Heliyon 9 (2023) e19736

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Chinese holistic processing: Evidence from cognitive mental architecture using Systems Factorial Technology

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ARTICLE INFO

Keywords:
Holistic perception
Mental architecture
Chinese characters processing
Systems Factorial Technology

ABSTRACT

Previous research has presented conflicting evidence regarding whether Chinese characters are processed holistically. In past work, we applied Systems Factorial Technology (SFT) and discovered that native Chinese speakers exhibited limited capacity when processing characters and words. To pinpoint the source of this limitation, our current research delved further into the mental architecture involved in processing Chinese characters and English words, taking into consideration information from each component. In our current study, participants were directed to make the same/different judgments on characters/words presented sequentially. Our results indicated that participants utilized a parallel self-terminating strategy when both or neither of the left/right components differed (Experiment 1). Faced with the decisional uncertainty that either the left/right component would also differ, most participants processed with a parallel exhaustive architecture, while a few exhibited the coactive architecture (Experiment 2). Taken together, our work provides evidence that in word/character perception, there is weak holistic processing (parallel self-terminating processing) when partial information is sufficient for the decision; robust holistic processing (coactive or parallel exhaustive processing) occurs under decisional uncertainty. Our findings underscore the significant role that the task and presentation context play in visual word processing.

1. Introduction

Holistic or "whole unit" processing is considered a marker of perceptual expertise [1]. It has been observed in the visual identification of faces [2], cars [3], gestalt line patterns [4], and English words [5]. Traditionally, holistic processing has been diagnosed as a failure of selective attention [1]. For example, in a composite-face paradigm, participants categorize faces using one face-half (e.g., the top half) while ignoring the other (e.g., the bottom half). Holistic processing is determined by the ensuing congruency effects (c.f., [6])

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https://doi.org/10.1016/j.heliyon.2023.e19736
Received 17 January 2023; Received in revised form 27 August 2023; Accepted 31 August 2023
Available online 7 September 2023
2405-8440/

such that performance is facilitated by facial congruency and impeded by facial incongruency, a phenomenon suggesting participants cannot selectively ignore the irrelevant face-half (e.g., Refs. [7,8]).

Using the diagnostics provided by failures in selective attention, [9] implemented a composite task for recognizing Chinese characters among native and non-native Chinese speakers. In their task, participants were required to attend to either the top or bottom half of a Chinese character (e.g., congruent same: "盟" – "盟"; congruent different: "架" – "吾") to make a same/different judgment. Contrary to expectations, Hsiao and Cottrell reported that novice (non-native) Chinese speakers processed characters more holistically than expert (native) Chinese speakers. Experts also demonstrated a strong preference for using the left side of the chimeric character to determine matches. Likewise, [10] found that proficient Chinese writers perceived characters less holistically than writers and novices with less experience in Chinese. These studies suggest that writing and reading experience can lead to the less holistic, part-based processing of Chinese characters and a left-side bias.

Using a composite character task (à la., [9]), [11] found conflicting results, observing holistic processing for both novice and expert Chinese speakers. They theorized that both experiences in processing and inefficiency in decomposing characters would lead to holistic processing for experts and novices, respectively. [12] extended this work, finding that expert holistic word recognition improved when Chinese characters were presented in the familiar upright orientation. This suggests that holistic processing depends on the broader visual context of a character or word, not just its visual features, and that processing may change under different conditions.

In everyday life, Chinese speakers may naturally separate character features into discernible components [13] or group features into configural information [14]. However, the configural tasks described so far have required participants to focus on only part of a word or character when deciding. In terms of processing architecture, this is tantamount to confusing a holistic or coactive system – a unique case of parallel processing where feature information is gathered to reach a single decision – with a parallel self-terminating system (i.e., where multiple features are processed but only one feature is used to reach a decision). Fortunately, diagnosing issues of stopping rule and processing architecture is the purview of Systems Factorial Technology (SFT; [15,16]).

[17] employed SFT to assess the other-race effect, which refers to the phenomenon that it is more difficult to discriminate faces from other ethnic and racial groups. SFT analysis showed that own-race faces were processed using a holistic or parallel processing architecture, while other-race faces were processed using a sequential "serial" self-terminating strategy. It may be that previously conflicting results in Chinese word and character processing reflect a similar change in processing architecture (coactive, parallel, or serial), stopping rule (self-terminating or exhaustive), or both.

