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Neural Mechanisms underlying Different Degrees of Causal Inference in Processing Chinese Word Pairs

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Abstract:

The present study used ERP technique to uncover the neural mechanisms underlying different degrees of causal inference in processing Chinese word pairs. We asked participants to read and judge the causal relatedness of word pairs with different degrees of causal relation, namely, highly-related, intermediately-related and unrelated causal condition. The results showed that the intermediately-related causal conditions elicited a larger N400 and a smaller late positive component (LPC) than the highly-related causal conditions. These results indicate that processing of intermediately-related causal relation requires more cognitive effort relative to highly-related causal relation, and the causal inference can influence early semantic processing and later integrative processing of an incoming word. The results empirically support the memory-based models of discourse processing generally, at least when readers participate in establishing causal coherence in Chinese word pairs.

Keywords*: Chinese word pairs, Causal inference, ERP, N400, LPC.*

I. INTRODUCTION

Inference, defined as any piece of information not explicitly illustrated in the text [1], is generated based on the text representation and the reader's general world knowledge retrieved from memory, thus filling the gaps between explicitly illustrated and the fully filled-in message intended to express [2]. Causal inference, as a common category of inference, allows the readers to identify how the event or fact in one sentence causally relates to that in another. Consequently, the reader can establish causal coherence by constructing a causally and semantically integrated representation of text.

1.1 The Role of Causal Inference in Processing

Causal inference has been shown to facilitate reading comprehension, as indexed by faster reading times [3-5], faster recognition [6], quicker lexical decision [7] for causally related expressions than causally unrelated ones, or for the cause-effect order (e.g., *virus-epidemic*) than the effect-cause order (e.g.,

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epidemic-virus) [8-11]. Meanwhile, some researchers have tried to uncover the generation of causal inference by exploring reader's brain activation when they are processing sentences and word pairs. For example, scenarios needing the generation of causal inference-bridging inference elicited a smaller N400 effect than those not encouraging such a causal inference-elaborative inference [12]. Such an effect of bridging inference on the generation of causal inference was also explored by Yang et al. [13] as a transient N400 reduction was elicited by the repetition (e.g., *exploded*) and paraphrasing (e.g., *blew up*) of the target word (e.g., *explosion*) than the condition in which a predictive inference is needed (e.g., *…the bomb hit the ground. The explosion…*). Similarly, an N400 reduction was also found in Chinese word pairs with a cause-effect order than with the effect-cause order, indicating that the former has great salience in semantic memory than the latter [11]. Apart from N400, late positive component (LPC) elicited by sentences under the causally related and unrelated conditions was also investigated. Davenport [14] found causally related probes (e.g., *thief*) evoked a reduced N400 and an enhanced LPC than those of causally unrelated probes (e.g., *mouse*) following a short spoken narrative. Similarly, Steele et al. [15] found a reduced N400 and an enhanced LPC elicited by inference-primed probe words relative to unprimed probe in a lexical decision task. These findings revealed that a causal inference can affect earlier semantic processing via facilitation in congruent discourse and later stages of processing of an incoming word in incongruent discourse which triggers pragmatic and integrative processing.

Furthermore, studies also try to uncover the nature of different degrees of causal relatedness. Most of the behavioral studies found that the reading time increased as causal relatedness decreased during sentences reading [3,4,16,17]. However, intermediately-related causal condition was found to require longer reaction times than highly-related and causally unrelated conditions [18], reflecting the generation of inference for the intermediately-related causal conditions. As for ERP experiment, different result patterns were also found in different degrees of causal relation in discourse. For example, Kuperberg et al. [19] found that increasing causal coherence reduced N400 amplitude in a graded trend, indicating that the earliest stages of semantically processing incoming information can be affected by both simple and complex causal inference. However, there was no related P600 effect in their study, different from Burkhardt [20] which found modulations of casual relation on the P600 of target words (e.g., *pistol*) in three types of contexts (e.g., *Yesterday a Ph.D. student was shot / killed / found dead downtown. The press reported that the pistol…*). Given this map, different conclusions were drawn on whether and how causal inference affects the early stage of semantic processing as reflected by N400, or the later stage of semantic integration indexed by LPC/P600, or both.

