCarthy (1994) concluded that 'The time window typically associated with N400 was shown to contain multiple ERP features with distinct spatial distributions over the scalp. ' They found that sentence-ending words and content words in lists both showed similar features but at different latencies – 332 and 316 ms, respectively. Whatever the actual number of distinct components, the complexity of this pattern shows that the region of the N400 is clearly not a region of electrical silence, as implied by Curran et al. (1993) and never accepted by Kutas. Ample evidence demonstrates that the N400 is a region of activity and not merely a dead-time uncovered by a delay in P3 latency (as also suggested by Polich (1985)). Perhaps Curran et al.'s results were due to the distance-weighted average reference they used. Certainly their N400s looked similar to all the previous reports in the literature prior to the re-referencing procedure. For present purposes, however, we refer to the N400 effect as the difference between ERPs to items that do and do not fit a prior semantic context without any commitment to actual number of subcomponents. This issue will be addressed again in Section 4.

between the repetitions, (6) words preceded by a semantically or associatively related word elicit smaller N400s than words preceded by unrelated words and (7) real words and pseudowords (e.g. orthographically legal and pronounceable non-words) elicit larger N400s than do non-words (i.e. orthographically illegal, unpronounceable letter strings). Thus, it seems that both lexical and contextual (especially semantic) factors influence the amplitude of the N400 component.

A critical finding was the dissociation of the truth or falsity of a statement from the semantic relation between its subject and predicate (e.g. Fischler et al., 1983; Fischler and Raney, 1991; Kounios and Holcomb, 1992). Specifically, Fischler et al. (1983) demonstrated that large N400s were elicited by the final words of propositions whenever the subject and predicate on N400 amplitude were semantically unrelated, regardless of the validity of the sentence. Subsequent work from Fischler's laboratory revealed that if all the stimulus sentences were affirmative, then sentence validity (i.e. sentence-level constraints) did modulate the size of the N400 somewhat. Nonetheless, the lexical relation between the subject and predicate remains a powerful factor in determining the overall amplitude of the N400 in such short sentences.

In summary, across several laboratories N400 amplitude has been found (1) to vary with a number of different semantic variables (Kounios and Holcomb, 1992) and (2) to be relatively insensitive to decision-related and response-selection mechanisms (e.g. Heinze et al., 1998) that do, however, affect the speed of the eventual response (response time). Thus, it has been suggested that the N400 can be used to ask questions about the organization of semantic memory and how it is utilized in such tasks, irrespective of task demands and specific decision-related effects. It is in this vein that we examined the hypothesis that, insofar as age-related changes are observed in certain semantic-categorization or semantic-priming tasks, the young–old differences arise from differences in access to or decisions about the memory rather than its structure per se. To this end, we studied the effects of normal aging on semantic categorization via ERP recordings.

Although most of what we currently know of the N400 and the factors that modulate it is based on work with college undergraduates, a few studies provide some data on the changes in N400 with development and late-life aging. Holcomb et al. (1992) reported on a large study of individuals between 5–26 years of age as they heard or read sentences that either ended with a highly-expected ending or a semantically-anomalous word (in the reading version, the minimum age was 7). While all age groups showed an N400 effect in both modalities, the size of the effect was inversely correlated with age. The results were interpreted as consistent with other reports showing that as children acquire good language skills they rely less on semantic context (but see also Juottonen et al., 1996; Gonzalez-Garrido et al., 1997).

Harbin et al. (1984) were the first to examine the effects of aging on ERPs in a categorization task. They recorded ERPs from 3 midline locations of a younger (mean age 21 years) and an older group (mean age 71) making decisions about the 5th of a series of visually-presented words in an Identity and a Category condition. In the Category condition, the first 4 words all belonged to the same semantic category and subjects were asked to indicate whether or not the 5th word also belonged. Given their interest in the P3 component of the ERP and the sensitivity of the P3 to event probabilities, the 5th word matched the previous 4 on only 15% of the trials. Both reaction times and the latency of the N400 to mismatches were noticeably longer in the older group, although the difference N400 (mismatch – match ERP) reportedly peaked at approximately 540 ms for both groups. Gunter et al. (1992) compared the ERPs elicited by congruous and incongruous endings of sentences of medium-to-high contextual constraint from a group of young students with those from a group of highly-educated middle-aged academics (mean age 55 years). The N400 effect in the older group was both delayed in latency (by 120 ms) and reduced in amplitude. These basic findings have been replicated by others in small groups of middle-aged and elderly individuals (Gunter et al., 1995; Gunter et al., 1996; Ford et al., 1996).

The present experiment was aimed at replicating and extending these findings to men and women from 20 to 80 years of age. Congruent and incongruent words were flashed visually after the context (category name) was spoken by the experimenter. We chose this paradigm with auditory context and visual target word because we have found that it is a task that can be performed by patients of various mental capabilities[4] and that it produces a robust N400 in response to semantically-incongruent words (see Kutas et al., 1988; Iragui et al., 1996).

Given the known reduction in N400 amplitude with increasing strength of semantic association and its inverse correlation with degree of contextual constraint, we thought it useful to make a similar comparison in this simpler semantic categorization task (Kutas and Hillyard, 1984, 1989; Kutas et al., 1984; Van Petten and Kutas, 1991a,b; Van Petten et al., 1991). To that end, the stimulus set included approximately equal numbers of highly constraining antonym contexts (e.g. 'the opposite of black') for which there is only one reasonable outcome (e.g. 'white') and moderately constraining category contexts (e.g. 'a piece of furniture') for which there are several reasonable alternatives (e.g. 'table', 'chair', 'couch', 'cabinet', etc.). Antonymic and categorical relations also map onto the distinction that has been made between semantic and associative priming (for review see de Groot, 1990) as well as the distinction between a prediction-based versus an expectancy-based strategy for utilizing contextual information, respectively (e.g. Becker, 1980, 1982). Thus, while we

[4] Including patients diagnosed with senile dementia of the Alzheimer's type, with Huntington's disease, Parkinson's disease, Broca's aphasia, and with commissurotomy.

expect to obtain large N400 effects for both stimulus types, the proposed differences in the lexical and/or contextual mechanisms underlying semantic and/or associative priming with antonyms and categories would predict some ERP differences as well.

## 2. Methods and materials

### 2.1. Participants

Seventy-two adults were paid for participating in the experiment after consent was obtained. There were 12 subjects in each of 6 decades between 20 and 80 with approximately half of the subjects men, and half women. See Table 1 for a description of subject groups in terms of gender, handedness, age and educational history. On the average, those in their fifties had slightly fewer years of education than those in the other age groups.

### 2.2. Procedure

Target words were displayed in the form of brightened dot matrices on a CRT controlled by an Apple II microcomputer. The screen was occluded except for a rectangular slit in the center through which the words were viewed. All words were exposed for 265 ms and ranged in length from two to 8 letters (median = 5 letters). Participants sat approximately 95 cm from the monitor screen; the words subtended 0.3 (visual angle vertically and 0.3–2.9 (visual angle horizontally.

Participants were tested in one session that lasted between 2 and 2.5 h, while reclining in a comfortable chair. Participants were presented with a total of 216 trials. Each trial consisted of an auditory phrase read by the investigator, followed approximately 1000–1400 ms later by a word presented in the center of a video monitor. There were 4 different trial types: congruent antonyms or opposites ($n = 50$),incongruent antonyms or opposites ($n = 50$), congruent category members ($n = 58$) and incongruent category members ($n = 58$). The two antonym trial types began with the phrase ‘the opposite of’ (e.g. the opposite of black or the opposite of lost); these were followed by a visual flash of an appropriate word (e.g. white and found, respectively) or by an inappropriate, incongruous word (e.g. peach). Similarly, the two category trial types began with a phrase such as ‘a piece of furniture’ or ‘a male relative’ followed either by a category instance (e.g. table) or not (e.g. noose). The 4 different trial types were intermixed and presented in random order.