Together, most research in holistic Chinese character processing has employed the composite paradigm with conflicting results. Holistic processing is either exclusively the domain of novices (e.g., Ref. [9]) or novices and experts (e.g., Ref. [11]), and no study has considered whether decisions are made before the completed processing of a word or character. Our previous related work examined the processing efficiency of Chinese characters and English words [18]. The results indicate that processing efficiency violates the assumption that character components are processed independently and in parallel. Here, we extend these implications to support a holistic account of character processing that could not be examined by the divided attention paradigm (e.g., Refs. [9,11]) using the framework of SFT.

SFT is a nonparametric, model-based statistical framework that categorizes cognitive systems with multiple information processing channels. It operates on the assumption that the cognitive system is an information-processing black box that accepts two or more channels as inputs and produces a response as output after some time [19]. Specifically, the character or word function components are the inputs, and the output is the response to the same or different judgment in our study.

SFT discusses four critical qualitative properties of the information processing characteristics: *mental architecture*, *stopping rule*, *stochastic (in)dependence*, and *workload capacity*. Detailed descriptions of these processing characteristics can be found in the supplementary materials and other related prior works (e.g., Refs. [17,20,21]). In brief, *architecture* differentiates whether participants process component characters simultaneously (parallel) or sequentially (serial). The *stopping rule* refers to the distinction between participants using only one component to make the judgments (self-terminating), or both (exhaustive). To investigate these two characteristics, Experiment 1 employed the same/different judgment in which participants were instructed to judge whether two sequentially presented characters/words were the same or different. Experiment 2 introduced more decisional uncertainty by allowing the comparable stimuli's left or right to differ, thereby compelling participants not to rely on a single component when deciding. We expect that by such implementation, we can untangle the processing puzzle left by the previous studies (e.g., Refs. [9,11]).

2. Experiment 1

2.1. Methods

2.1.1. Participants

Eleven university students[1] with normal or corrected-to-normal vision (M_{age} = 23.82 years, SD_{age} = 2.82, Female = 6) from the National Cheng Kung University volunteered to participate in Experiment 1. All participants were native Chinese speakers and reported that English was their second language. Participants were provided the signed informed consent that the Institutional Review Board approved at the Department of Psychology, National Cheng Kung University (protocol code: 1062-3). Participants received NTD 120 (approximately $4) per hour for participation in the task. Four participants were excluded from the final data analysis due to their

[1] The small number of participants was decided to be comparable with previous SFT studies (e.g., Refs. [17,19]) to examine individual participant-level performance over a large number of observations (c.f., [36]).

low accuracy performance (not within the 3.5 SD of the group), leaving data from seven participants for analysis.

2.1.2. Materials

The experiment was programmed using MATLAB R2013a. The stimuli of characters and words were presented using the Microsoft Jheng-Hei bold font and Times New Roman bold font, respectively. The stimuli subtended $2.27^\circ \times 2.40^\circ$ visual angle. The stimuli were presented on a 19-inch CRT monitor with a resolution of 1024×768 pixels and a refresh rate of 85 Hz. Participants viewed the screen at a distance of 60 cm.

2.1.3. Design

Consistent with our previous study [18], we used *character/word, pseudo-character/word,* and *non-character/words* to examine the influence of experience on holistic processing.[2] For our participants with Chinese as the first language and English as the second language, our study comprised a 2 (language condition: English/Chinese) $\times$ 3 (experience level: character/word, pseudo-character/word, non-character/word) $\times$ 2 (structural type: same/different) within-subjects factorial design (Table 1) to investigate the processing mental architecture of both Chinese and English. Specifically, the term "structural type" refers to whether stimuli were compared to themselves (resulting in the response "yes, same") or to a different stimulus ("no, different"). With the implementation of the same/different structural type, we can, therefore, explore whether participants relied on the single component or both components to make the sameness judgments.

To further identify the properties of architecture and stopping rule jointly, it is necessary to selectively influence the rate of information processing in each channel using different salience manipulations within the framework of SFT accordingly. The processing rate for one of the two information channels may be lowered (slowed) by selectively adding noise. Manipulating information channels this way gives rise to four salience combinations (Table 2).[3]

2.1.4. Procedure

Participants completed eight 1-h experimental sessions, with no more than two sessions per day and with sessions evenly divided between English and Chinese stimuli. Each session commenced with 24 practice trials, followed by five blocks of 120 trials (600 trials per session, 2400 trials per language condition). In total, participants completed 100 trials per factorial combination of language type (2: English, Chinese), experience level (3: character, pseudo, non-word), structural type (2: same, different), and salience combination (4: HH, HL, LH, LL), totaling 4800 trials.