Regarding previous studies, on the one hand, most of these studies centered on binary contrast between causally related and causally unrelated conditions, and little attention was devoted to the different degrees of causal relation. On the other hand, in terms of methodological concern, the target words used in the word pairs in the previous studies are different, which may lead to differences in experimental results. Since the use of the same target words in each of the graded levels can eliminate the possibility that the results may show unintended differences in the lexical characteristics of the target words [21]. Thus, our study aimed to further investigate the neural mechanisms underlying different degrees of causal inference in processing Chinese word pairs by manipulating the degree of causal relation and keeping the target

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words same in each of the graded levels.

1.2 Theoretical Accounts of Causal Inference

As for the accounts of how causal inference is achieved, since the contexts can range from the single word to the passage [22,23], we consider that a related context and scenario can also be evoked even by word pairs in order to establish causal coherence, and thus we especially focus on the memory-based models of discourse processing to provide explanations. Memory-based models, including the resonance model [24], construction-integration model [25] etc., put emphasis on the bottom-up processing but also allow for bottom-up input to activate more complex contents for processing [14]. The critical mechanism is "resonance" [24] in which incoming information interacts with general world knowledge and previous information automatically, and resonates accordingly based on the degree of match. "Unrestricted" and "dumb" are the two key elements of this resonance process in connection with inferences [26]. Thus, within memory-based models, information can only be obtained through a fast, dumb, and passive activation mechanism. Only when these basic processes fail to generate coherence will the reader engage in slower and deeper inferential processing that requires more cognitive resources [27].

1.3 The Present Study

This study aims to explore the neural mechanisms underlying casual inference in processing Chinese word pairs involving highly-related (e.g., *'daxue - hanleng' / 'heavy snow - cold'*), intermediately-related (e.g., *'mianyi - hanleng' / 'cotton-padded clothes - cold'*) and unrelated (e.g., *'xianyan - hanleng' /'vividness - cold'*) causal condition. Specifically, N400 and LPC are chosen as the indexes, as the former is sensitive to different degrees of causal relations [19], and the latter reflects processes engaged in meaning reanalysis [28] and a further analysis of incoming word in respect of its context and information in the memory [19]. According to the memory-based accounts, it is hypothesized that if a causal inference involves in an initial detection of coherence gap and further analysis to fill in the gap by related real-world knowledge selection, the target words in intermediately-related causal condition should elicit an enhanced N400 than those in highly-related causal condition. Also, in order to perceive the intermediately-related causal condition as a coherent discourse in a later stage, a more complex and inference-driven interpretive process is expected as reflected by LPC.

II. METHODS

2.1 Participants

Twenty-five native Chinese speakers (19 females, average age = 24, range 22-27) from Sichuan International Studies University (Chongqing, Chongqing City) were recruited and received financial rewards for their participation. All had normal or corrected-to-normal vision, and were not taking any psychoactive medication. They were completely unaware of the aim of the experiment and signed the written consent before the formal experiment. Four participants were discarded in offline analysis due to

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their excessive artifacts in EEG recordings.

2.2 Stimuli

This present study manipulated the degrees of causal relatedness across Chinese word pairs (highly-related vs. intermediately-related vs. unrelated causal relation). Forty-eight sets of materials were initially constructed and the sample of materials was shown in TABLE I, each containing three conditions, namely highly-related, intermediately-related, unrelated causal relation. Each item consisted of a word pair containing two-character Chinese phrases, with the first two-character phrase presented as the cause and the second as the effect. The effect (the second phrase) was the same among each set of materials. In the highly-related causal relation condition (e.g., '*queshui - ganhan*' / '*water shortage - drought*'), the second phrase was causally related to the first phrase by a simple inference, as the real-world knowledge needed to establish causal relation can be accessed directly. In the intermediately-related causal relation condition (e.g., '*kusi - ganhan*' / '*wither - drought*'), there was a causal coherence gap initially requiring a more complex inference in order to establish a causal coherence successfully; that is, one must get access to the real-world knowledge that the drought causes plants to wither, and it is not withering of plants that causes drought, but the causal coherence will be established successfully by means of inference from the phenomenon of the withering of plants. In the unrelated causal relation condition (e.g., '*taoqi - ganhan*' /'*mischief - drought*'), cause and effect relation is not in accordance with our logic and real-world knowledge, so participants usually cannot establish causal coherence successfully.