Following each visually-presented word by approximately 1.5 s, subjects were asked to indicate whether or not the word they saw was or was not an acceptable completion and to report the word they saw. The inter-trial interval varied between 2.5 and 6.5 s.

Table 1

Group composition: gender, age, handedness, years of education

| Decade | No. men | No. women | Mean age | Handedness | Education |
|---|---|---|---|---|---|
| 20s | 7 | 5 | 24 (2.9) | 10 R, 2 L | 15.5 (2.1) |
| 30s | 5 | 7 | 34 (3.7) | 12 R | 17.6 (2.3) |
| 40s | 5 | 7 | 45 (3.6) | 12 R | 17.0 (2.3) |
| 50s | 6 | 6 | 54 (3.3) | 12 R | 14.7 (3.0) |
| 60s | 6 | 6 | 66 (2.8) | 10 R, 2 A | 16.3 (2.5) |
| 70s | 6 | 6 | 74 (3.1) | 11 R, 1 A | 16.3 (2.8) |

No subject had any left-handed family members in their immediate family. For age and years of education, standard deviation around the mean is presented in parentheses.

R, right-handed; L, left-handed; A, ambidextrous.

### 2.3. Recording system

Electroencephalographic (EEG) activity was recorded from 13 scalp electrodes and the right mastoid, each referred to the left mastoid; data were re-referenced off-line to an average of the activity at the left and right mastoids. Seven were placed according to the international 10–20 system at central (Cz) midline as well as lateral frontal (F7/F8), temporal (T5/T6), and occipital (O1/O2) locations. Symmetrical anterior temporal electrodes were placed halfway between F7 and T3 and F8 and T4 sites, respectively (approximately over Broca’s area and its right-hemisphere homolog). Symmetrical parietal electrodes were placed lateral (by 30% of the interaural distance) and 12.5% posterior to the vertex (approximately over Wernicke’s area and its right hemisphere homolog). Symmetrical central electrodes were placed along the interaural line, 33% of the interaural distance. In addition, eye movements were monitored via an electrode placed below the right eye and referred to the left mastoid for vertical movements and blinks, and via a right to left canthal bipolar montage for horizontal movements.

The EEG and EOG were amplified with Grass 7P511 preamplifiers modified to have an 8 s time constant (high-frequency half-amplitude cutoff, 60 Hz).

### 2.4. Data analyses

Separate ERP averages were obtained for correctly-detected congruous and incongruous target words for both the antonym (opposite) and category conditions. Each averaged waveform consisted of a 1530 ms epoch including 100 ms baseline prior to stimulus onset. Trials contaminated by eye blinks or lateral eye movements, excessive muscle activity, or amplifier blocking were rejected by a computer algorithm prior to averaging (between 7% and 28% of trials were lost due to artifacts; the percentages from the 20s to the 70s were 26.8%, 8.3%, 6.8%, 17.4%, 19.2%, and 28.1%, respectively).

Peak and mean amplitude measurements for P1, N1 and P2 components in the raw ERPs for both congruous and incongruous words in the antonym and category conditions were taken in specified latency windows relative to the baseline activity in the 100 ms prestimulus.

The bulk of the N400 measures were taken in difference waveforms derived from a point-by-point subtraction of the ERPs to congruous words from the ERPs to incongruous words. The peak of the N400 effect was identified as the maximum negativity between 200 and 600 ms poststimulus; both latency and amplitude were measured at this point. The latency at which the amplitude of the difference wave reached 10% of its peak amplitude value (i.e. fractional peak latency) was taken as an estimate of onset latency; this measure was restricted to recordings from the right Wernicke's site. In addition, mean amplitudes (the average voltage within a latency range) were measured using windows of 100 ms around the peak amplitude for each subject's data as well between 200 and 400, 400 and 600, and 600 and 800 ms.

Amplitude and latency values were subjected to repeated measures ANOVA with age group (20s, 30s, 40s, 50s, 60s, 70s) as a between-subjects factor and condition (antonym versus category) and electrode site (13 levels) as within-subject factors. Additional analyses excluding data from the vertex site divided the electrode factor into two: location along anterior-to-posterior (A–P) dimension (6 levels including frontal, anterior temporal, central, temporal, Wernicke's, occipital) and hemisphere (left vs. right). The probabilities reported for interactions are those obtained after Greenhouse–Geisser correction (Keselman and Rogan, 1980). Furthermore, significant factor by electrode site interactions were reassessed with repeated measures ANOVAs of normalized amplitudes as outlined by McCarthy and Wood (1985). We report only those interactions that were significant on normalized amplitude measures.

Multivariate regression analyses were conducted, using both amplitude and latency measures on the difference waves (based on recordings from the vertex, over Wernicke's area and its homolog in the left and right hemispheres, respectively) from the category and antonym conditions as dependent variables and age as the independent variable.

## 3. Results

Fig. 1a,b shows the grand average ERPs ($n$ = 12/decade) elicited by congruous and incongruous words for both the opposite and category conditions for subjects from each decade between 20 and 80 years of age for 6 pairs of lateral electrodes from the front to the back of the head. The first noticeable component is a small positive peak around 100 ms in the ERP waveforms at temporal and occipital sites for some but not all subjects. This component was generally larger over the right than the left hemisphere and was easier to identify in the ERPs of subjects who did not elicit a large N136; its occurrence was too unreliable for statistical analysis.

The earliest components that were reliably present was a posterior N136 peaking between 100 and 200 ms at temporal and occipital sites (equivalent to an occipital N1 or N180 for peripheral visual flashes) and the P126 component peaking in the approximately same time-range at frontal, central and parietal sites (equivalent to a visual P2). When present the N136 showed a left greater (i.e. more negative) than right asymmetry whereas the P126 was larger (i.e. more positive) over right hemisphere sites. Specifically, the N136 component was present (i.e. measurable) in only 55 of the 72 subjects).[5] Collapsed across all subjects and conditions, the N136 averaged –6.14 $\mu$V over the left occiput and –4.98 $\mu$V at the right occiput (main effect of hemisphere, $F(1,49) = 12.78$, $P < 0.0008$).

The frontal P126 component was difficult to assess statistically, because it overlapped with a subsequent late positivity, most likely a member of the P3 family. There were no systematic effects of either congruity or condition (i.e. antonyms versus categories) on either the N136 or the P126 component. Similarly, there were no significant effects of age on either N136 or P126 amplitude. However, at the occipital sites, the N136 appeared to be significantly delayed in latency as a function of age. A linear regression of age on the peak latency of the N1 measured at the right occipital site for incongruous words in the antonym condition yielded a correlation of 0.49 and a slope of 0.65 ms/year. Subsequent to the P126 and N136 components there were clear and reliable effects of both congruity and condition on the ERPs. Starting at around 200 ms post-stimulus onset, the ERPs to incongruent words were more negative than the ERPs to congruent words (for mean amplitude 200–400 ms, main effect of congruity, $F(1,66) = 127.23$, $P < 0.0001$), albeit less so for older individuals (age group by congruity, $F(5,66) = 6.39$, $P < 0.0001$). The characteristics of the congruity effect will be described in detail in the analysis of the incongruous minus the congruous difference ERPs. However, it is important to briefly examine the ERPs to the congruous and incongruous words per se so as to better understand their independent contributions to the difference ERPs and the effects they reveal. In Fig. 2 the ERPs to congruous and incongruous words from the antonym and category conditions recorded at 4 right-hemisphere positions from the front to the back of the scalp are directly compared. First note that while there are some differences in the ERPs elicited across the decades, the pattern of effects due to the two primary manipulations (congruity and context type) are remarkably similar. Clearly, congruity has a much larger effect than the type of context, the effects of which are by and large restricted to the ERPs elicited by the congruous words (for mean amplitude 200–400 ms, congruity by condition, $F(1,66) = 6.14$, $P < 0.016$). Specifically, the ERPs to incongruous words differ only slightly as a function of whether they had occurred in the antonym versus the cate-

[5] These were spread evenly across the decades with between 9 and 11 subjects in each age group except the 30s of whom only 6 showed the N136 component.