Fig. 1 indicates the basic trial procedure. Each trial started with a cross in the center of the screen for 1000 ms. Then, the study stimulus was presented for 400 ms, followed by a mask presented for 1000 ms. After that, participants were instructed to respond to whether the presented study stimulus and test stimulus were the same or different by clicking the mouse ("yes": left button; "no": left button) as quickly and accurately as possible. The inter-trial interval was 500 ms.

2.1.5. Analysis

The measures of mental architecture and stopping rule, the *mean interaction contrast* (MIC), and *survivor interaction contrast* (SIC) are calculated using the mean and RT distributions of target salience combinations within the redundant-target condition, where either feature may terminate in a correct response. The MIC is thus expressed as:

$$\mathrm{MIC} = \left[\overline{RT}_{(\mathrm{L,L})} - \overline{RT}_{(\mathrm{L,H})}\right] - \left[\overline{RT}_{(\mathrm{H,L})} - \overline{RT}_{(\mathrm{H,H})}\right],$$

where $\overline{RT}$ represents the mean RT of one of the redundant-target conditions. The two subscripts refer to each salience combination, with L and H referring to low salience and high salience, respectively. A zero MIC indicates a linear addictive relationship between two processes and a serial processing architecture. By contrast, a parallel exhaustive processing model leads to a negative MIC, while a parallel self-terminating or coactive processing model exhibits a positive MIC.

The SIC provides a distributional form of the MIC and calculates an interaction contrast of the salience survivor functions – the cumulative probability that a response has not been made by time t – and is expressed as:

$$\mathrm{SIC}(t) = \left[\mathrm{S}_{(\mathrm{L,L})}(t) - \mathrm{S}_{(\mathrm{L,H})}(t)\right] - \left[\mathrm{S}_{(\mathrm{H,L})}(t) - \mathrm{S}_{(\mathrm{H,H})}(t)\right],$$

where S(t) refers to the survivor function of one of the redundant-target conditions. The resulting SIC function generates unique SIC functions for each combination of mental architecture and stopping rule. As depicted in Fig. 2, coactive signatures closely resemble serial exhaustive (Serial-AND) signatures (a first-negative-then-positive SIC function). However, they can be differentiated by their positive mass (i.e., MIC > 0), while the serial exhaustive processing has approximately identical negative and positive areas under the curve. Besides that, the serial, self-terminating (Serial-OR) processing exhibits flat SIC functions equal to zero for all the time *t*. By contrast, parallel self-terminating (Parrallel-OR) and parallel, exhaustive (Parrallel-AND) processings exhibit all positive and negative

[2] A detailed description of pseudo-characters and non-characters can be found in our previous study [18]. Put simply, a pseudo-character is created by replacing a radical while still adhering to the positional regularity rules of Chinese characters, whereas a non-character is created by violating these rules.

[3] Selective influence is determined by the high salience manipulation, resulting in a faster rate of processing than the low salience condition (i.e., $RT_{HH} < RT_{HL}$, $RT_{LH} < RT_{LL}$), which is known as stochastic dominance [37].

Table 1
Full set of stimuli used in Experiment 1.

	Type	Stimuli	
		Same	Different
Chinese	Character	目青	言登
	Pseudo	彳 召	扌 頁
	Non	力糸	斤車
English	Word	crew	stop
	Pseudo	lerb	namf
	Non	rlkf	vtjk

Notes. In the “different” comparison scenario, the left and right components differed.

Table 2
The salience manipulation for example stimuli in Experiment 1
Note. H: High salience manipulation, L: Low salience manipulation.

Right / Left	Same H	Same L	Different H	Different L
H	HH 	HL 	HH 	HL 
L	LH 	LL 	LH 	LL 

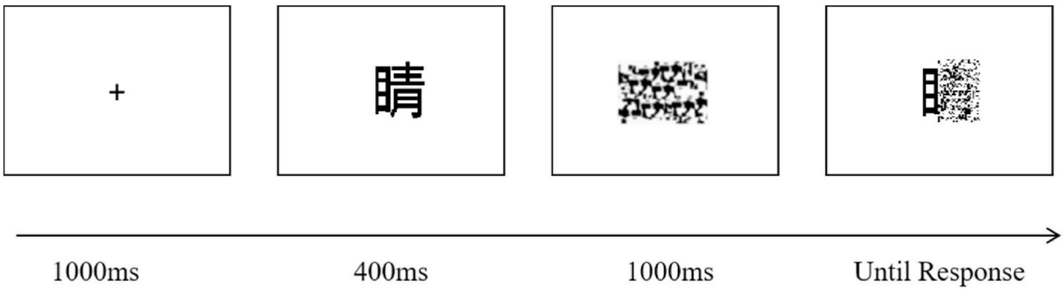

Fig. 1. The procedure of a trial, which displays an example trial from the HL saliency combination condition.