TABLE I. Examples of materials

CONDITIONS	EXAMPLES
HIGHLY-RELATED	*queshui - ganhan*
	water shortage - drought
INTERMEDIATELY-RELATED	*kusi - ganhan*
	wither - drought
CAUSALLY UNRELATED	*taoqi - ganhan*
	mischief- drought

A pretest of causal relatedness rating was conducted to improve experimental materials. In a paper-and-pencil rating task, forty-five undergraduate students from Sichuan International Studies University (35 females, average age = 20, range 19-22) who did not participate in the formal ERP experiment rated the causal relatedness between the first two-character phrase and the second two-character phrase in a 7-point scale (1 = unrelated, 7 = highly-related). The order of the trials was randomized. Word pairs were then kept if the average rating met the following criteria: First, the average rating was above 4 for highly-related causal condition, above 3 for intermediately-related causal condition, and below 3 for causally unrelated condition; second, the mean scores of rating for highly-related causal condition was higher than that for intermediately-related causal condition. Besides, the frequency of word pairs was controlled based on the Sketch Engine. Finally, 90 Chinese word pairs (30 highly-related, 30

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intermediately-related, and 30 causally unrelated) were sieved out as final materials. The mean scores of causal relatedness rating for the highly-related, intermediately-related, and causally unrelated conditions were 6.0 (SD = .46), 4.7 (SD = .50) and 1.2 (SD = .31) respectively, with significant differences among them ($F(2, 52) = 1358.738$, $p < .001$, $\eta^2 = .981$). Meanwhile, the frequency ($F(2, 87) = 2.476$, $p > .08$, $\eta^2 = .054$) and the strokes ($F(2, 87) = .872$, $p > .40$, $\eta^2 = .020$) of priming words in word pairs across three causal conditions did not yield significant differences. The mean word frequency and stroke were 57722.57 (SD = 138001.602) and 15.83 (SD = 3.975) for the highly-related, 11171.77 (SD = 27613.214) and 17.20 (SD = 5.006) for the intermediately-related, and 24580.63 (SD = 32643.771) and 15.87 (SD = 4.674) for the causally unrelated conditions respectively. For the purpose of obtaining stable and reliable ERP results, one third of word pairs were repeated once. Thus, a total of 120 trials (40 highly-related trials, 40 intermediately-related trials, and 40 causally unrelated trials) were used as experimental materials at last.

2.3 Experimental Procedure

Participants sat in a chair in a sound-attenuated room, separating from the experimenter. Each trial began with a 500 ms fixation in the center of the screen, and then the first two-character phrases (S1) were presented. After 500ms, the blank screen appeared for 500 ms. Then the second two-character phrases (S2) appeared and remained until participants made a response. In this task, participants were required to make judgments rapidly about the degree of the causal relatedness between the first two-character phrases (S1) and the second two-character phrases (S2) by pressing one of three keys ("1"-causally unrelated, "2"-intermediately-related, "3"-highly-related) which were counterbalanced across subjects. After a delay of 500ms, the next trail started. With short breaks between blocks, materials were randomly presented in four blocks, each containing thirty trials. Participants were given nine practice trials before the experiment to get familiar with the experiment.

2.4 EEG Recording and Data Analysis

Electroencephalogram (EEG) was continuously recorded (band pass 0.05-100 Hz, sampling rate 1000 Hz) from 32 electrodes held in place on the scalp by an elastic cap, which has a ground electrode on the medial frontal line and references on the left and right mastoid [29]. Vertical and horizontal electro-oculograms were recorded. Electrode impedances were maintained below 5 kΩ.

EEG signals were sampled at 500 Hz and filtered with a band pass of 0.1-30 Hz (24 dB/ octave). The EEGs were re-referenced offline to the average of all electrodes [29]. The ERPs of the second two-character phrases were measured in epochs of 1200 ms, including a 200 ms pre-stimulus baseline. Furthermore, off-line computerized artifact rejection was applied to exclude trials with mean EOG (ocular movements and eye blinks), artifacts produced by amplifier clipping, bursts of electromyographic activity, or peak-to-peak deflections exceeding ±100 μV.

According to the previous ERP studies on causal inference [30, 31], nine representative electrodes were selected as data analysis. Based on overall averages (Fig. 2), a repeated measures ANOVA with the causal

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condition (highly-related, intermediately-related, causally unrelated), hemisphere (left: F3, C3, P3; midline: Fz, Cz, Pz; right: F4, C4, P4) and region (anterior: F3, Fz, F4; central: C3, Cz, C4; posterior: P3, Pz, P4) as repeated factors was conducted on the mean amplitude of 360-500 ms and 500-800 ms. Greenhouse-Geisser corrections were applied when needed.