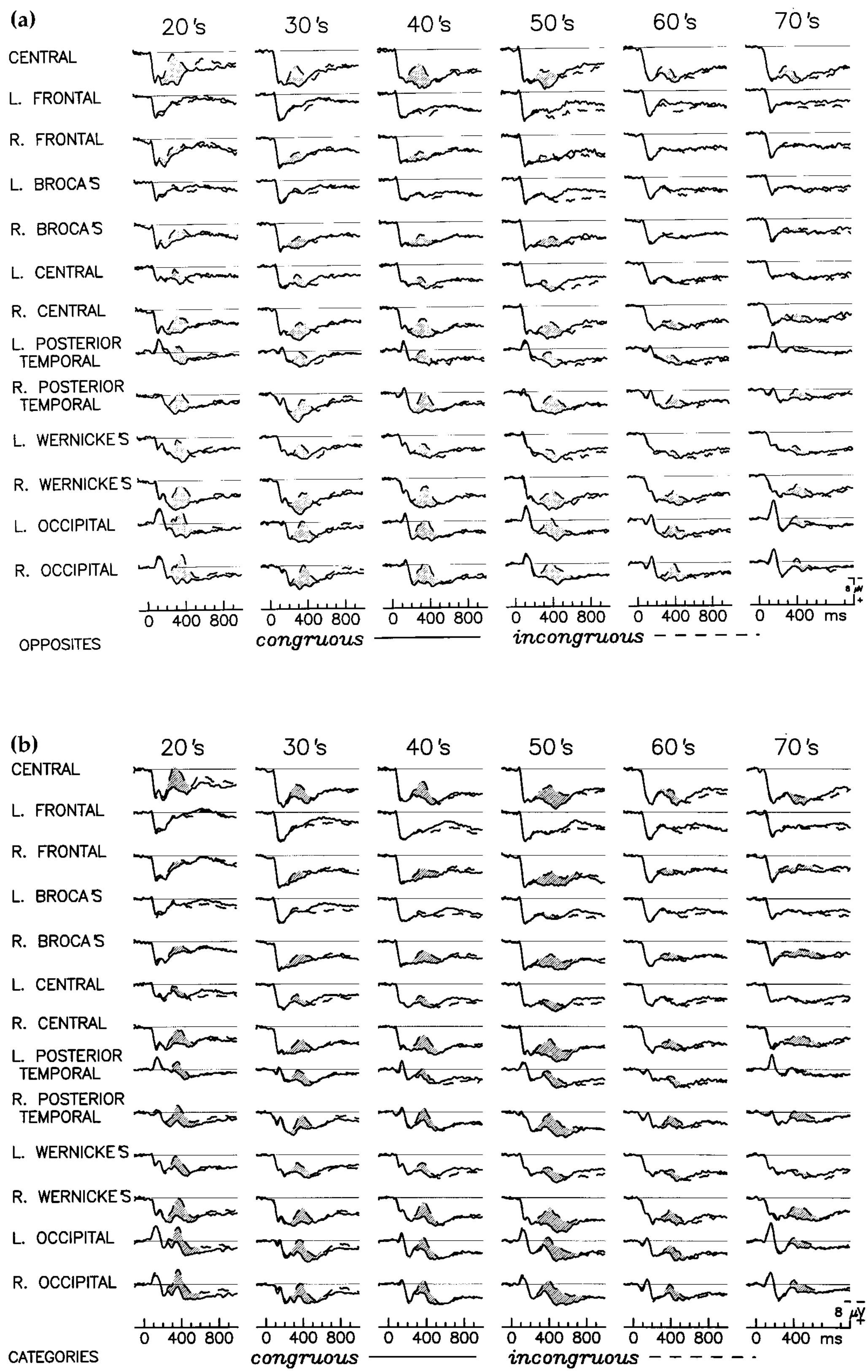


Fig. 1. (a,b) Grand average ERPs for each decade between 20 and 80 years ($n$ = 12 individuals per decade) elicited by congruous (solid line) and incongruous (dashed line) target words presented visually, following a short auditory phrase for the opposite or antonym (a) and category conditions (b), respectively over left and right frontal, Broca's, central, posterior temporal, Wernicke's and occipital sites. The shaded area in each comparison represents the 'N400 effect'. Negativity is plotted upwards on this and all subsequent figures.

gory condition. On the other hand, the ERPs to congruous words from the two stimulus conditions differ noticeably especially between 200 and 400 ms poststimulus, with the potential to antonyms being significantly more positive than to category members (for mean amplitude 200–400 ms, main effect of condition for congruous words, $F(1,66) = 7.48$, $P < 0.008$; antonyms = 5.29 $\mu$V and category = 4.88 $\mu$V). This positivity for the congruous words has a centro-parietal maximum (main effect of anterior–posterior (A–P) site, $F(5,330) = 37.67$, $P < 0.0001$). Although it appears to the eye that the anterior/posterior voltage gradient is somewhat less steep for the older than younger participants and that the condition effect may be lessened with age, neither the anterior–posterior distribution nor the condition factors interact significantly with age.

Between 200 and 400 ms, the ERPs to both congruous and incongruous words are asymmetric, being more positive over the right hemisphere sites (main effect of hemisphere, $F(1,66) = 32.27$, $P < 0.0001$), although the size of the asymmetry is larger for congruous than incongruous words (congruity by hemisphere, $F(1,66) = 85.57$, $P < 0.0001$). Collapsed across congruity, the ERPs are most