SIC functions, respectively.

2.2. Results

Participants’ responses within the range of 150 ms and 1500 ms were included for further analysis. JASP [22],[4] was used for repeated-measures ANOVA analyses for participants’ responses to sameness judgments. In addition, we used Greenhouse-Geisser for sphericity correction and Bonferroni corrections for the post hoc analyses. The *SFT* package [23] was employed in R [24] for MIC and SIC analyses. Only corrected responses were included for RTs and mental architecture/stopping rule analyses.

[4] Character/word processing was initially analyzed with structural type (same or different) as a main effect, however, this did not fundamentally change the reported results. We report the ANOVA without structural type for simplicity here. Rather, we include structural type as a main effect to explore the effect of stopping rule.

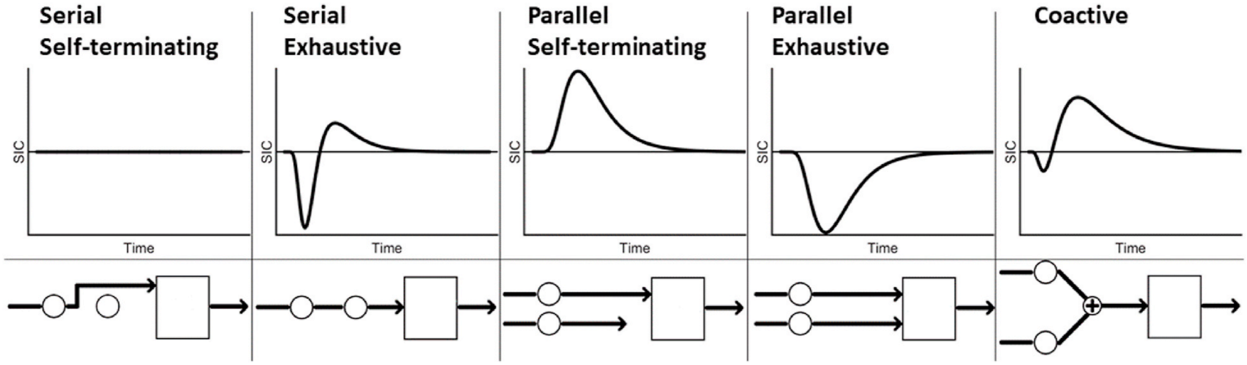

Fig. 2. Possible combinations of processing two sources of information diagrammed (bottom) along with the corresponding predicted SIC shape (top). In the SIC shape image (top), the flat, light gray lines represent SIC(t) = 0.

2.2.1. Accuracy

Fig. 3 illustrates mean accuracy across the different saliency and experience level combinations. Across both language conditions, participants exhibited the lowest performance in the LL saliency condition, Chinese ($M = 0.92$, $SD = 0.06$) and English ($M = 0.92$, $SD = 0.08$). More specifically, within the LL saliency condition, participants displayed less accuracy for non-character/word compared to pseudo-character/word and word/characters (Chinese: $M_{character} = 0.93$, $SD = 0.05$; $M_{pseudo} = 0.93$, $SD = 0.05$; $M_{non} = 0.90$, $SD = 0.08$; English: $M_{word} = 0.95$, $SD = 0.04$; $M_{pseudo} = 0.95$, $SD = 0.05$; $M_{non} = 0.90$, $SD = 0.08$).

The repeated-measures ANOVA on accuracy indicated a significant main effect of saliency, $F(1.02, 6.12) = 9.65$, $p = .02$, $\eta_p^2 = 0.62$. Compared to responses under the LL saliency condition, participants were significantly more accurate when responding to HH ($t(41) = 4.60$, $p = .001$, $d = 1.90$), HL ($t(41) = 4.23$, $p = .003$, $d = 1.75$), and LH conditions ($t(41) = 4.30$, $p = .003$, $d = 1.77$). Additionally, a significant interaction was found between experience level and saliency, $F\ (1.53, 9.17) = 6.61$, $p = .02$, $\eta_p^2 = 0.52$. Post-hoc analysis indicated that in the non-word/character comparisons, the LL condition resulted in lower accuracy compared to HH ($t(13) = 6.33$, $p < .001$, $d = 2.88$), HL ($t(13) = 6.27$, $p < .001$, $d = 2.85$), and LH conditions ($t(13) = 5.57$, $p < .001$, $d = 2.54$). However, this difference was not found in the word/character or pseudo-word/character comparisons.