III. RESULTS

3.1 Behavioral Results

In TABLE II, participants responded differently to different types of linguistic stimuli. The results showed a significant main effect of the causal conditions for the causal relatedness judgment ($F(2, 40) = 804.502$, $p < .001$, $\eta^2 = .976$). It revealed that the significant differences were found between the highly-related and the intermediately-related causal condition ($F(1, 20) = 68.491$, $p < .001$, $\eta^2 = .774$), and between the intermediately-related and the causally unrelated condition ($F(1, 20) = 702.112$, $p < .001$, $\eta^2 = .972$), with the former all judged more causally related than the latter. Meanwhile, the results of RTs revealed that the main effect of causal conditions also reached significance ($F(2, 40) = 18.469$, $p < .001$, $\eta^2 = .480$). Further analysis indicated that participants reacted longer in the intermediately-related causal condition than in the highly-related causal condition ($F(1, 20) = 17.801$, $p < .001$, $\eta^2 = .471$), but shorter in the causally unrelated condition compared with the highly-related causal condition ($F(1, 20) = 6.481$, $p < .02$, $\eta^2 = .245$).

TABLE II. Means and standard deviations of the causal relatedness rating and RTs

	HIGHLY-RELATED	INTERMEDIATELY-RELATED	CAUSALLY UNRELATED
RATING	2.9 (.12)	2.4 (.24)	1.0 (.06)
RTS (MILLISECONDS)	1336.47 (479.23)	1652.72 (593.36)	1107.10 (237.36)

3.2 Electrophysiological Data

3.2.1 360-500 ms

In this time window, there existed a significant main effect of causal condition ($F(2, 40) = 3.450$, $p < .05$, $\eta^2 = .147$) and a significant interaction of causal condition × region× hemisphere ($F(8,160) = 4.752$, $p < .001$, $\eta^2 = .192$). Further analyses revealed significant effects of causal condition at posterior areas ($F(2, 19) = 10.170$, $p < .002$, $\eta^2 = .517$), midline sites ($F(2, 19) = 3.747$, $p < .05$, $\eta^2 = .283$) and right sites ($F(2, 19) = 8.186$, $p < .004$, $\eta^2 = .463$), showing that the amplitudes of N400 elicited by the intermediately-related causal condition fell in between the causally unrelated condition and the highly-related causal condition which was the smallest (Fig. 2).

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3.2.2 500-800 ms

There existed no significant main effect of causal condition, while a significant interaction of causal condition× region× hemisphere ($F(8, 160) = 2.293$, $p < .03$, $\eta^2 = .103$) was observed. Further analysis revealed that the difference among causal conditions mainly at posterior areas ($F(2, 19) = 4.478$, $p < .03$, $\eta^2 = .320$), midline sites ($F(2, 19) = 3.967$, $p < .04$, $\eta^2 = .295$) and right sites ($F(2, 19) = 4.116$, $p < .04$, $\eta^2 = .302$). The intermediately-related causal condition evoked smaller late positive amplitudes than the highly-related causal condition at posterior areas ($F(1, 20) = 5.852$, $p < .03$, $\eta^2 = .226$) and right sites ($F(1, 20) = 5.615$, $p < .03$, $\eta^2 = .219$) (Fig. 2).