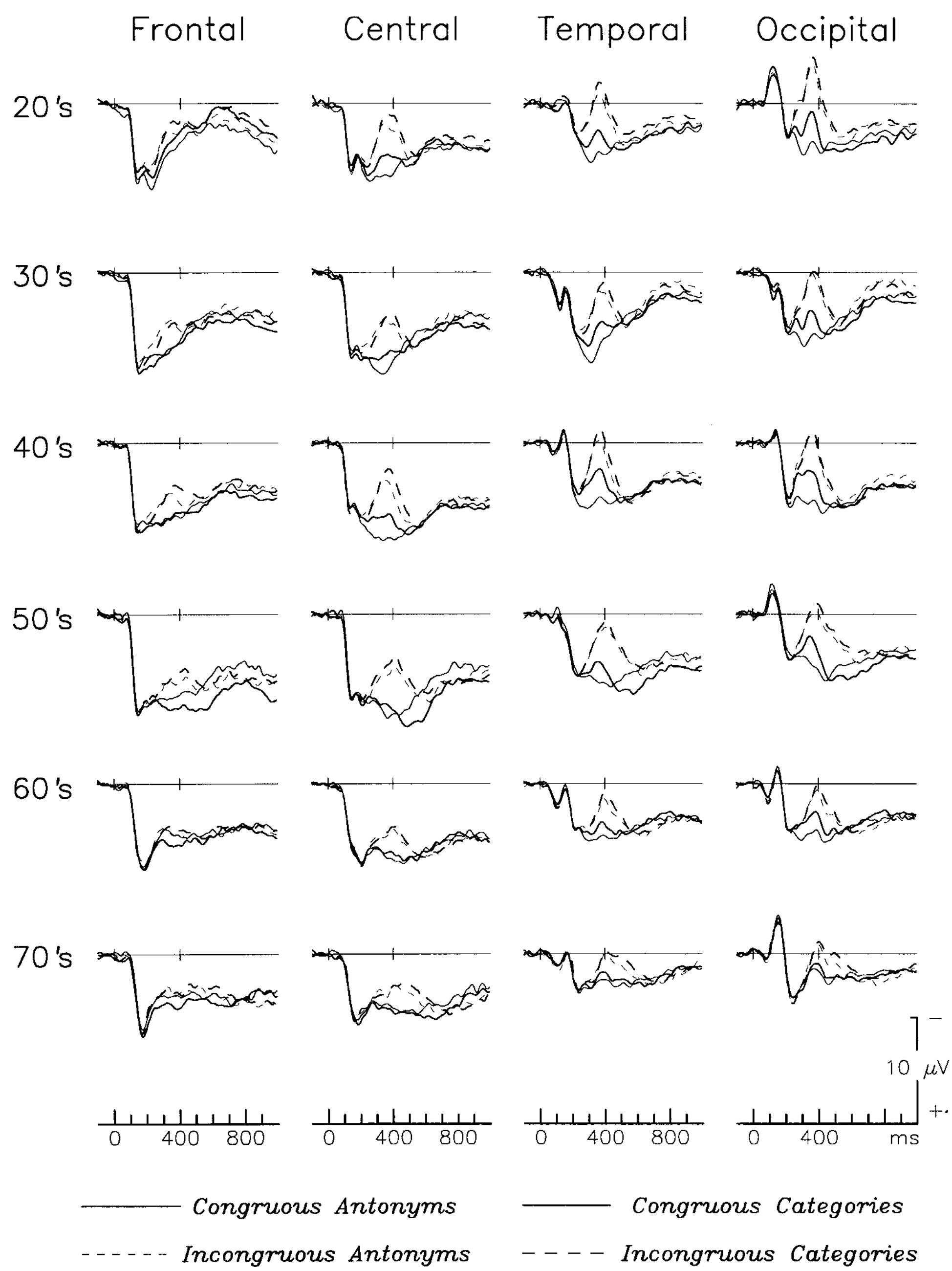


Fig. 2. Overlapped are the grand average ERPs ($n = 12$ per decade) elicited by congruous and incongruous target words in the opposite (antonym) and category conditions from the frontal, central, temporal and occipital sites of the right hemisphere for each decade separately.

asymmetric at the temporal sites and least asymmetric at the occipital sites. In addition, congruous words show a frontal asymmetry only slightly smaller than the temporal one (congruity by A–P by hemisphere, $F(5,330) = 19.18$, $P < 0.0001$).

On the whole, analyses of the mean amplitudes for the congruous and incongruous words between 400 and 600 ms poststimulus show similar effects of congruity and laterality as well as some more opaque higher-order interactions. Thus, the ERPs to incongruous words are more negative than those to congruous words $F(1,66) = 44.54$, $P < 0.0001$) with this difference being somewhat larger for words from the category than the antonym condition (congruity by condition, $F(1,66) = 15.89$, $P < 0.0001$). As in the earlier measurement epoch, the ERPs from right-hemisphere sites are more positive than those from the equivalent left-hemisphere sites, with the asymmetry being more pronounced for congruous than incongruous words (congruity by hemisphere, $F(1,66) = 84.06$, $P < 0.0001$). Examination of the means for the higher-order interactions on normalized mean amplitudes between 400 and 600 ms were not particularly revealing; however, they indicated that for both congruous and incongruous words, (1) ERPs from the frontal sites tend to be more positive with advancing age and (2) the degree of asymmetry interacts with age. Specifically, the ERPs for congruous words are almost symmetric for the individuals in the 60s and 70s whereas the ERPs for incongruous words show a reversal of asymmetry so that by 60s the right hemisphere is more negative than the left. Some of these effects may be due in part to the fact that the latency of the N400 changes with age such that different aspects of the waveform are being measured for a fixed window in the different age groups.

### 3.1. Difference ERPs

#### 3.1.1. Peak and mean amplitudes

The N400 difference waveforms (i.e. the N400 effect) derived from a point-by-point subtraction of the ERPs to congruous words from the ERPs to incongruous words recorded at the lateral parietal sites (Wernicke's and its right hemisphere homolog) for the antonym and category conditions are displayed in Fig. 3. The individual subject difference waves that comprise the grand average difference ERPs for each decade for the right Wernicke's site are shown overlapped in Fig. 4. For all age-groups, the N400 difference wave for both conditions is primarily a monophasic negativity between 200 and 600 ms with a parieto-occipital maximum; some subjects also show a positive-going component after the negativity. The N400 effect is slightly larger over the right than the left hemisphere overall, although the asymmetry is bigger over anterior (frontal, central) than posterior (Wernicke's, occipital) recording sites. Overall, the N400 effect is slightly smaller and peaked somewhat later in the category than opposite conditions. And, finally, there is a small but clear reduction in the amplitude of the N400 effect with advancing age.

These observations based on visual inspection of the data were assessed statistically via an ANOVA with age as a between-subjects variable (20, 30, 40, 50, 60, 70), conditions (antonyms, categories), anterior–posterior dimension (6 levels from frontal to occipital), and hemisphere (left, right) as within-subjects variables; the dependent measure was the mean amplitude of the 100 ms around the peak (50 ms on either side) of the N400 difference wave measured at the right Wernicke's electrode (i.e. where the N400 effect was most reliable and tends to be the largest across studies). As can be seen in Fig. 5, across all ages, the N400 effect is smallest over the front of the head (frontal and anterior sites), largest over the back of the head (Wernicke's and occipital sites), and intermediate in amplitude over the mid-scalp locations (central and temporal sites) (main effect of anterior–posterior, $F(5,330) = 132.34$, $P < 0.0001$).

Similarly, all age groups exhibit a similar lateralization of the peak N400 effect. Specifically, all lateral comparisons across the scalp, with the sole exception of the occiput, showed the right hemisphere to be 1–2 $\mu$V more negative than the homologous left-hemisphere site; there is tendency

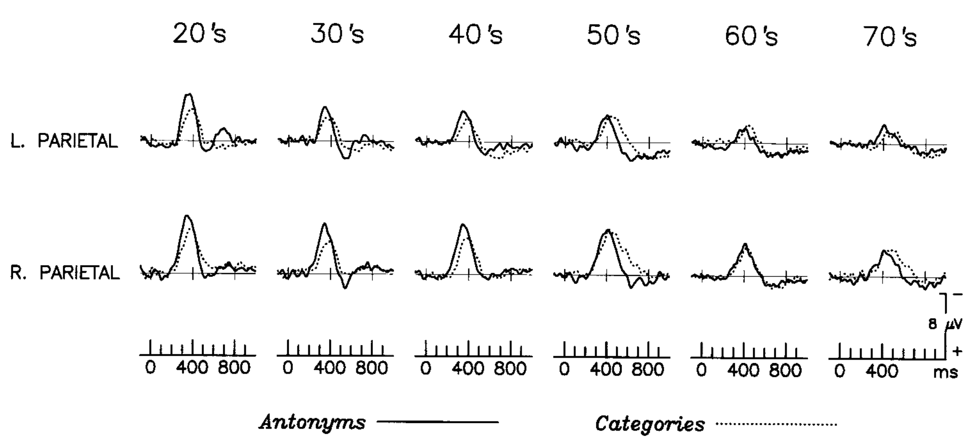


Fig. 3. For each decade, overlapped are the difference ERPs from the opposite or antonym (solid) and category (dashed) conditions over Wernicke's and its right hemisphere homolog. For each condition, the difference ERP is the result of a point-by-point subtraction of the ERP elicited by congruous target words from the ERP elicited by incongruous target words.

for the size of the asymmetry to decrease from front to the back of the head so that by the occiput the N400 effect is bilaterally symmetric (anterior–posterior by hemisphere, $F(5,330) = 61.24$, $P < 0.0001$). Although visual inspection suggested that the slope of the N400 effect from frontal to occipital sites was less steep as a function of advancing age, this was not borne out by a statistically-significant age by electrode interaction.