2.2.2. RT

Fig. 4 displays the mean RT for different saliency and experience level combinations segmented by language conditions. Our results observed no speed-accuracy trade-off; higher accuracy in the HH, HL, LH, and LL combinations depicted in Fig. 2 did not correspond with slower RTs. Participants responded with the slowest RTs in the LL condition, both in Chinese ($M = 644.50$, $SD = 93.98$) and English ($M = 638.40$, $SD = 101.61$).

The repeated measure ANOVA indicated a significant main effect of experience level ($F(2,12) = 20.06$, $p < .001$, $\eta_p^2 = 0.77$).

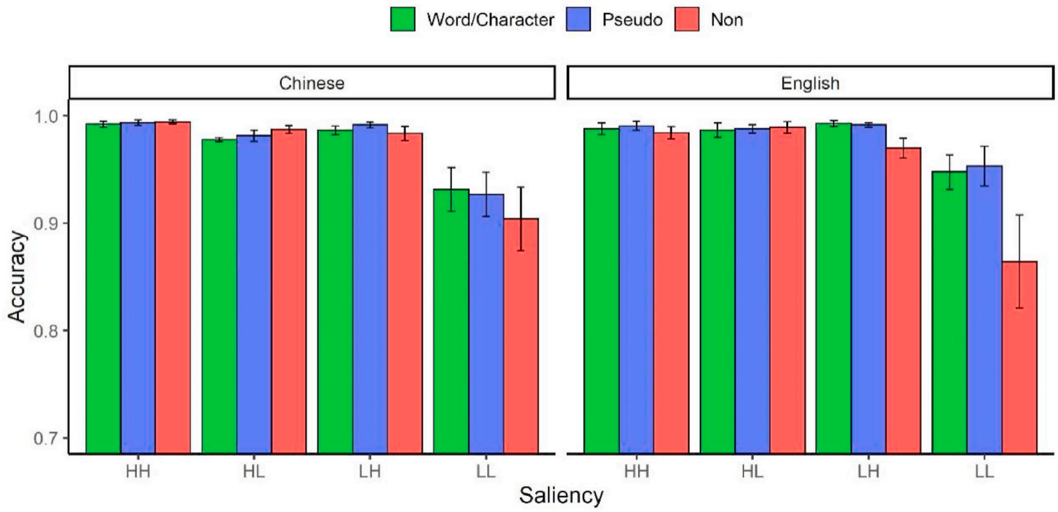

Fig. 3. Mean Accuracy across saliency (High-High, High-Low, Low-High, and Low-Low) and experience level for Chinese (left panel) and English (right panel) comparisons. Error bars indicate ± one standard error within each group.

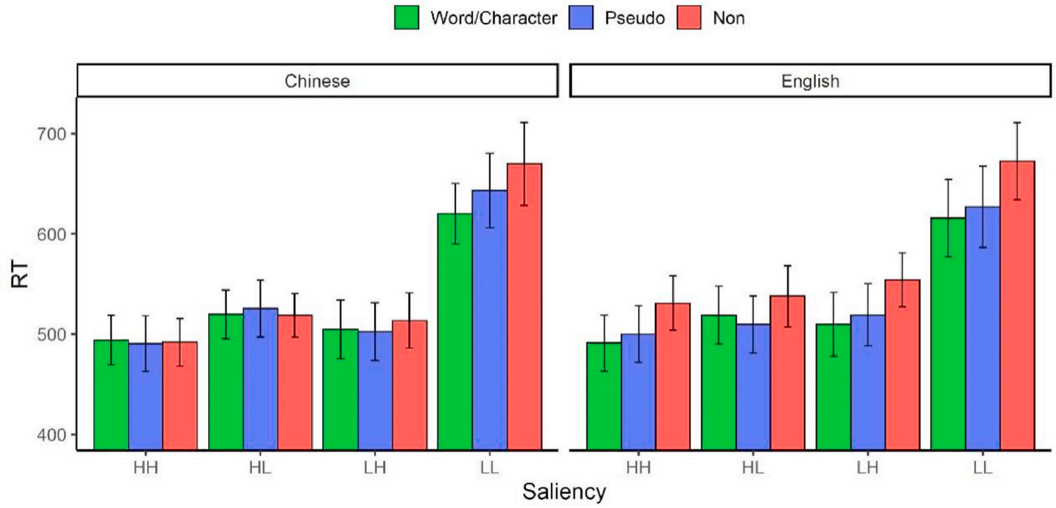

Fig. 4. Mean RT across saliency (High-High, High-Low, Low-High, and Low-Low) and experience level for Chinese (left panel) and English (right panel) comparisons. Error bars indicate ± one standard error within each group.