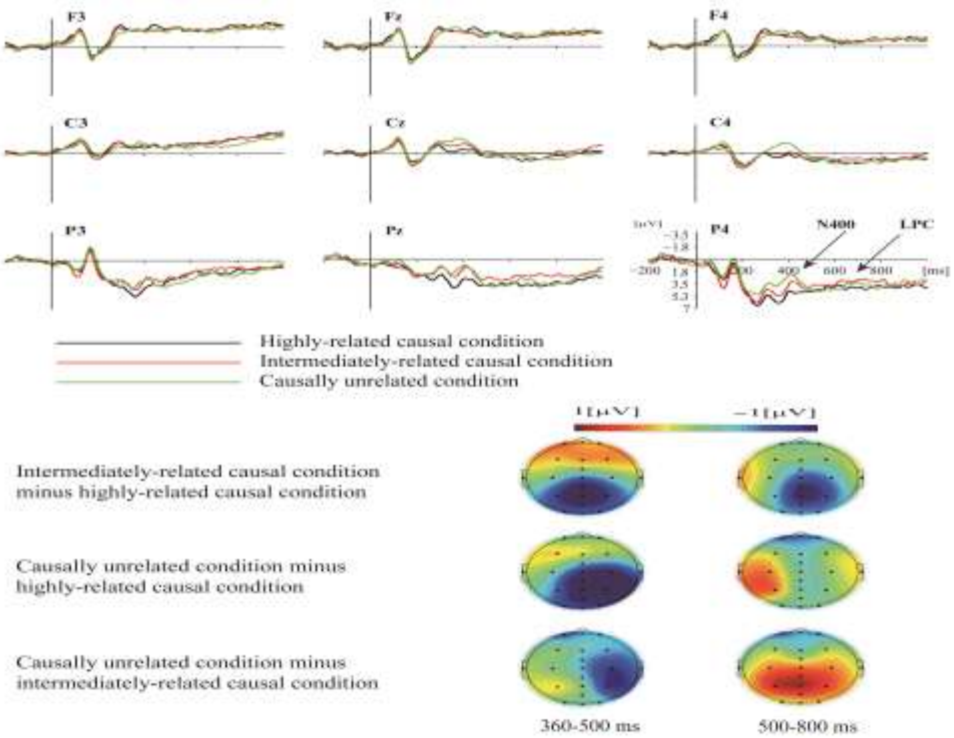

Fig. 2 Top: Grand average ERPs of the target words for three different causal conditions. Bottom: Topographic maps for difference waves of the target words in three different causal conditions in the time windows of 360-500 ms and 500-800 ms.

IV. DISCUSSION

The present study examined the neural mechanisms of processing different degrees of causal inference in Chinese word pairs during online comprehension employing ERP technique. Constructed and presented in cause-effect order, the target words in different degrees of causal relatedness have been discovered to elicit different N400 and LPC. The causally unrelated condition evoked the largest N400 effect, then the intermediately-related causal condition and the highly-related causal condition. However, the intermediately-related causal condition evoked smaller LPC amplitudes than the highly-related causal

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condition. In general, the results indicate that causal inference affects the processing of Chinese word pairs from early semantic processing of incoming word indexed by the N400 to later integrative processing indexed by LPC, generally supporting memory-based models, at least in Chinese word pairs with different degrees of causal relatedness.

4.1 Neural Mechanisms of Processing Chinese Word Pairs with Different Degrees of Causal Inference

Causal inference can affect the early stage of semantic processing of Chinese word pairs by detecting the breaks of causal coherence. In the current study, a smaller N400 was observed in the highly-related causal condition compared with the intermediately-related causal condition and causally unrelated condition, which was consistent with previous studies [11-15,19] that also reported similar result patterns when ERPs of establishing causal coherence were examined across sentences and word pairs. N400 is sensitive to semantic relations [32], and the strength of causal relatedness with reduced N400 amplitude in a graded trend by increasing causal coherence [19] and its amplitude is inversely proportional to the predictability of a stimulus in view of its context [33]. Thus, the result showed that when the second two-character phrases (S2: e.g., *ganhan / drought*) following the first two-character phrases (S1: e.g., *kusi / wither*) were presented in the intermediately-related word pairs, readers were immediately sensitive to coherence breaks during comprehension, and a larger N400 was evoked due to the break of causal inference contrasted to the highly-related causal condition. The break of causal inference leads to an effort to suppress the inference, which is consistent with Davenport and Coulson's [34] findings that the unexpected incoming information makes a challenge to the prediction earlier processed in participant's mind. In the present study, the target words in the intermediately-related condition lack a direct causal link with the priming word, incurring higher processing cost.

Meanwhile, more complex integrative processing is needed to establish causal inference at the later stage. A smaller LPC was elicited by intermediately-related causal condition compared with highly-related causal condition. The results are similar to the results of Davenport [14] and Steele et al. [15] that causal unrelated conditions elicited smaller LPC than causal related conditions. The posterior LPC is similar to P3b which has been suggested to reflect the association with context maintenance [35] or memory updating [36], and smaller LPC was elicited with larger memory loads and more complex mental activity [35] and more complex inference-driven integration of information [37]. Compared with highly-related causal condition, intermediately-related causal condition requires participants not only to maintain activated semantic information online in order to integrate with incoming content, but also to carry out the task of causal relatedness judgment. As a result, intermediately-related causal condition evoked smaller LPC than highly causally related condition. Similarly, the smaller LPC in the present study may reflect more complex processes of inference-driven interpretation.