As can be seen clearly in Fig. 3, the size of the N400 effect decreases systematically with age.[6] The nature of the function relating age to the amplitude was assessed via series of regression analyses performed on peak N400 difference ERP measures separately from all but the frontal recording sites. The scatter diagram of age on peak amplitude of the N400 effect for the left Wernicke's site for the antonym and category conditions is shown in Fig. 6. The regression analysis reveal small but significant correlations between 0.33–0.48 with slopes ranging between 0.04 and 0.07 $\mu$V reduction per year. The correlations, slopes and statistical significance ($P$ values) for the same regression analyses performed on the data from the other recording sites are presented in Table 2.

### *3.1.2. Peak latency*

As can be seen in Fig. 7, the N400 effect (shown for right occipital site) becomes progressively not only smaller but also later with advancing age. Scatter plots of the relationship between the peak latency of the N400 effect measured at the right Wernicke's and age are presented in Fig. 8a,b for the antonym and category conditions, respectively. Note that while the data from men and women are distinguished on the figure, no reliable gender differences were observed. The regression of age on the N400 effect at right Wernicke's reveals a significant ($P < 0.0001$) correlation of between 0.64 and 0.68 for the opposites (antonyms) and categories, respectively. Thus, age accounted for approximately 40–45% of the variance in the amplitude of the N400 effect. The slope of the regression indicated that at right Wernicke's the N400 effect was delayed by approximately 1.8–1.9 ms/year. The correlations and slopes of the regression of age on the peak latency of the N400 effect for all but the two pairs of frontal sites are presented in Table 3. In summary, the correlations range between 0.43 and 0.68 and the slopes between 1.23 and 2.09 ms/year.[7]

A comparison of the regression equations for the opposite (antonym) and category data in Fig. 8a versus Fig. 8b revealed one of the differences between the two conditions; namely, that the effect was delayed by about 20–30 ms for the category condition (see intercept).

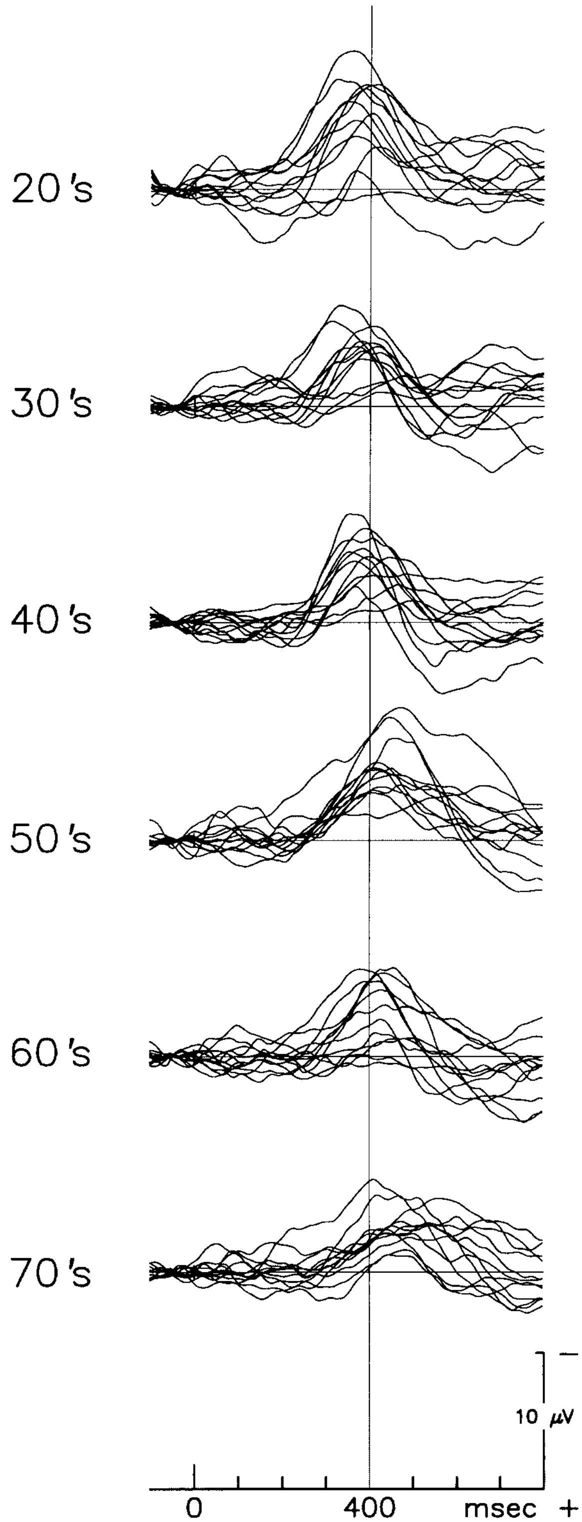


Fig. 4. N400 Difference waves from each of the 12 participants in each decade from over right Wernicke's in the category condition. Two of the 3 subjects with the largest N400 effects in the fifties group also had the fewest years of formal education.

[6] On average, the amplitude of the N400 difference wave for the 50s seems to break the trend, however, this is primarily due to 3 outliers. Further research is needed to determine whether this relates to their having fewer years of formal education.

[7] We also examined the possibility of a curvilinear relationship between the peak latency of the N400 effect and age by fitting orthogonal polynomial regression equations to the data in a stepwise manner. Only the first degree (linear) was significant; adding a curvilinear (quadratic) factor to the linear regression did not increase the percent of variance accounted for significantly.

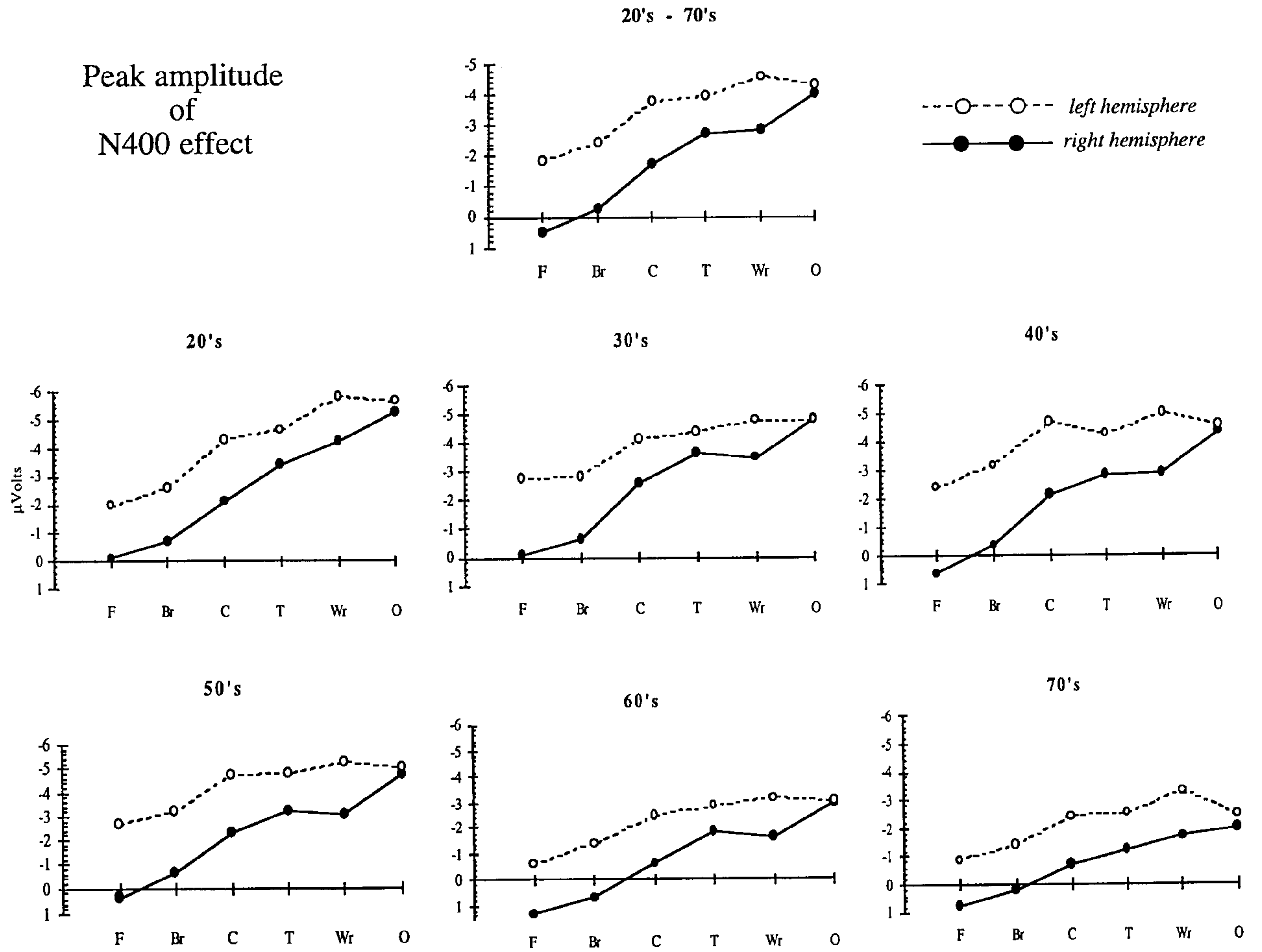


Fig. 5. Mean amplitude of the 100 ms epoch around the peak of the N400 measured in the difference ERP (collapsed over opposite or antonym and category conditions) over frontal (F),Broca's (Br), central (C), posterior temporal (T), Wernicke's (Wr), and occipital (O) sites. The data for the right (dashed) and left (solid) hemispheres are plotted separately. At the top are the measurements collapsed across all age groups. In the remainder, the consistency of the scalp distribution of the N400 effect across age can be assessed as the data are shown for each age group, separately. For the ERPs, negative-going is plotted upward.

### *3.1.3. Onset latency*

The onset latency of the N400 effect was measured in the ERPs from the right Wernicke's site where the effect is generally most reliable. The measurement was based on a fractional peak latency estimate. For each subject this involved first locating the latency of the peak amplitude between 200 and 600 ms post-stimulus onset. From this value, the latency at which 10% of the peak value was reached was calculated (backwards in time). This point in time was then taken as an estimate of the onset latency of the N400 effect in the difference ERP. Overall, the onset latency of the N400 effect at right Wernicke's averaged 268 ms; its onset is about 20 ms later for the ERPs from the category (277 ± 9 ms) than the opposite (259 ± 8 ms) conditions (main effect of condition, $F(1,66) = 2.97$, $P < 0.089$).

As expected, the onset latency of the N400 effect increased significantly with age, being on the average 236 ms in the 20s, 245 ms in the 30s, 254 ms in the 40s, 267 ms in the 50s, 284 ms in the 60s, and 324 ms in the 70s (main effect of age, $F(5,66) = 3.95$, $P < 0.0035$).

## 4. Discussion

The primary purpose of this investigation was to more fully characterize the relationships between normal aging and various parameters of the N400 congruity effect. A few reports have noted a decline in the amplitude and a delay in the latency of the N400 semantic congruity effect in older relative to younger subject groups (Harbin et al., 1984; Gunter et al., 1992, 1996; Woodward et al., 1993; Ford et al., 1996; Schwartz et al., 1996). The present experiment provides a more detailed look at the changes in the amplitude, scalp topography, and timing (onset and duration) of the N400 effect throughout the adult lifespan from 20 to 80 years of age. Our larger aim in so doing is to get a better understanding of the consequences of aging on the

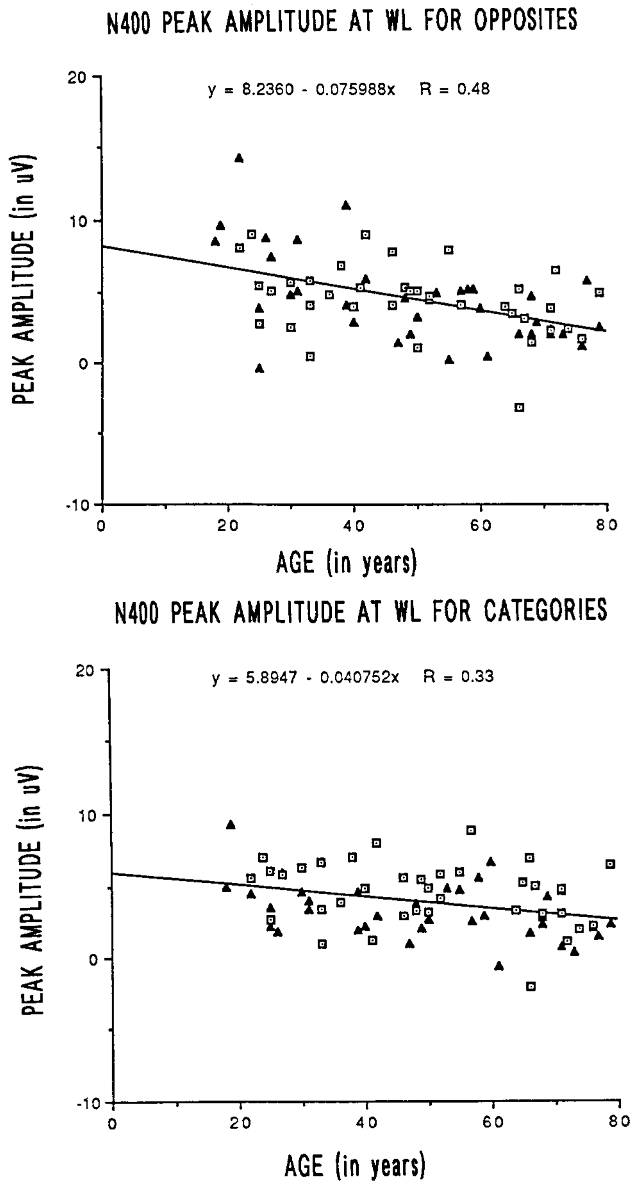


Fig. 6. Scatter diagrams of age regressed on amplitude of the N400 peak measured in the difference ERP from the left Wernicke's site for the (a) opposite and (b) category conditions. Note that the data from the men (colored triangles) and women (open squares) are distinguished, even though there are no significant gender differences and the regression equation is based on all the data.

human brain, on semantic processing and categorization, and thereby on the general mapping between the brain and the psychology of all humans whatever their age.

The present data set shows that a similar negative difference, the 'N400 congruity effect' (derived from a point-by-point subtraction of the congruous ERP from the incongruous ERP) is observed across the adult lifespan. The N400 effect to visually-presented words has been characterized by a slight right posterior distribution; that is, the N400 difference ERP is typically larger over posterior (central, parietal, and occipital sites) than anterior (frontal) regions of the scalp and slightly larger and of longer duration over the right than the left hemisphere. The current results replicate these findings and indicate that neither the anterior–posterior nor the left/right distribution of this N400 effect is affected significantly by normal aging. Across volunteers from all the decades, the N400 effect to these visually-presented words following spoken contexts is largest posteriorly (parietal and occipital sites), intermediate at the central and temporal sites, and smallest in amplitude anteriorly (frontal and anterior temporal sites). Likewise, across all age groups, the N400 effect is slightly larger (and sometimes longer) over the right than the left hemisphere.