Furthermore, smaller LPC has been found in some single-word priming experiments [38, 39] where participants needed to target at the semantic content of the word, but not in other experiments that required participants to pay less attention to the meaning such as using a lexical decision task [40]. Deeper processing may encourage conscious reflection on prime-target relatedness, resulting in attempts to

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construct semantic relationships between priming words and less related target words indexed by a smaller LPC. Similarly, in the current study, the smaller LPC occurred for word pairs in which the causal relation of the words needed further interpretation in order to arrive at a coherent causal relation.

However, the patterns of N400 and LPC in the present study are partially inconsistent with those of previous studies, which can be explained by different experimental paradigms, especially different manipulation of specific and detailed context affecting later stage of causal relation integration. For example, the present results are different from those of Burkhardt [20] that only found that P600 modulation were associated with conditions requiring complex causal bridging inferences, and the difference may be caused by different task and the effect of context explained by Kuperberg et al. [19]. In current study, participants' task is to make a casual relatedness judgment explicitly, while a comprehension question task which is used to probe the participants' attention is adopted in Burkhardt [20], and the former requires a relatively high standard of coherence. Meanwhile, context used in the present study consists of a Chinese word pair which provides less detailed and sufficient context relative to the sentence-level condition [19,20], and thus more efforts are needed to generate coherent causal relation at the later stage reflected by the LPC effect after the break of causal coherence at the initial stage in the intermediately-related causal condition. Furthermore, the absence of specific context may be a possible reason for the difference of result between the present study and Kuperberg et al. [19], which only found the N400 effect, although both of them have the similar three types of causal relations and experimental task.

4.2 The Memory-based Processing of Chinese Word Pairs with Different Degrees of Causal Inference

The current study, especially evidence of N400 and LPC obtained from the experiment, potentially support the assumption of the memory-based models [24,25] in the processing Chinese word pairs with different degrees of causal inference. These memory-based models pay attention to the information implicitly activated from the memory in the process of coherence establishment [24]. The critical mechanism in memory-based processing is resonance, which is autonomous, unrestricted and dumb, and that concepts from earlier information and general world knowledge resonate with the input depend on the degree of match. Memory-based models contain several models that share the common critical mechanism of discourse processing. For example, construction-integration model [25] suggests that a fundamental construction-plus-integration process is usually sufficient for comprehension. In other words, the underlying mechanism of comprehension is that concepts from earlier content and world knowledge implicitly resonate with the incoming input with a fast and easy feature matching, and that the readers engage in "a slower, classical inference engine" [41] only when the basic and automatic process fails.

In the present study, the causal relation in highly-related causal condition has a better match and thus provides sufficient explanation for causal relation, as indicated by a smaller N400, which is a memory-based ERP component reflecting the retrieval of information stored within semantic memory [42]. However, when causal coherence breaks occur in intermediately-related causal condition, a causal inference will be required since the comprehension of the target word requires to bridge the coherence

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break, and then additional processes takes place, as reflected by a smaller LPC which is a late effect recalling the prediction based on the memory-based framework. This prediction is that an extended, strategic pragmatic process can be triggered by a break in discourse coherence caused by the probe word which fails to fill the causal coherence gap [14]. More specifically, the first word created a scenario that did not directly cause the target scenario in the intermediately-related causal condition, resulting in a causal coherence gap occurring at the initial stage. In other words, there is an incongruence between the causal relation based on the structure of word pairs and causal relation established by the generally world knowledge. Therefore, the establishment of the causal coherence in the intermediately-related causal condition requires additional processes to recruit concepts from general world knowledge and earlier reading information in order to provide sufficient explanation for the establishment of causal coherence. Specifically, the intermediately-related causal condition expresses an epistemic causal relation that the consequence (e.g., *wither*) is interpreted as the cause of the conclusion about the cause (e.g., *drought*) [43]. Thus, they require more efforts and resources reflected in slower reading times and larger N400 and smaller LPC.

Therefore, the increased N400 amplitude related to intermediately-related causal condition relative to highly-related causal condition could reflect the initial explicit semantic anomaly at the early stage, while the decreased late positive component could manifest a further attempt to search for the implicit causal relation in order to gain coherent causal relation, which supports the memory-based models of discourse processing generally.

V. CONCLUSION

The present study examined the neural mechanisms of processing different degrees of causal inference in Chinese word pairs by conducting an ERP experiment. The differences in N400 and LPC among different causal conditions show that the processing of intermediately-related causal relation requires more cognitive efforts than that of highly-related causal relation. Also, causal inference in Chinese word pairs influences the early semantic processing and later integrative processing of an incoming word, at least when readers participate in the establishment of causal coherence. Further, this study generally supports the memory-based models of discourse processing.

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