Consistent with previous reports on the N400 congruity effect, we did find that its amplitude is diminished with age and its onset latency and peak latency are prolonged with age. Since we observed a delay in the peak latency of the occipital N1 component with age as well, we cannot ignore the possibility that the delay in the N400 is but a downstream consequence of an earlier processing deficit in feature extraction, for example. While this may explain a part of the N400 delay, there are several reasons to believe that the N1 and N400 delays are dissociable and therefore reflect different aspects of the workings of the brain. The correlations between age and the latency of the N400 effect are higher than those of age and the N1. The slope of the regression lines for the N1 and N400 are different. Moreover, other researchers, such as Gunter et al. (1992), also have found a later N400 peak in middle-aged academics without a concomitant increase in N1 latency. Note that their elderly were younger than our oldest subject group, but others also have not generally reported N1 delays that can account for the delay in the N400 congruity effect. In any case, even if the N1 delay were responsible for the N400 delay, it could not readily account for the decreasing amplitude of the N400 effect with age.

Since ERPs provide a psychophysiological measure of brain activity, it is possible to interpret the amplitude reduction and latency delay in the N400 congruity effect with normal aging at both a physiological and a psychological level; these may or may not be related to each other. Physiological brain aging is characterized by various biochemical and structural changes and imbalances among the different neurotransmitters and neuromodulators and second messenger systems directly involved in signal transduction (Fulop and Seres, 1994; Goldman et al., 1994; Gareri et al., 1995; Manaye et al., 1995; Arranz et al., 1996). Some of these changes will undoubtedly impact the pattern of electrical activity recorded at the scalp.

Normal aging is similarly accompanied by structural changes, although there is much controversy as to exactly what they are. Several laboratories have noted small numbers of amyloid plaques and neurofibrillary tangles in the brains of neurologically intact elderly, especially in mesial and inferior temporal lobe regions (e.g. Hof et al., 1996). However, there are those who contend that these are merely precursors to Alzheimer's disease. Similarly, there is little agreement as to whether normal aging is associated with

Table 2

Correlation coefficients (*r*) and slopes of regression of age onto the peak amplitude of the N400 difference ERP

| | Opposites | | | Categories | | |
|---|---|---|---|---|---|---|
| | *r* | slope | *P* | r | Slope | *P* |
| Vertex | 0.45 | 0.096 | 0.001 | 0.33 | 0.060 | 0.005 |
| L. central | 0.38 | 0.053 | 0.001 | 0.32 | 0.032 | 0.007 |
| R. central | 0.36 | 0.052 | 0.002 | 0.09 | 0.012 | n.s. |
| L. post. temporal | 0.47 | 0.064 | 0.001 | 0.34 | 0.040 | 0.003 |
| R. post. temporal | 0.40 | 0.056 | 0.001 | 0.24 | 0.032 | 0.039 |
| L. Wernicke's | 0.48 | 0.076 | 0.001 | 0.33 | 0.041 | 0.004 |
| R. Wernicke's | 0.46 | 0.071 | 0.001 | 0.20 | 0.030 | n.s. |
| L. occipital | 0.50 | 0.079 | 0.001 | 0.34 | 0.047 | 0.004 |
| R. occipital | 0.54 | 0.084 | 0.001 | 0.30 | 0.042 | 0.011 |

neuronal loss or simply shrinkage, and as to the functionality of the atrophied neurons (for review see Goldman et al., 1994). The newer neuroimaging techniques have revealed age-related changes in subcortical white matter that often occur periventricularly and in at least one study, these were correlated with slowing of mental and motor processing (Ylikoski et al., 1993). Since there is evidence for loss of neurons in subcortical nuclei and cortical changes in the neuropil such as dendritic loss and decreased arborization (Flood, 1993; Scheibel, 1996), age-related changes may be related to selective losses of cortical inputs and synaptic organization (Barnes, 1994). Since the ERP is presumably in large part a reflection of the sum of postsynaptic activity of pyramidal cells in the cortical layers, decreased arborization, modified synaptic connectivity, reduced synaptic efficiency, slower transmission, less synchronous activity and less-effective coupling between regions could all conspire to yield smaller and/or later ERP effects.

Intracranial recordings led McCarthy and colleagues (e.g. Nobre et al., 1994; McCarthy et al., 1995) to suggest that the N400 is generated in the anterior fusiform gyrus or parahippocampal and fusiform gyri. As noted above this area does show cell shrinkage and possibly neuronal loss.

While not all physiological changes have cognitive consequences, many do, and some of these are bound to affect semantic memory storage and use as well as language comprehension processes. Across a number of studies we have found that elderly participants are somewhat more perturbed by incongruous statements than are the younger ones. However, we do not find any indication from their behavior (i.e. explicit fit/no-fit judgments) that they found this relatively simple task any more difficult than did our younger participants. And yet, their smaller and later N400 effects implicate age-related changes in the rate and/or efficiency of the semantic-knowledge use during this categorization task. Our conclusion follows from what is known about the factors that influence the amplitude and/or the latency of the N400 component.

As of yet there is no consensus on the functional significance of the N400. Nonetheless, much data show that with language materials, the N400 is sensitive to many of the same factors that influence speed of word recognition, both in and out of context. Pseudowords elicit large N400s whereas orthographically and phonologically illegal non-words elicit no N400 at all; the N400s to real words fall in between depending on the eliciting word's frequency of usage in the language, repetition, lexical and semantic priming contextual constraint). Moreover, N400 amplitude is sensitive to semantic variables, being at one and the same time sensitive to local relations between words and more global contextual factors such as that provided by the buildup of sentential context and/or a title (i.e. integration). N400 amplitude to a word is reduced by a prior repetition, but only if the repeated word has the same meaning as on original presentation; repeating the same lexical form (homograph) but with a different meaning does not reduce N400 amplitude (Besson and Kutas, 1993). N400s to words

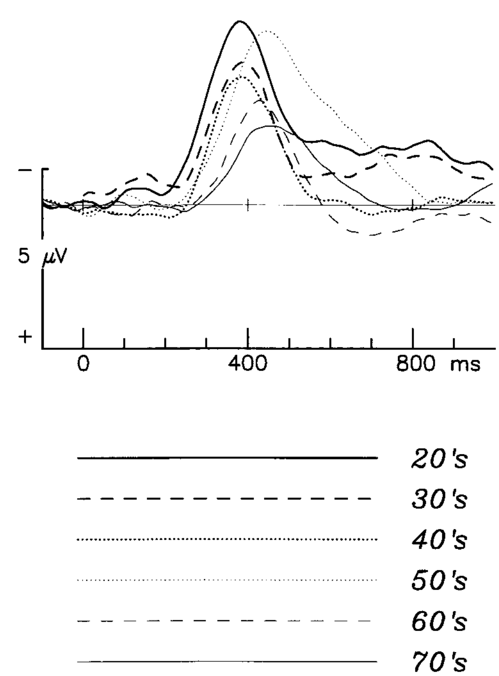


Fig. 7. Grand average difference ERPs derived from the right occipital recordings in the opposite conditions overlapped for all 6 decades ($n$ = 12 per decade).

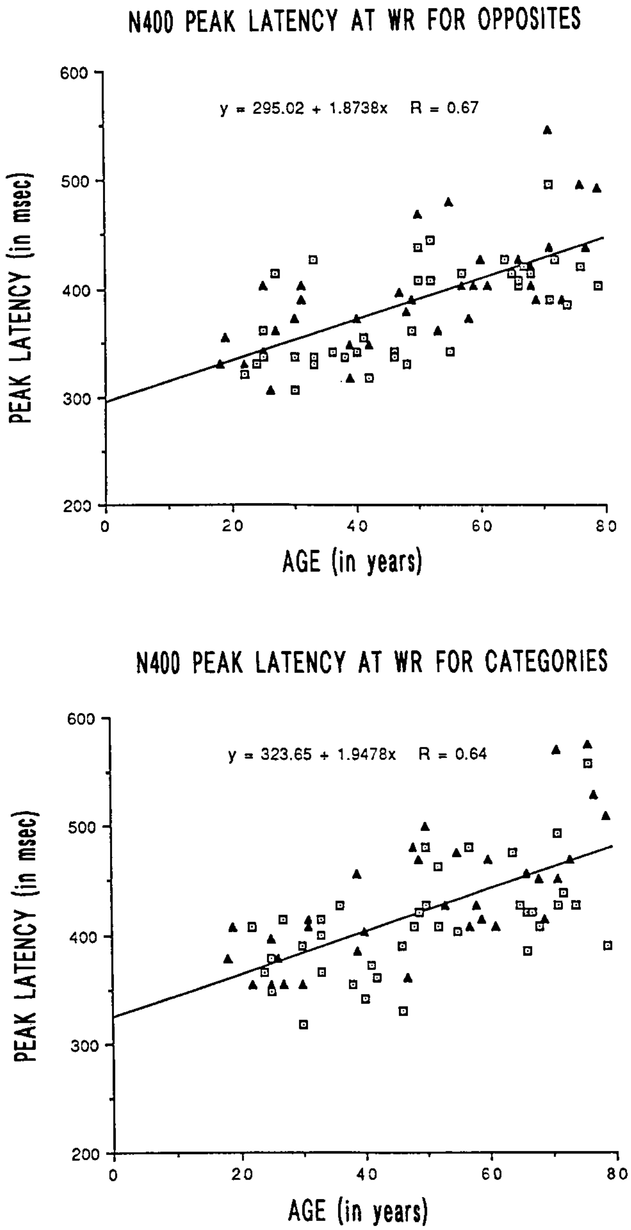


Fig. 8. Scatter diagrams of age regressed on the latency of the N400 peak measured in the difference ERP at the right Wernicke's site in (a) opposite or antonym and (b) category conditions. Data from men (colored triangles) and women (open squares) are marked.

in a list, word pairs or within sentences are reduced in amplitude by the prior occurrence of a semantically related (versus unrelated) word. The amplitude of the N400 to a word within a sentence also may be reduced to the degree that it is constrained by the context even if it is not preceded by lexical associate. Thus, N400 amplitude decreases with the eliciting word's ordinal position in a sentence; it is inversely correlated with close probability. The buildup of context which leads to the expectation of a particular lexical item (or class of such items) also supports the integration mechanisms indexed by the N400 (for review see Kutas and Van Petten, 1994). St. George et al. (1994) showed that N400 amplitudes to words in a text are also reduced by thematic level associations and constraints. During word by word reading of ambiguous paragraphs, the same words in a paragraph with disambiguating title that helped readers to interpret the passage yielded smaller N400s than when no title was given.

In sum, N400 amplitude correlates with a word's predictability (expectancy) within a context. With minimal context, N400 amplitude for real words seems to be driven by word frequency and factors such as concrete/abstractness. However, as context accrues, these variables lose their predictive potency and their effects are overridden, such that the amplitude of the N400 varies primarily as a function of a word's relation to the ongoing semantic context, and thus its ease of integration. The mechanisms of contextual integration must then make use of background knowledge (i.e. semantic memory) during normal comprehension. With all else equal (e.g. years of education, IQ) equal, we might expect 40–60 year olds to have a larger and more elaborate store of knowledge than 20–40 year olds. Such richness can have its benefits but also can take its toll on the speed and efficiency of processing. Expertise, for example, is usually associated with both more efficient chunking and slower retrieval times. The mean latency of retrieval of category exemplars, for instance, is a function of set size; the larger the set, the slower the retrieval times (e.g. Rohrer and Wixted, 1994). In fact, in general the more one knows about an item, the longer it takes to retrieve that information, as evidenced by the so-called 'fan effect'. And, several studies have shown that elderly subjects are more susceptible to the fan effect (Cohen, 1990; Gerard et al., 1991). In general, it appears that there is an age-related increase in interference during retrieval.

By contrast to the variable amplitude of the N400, both its onset and peak latencies are relatively stable across a variety of experimental manipulations. The most effective way of delaying the N400 to date, has been to increase the rate of word presentation (in sentences) to faster than normal reading rate. At a rate of one word every 100 ms (i.e. 10 words/s), the N400 to a semantically-anomalous word at the end of a sentence is delayed by 80–100 ms in college-aged readers

Table 3

Correlation coefficients (*r*) and slopes of regression of age onto the latency of the peak of the N400 difference ERP

| | Opposites | | Categories | |
|---|---|---|---|---|
| | *r* | Slope | *r* | Slope |
| Vertex | 0.54 | 1.54 | 0.63 | 1.92 |
| L. central | 0.43 | 1.17 | 0.56 | 1.80 |
| R. central | 0.61 | 1.75 | 0.61 | 1.82 |
| L. post. temporal | 0.59 | 1.52 | 0.63 | 2.01 |
| R. post. temporal | 0.67 | 1.77 | 0.56 | 1.82 |
| L. Wernicke's | 0.65 | 1.68 | 0.67 | 2.09 |
| R. Wernicke's | 0.68 | 1.87 | 0.64 | 1.95 |
| L. occipital | 0.53 | 1.23 | 0.65 | 1.96 |
| R. occipital | 0.58 | 1.52 | 0.61 | 1.77 |

(Kutas, 1987). The phenomenal experience is first reading most of the words as they come but not really understanding the sentence's meaning followed soon thereafter by comprehension. Within the auditory modality, Van Petten et al. (unpublished data) observed that onset latency of the N400 to semantic anomalies varies with the 'discrepancy point' – that is, when the acoustic input first diverges from expectations. They employed incongruous sentence completions that either diverged from the expected endings at the first phoneme or later (near the isolation point) and found almost 100 ms difference in the latency of the N400; they concluded that the semantic integration (indexed by N400) began before its isolation point (i.e. before sufficient acoustic information had accrued to uniquely identify the word). There is also a slight (10–30 ms) difference in the onset latency of the visual N400 to non-members following a category name versus a non-opposite following an opposite, in some, although not all, studies. A large effect can be seen when the contrast is the N400 effect, but this is primarily due to an earlier positivity to actual opposites than to category members. In fact, category members still show a small but noticeable positivity in this region. This effect is more pronounced in the younger than older subjects, and is much reduced, albeit in the same direction, in the 70 year olds. Perhaps, the opposites yielded larger ERP effects because it is possible to consciously expect and confirm a particular word more quickly in this case as opposed to the much larger set of words in the case of categories (see Becker, 1980; Becker, 1982), but with age individuals are not as efficient in summoning attentional resources to generate explicit predictions (i.e. specific expectations). Again, this could result from a reduced working memory capacity, less efficient inhibitory mechanisms, and slowed processing.

Delay of lexical access in aging is supported by behavioral studies that have found elderly individuals to be slower than younger ones; this pattern holds for lexical decision, pronunciation latency, and other estimates of semantic activation (e.g. Petros et al., 1983; Bowles and Poon, 1985; Howard, 1988; Nebes, 1989). Slower access to semantic memory because it is larger and more interconnected, or due to reduced neural processing speeds, and/or less effective inhibitory mechanisms could all lead to poor integration as indexed by a smaller N400.

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