Participants responded slower to non-word/character compared to pseudo-word/character ($t(55) = 4.78$, $p < .001$, $d = 1.81$) and word/character ($t(55) = 5.99$, $p < .001$, $d = 2.26$). There was also a significant main effect of saliency ($F(1.2, 7.20) = 78.06$, $p < .001$, $\eta_p^2 = 0.93$) with participants responded to LL slower than their responses to HH ($t(41) = 13.62$, $p < .001$, $d = 5.15$), HL ($t(41) = 11.52$, $p < .001$, $d = 4.35$), and LH ($t(41) = 11.94$, $p < .001$, $d = 4.51$). In addition, there was also a two-way interaction between the language type and experience level ($F(2,12) = 12.50$, $p = .001$, $\eta_p^2 = 0.68$). Post-hoc pairwise comparisons showed that participants responded significantly slower to English nonwords compared to pseudowords ($t(27) = 6.42$, $p < .001$, $d = 0.43$) and words ($t(27) = 7.36$, $p < .001$, $d = 0.49$). However, this difference was not observed in the Chinese comparisons.

2.2.3. Architecture and stopping rule

To interpret the MIC and SIC, we used a series of Kolmogorov-Smirnov tests to check the assumption of selective influence. Specifically, this assumption requires that survivor functions be ordered at all times t according to

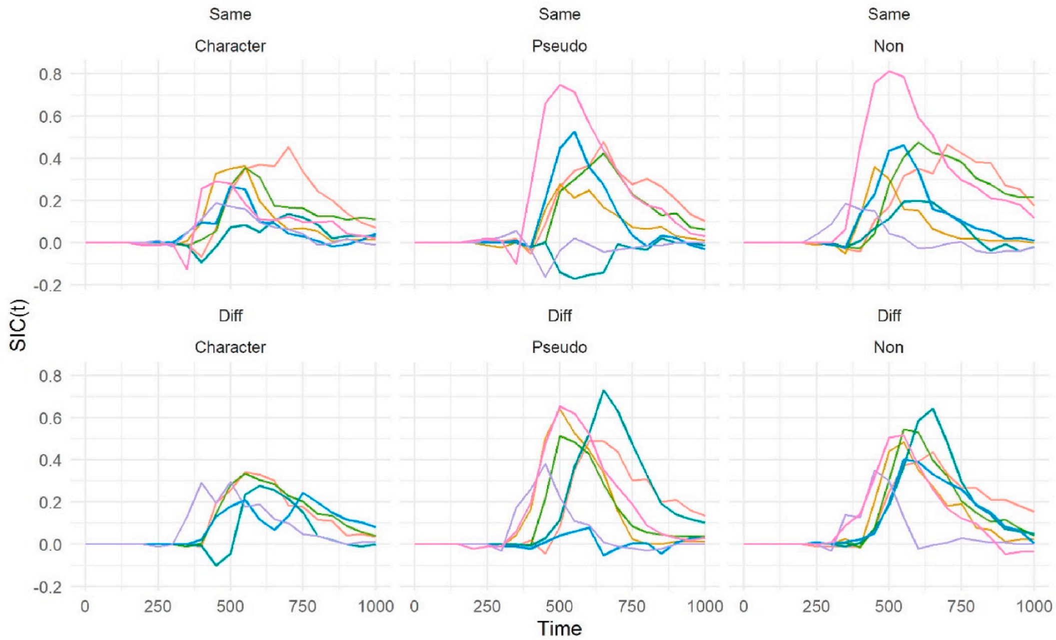

Fig. 5. Survivor interaction contrasts with Experiment 1 in Chinese processing for the same (top panel) and different (bottom panel) comparisons. Each line represents a single participant.

$$S_{(L,L)}(t) \le S_{(L,H)}(t), S_{(H,L)}(t) \le S_{(H,H)}(t),$$

with strict dominance at some *t*.

Our experimental design yielded 24 scenarios (2 language conditions × 3 experience levels × 2 structural types) within which we interpreted participants' processing architecture and stopping rule, specifically for participants who passed our selective influence checks (Supplementary Material, Table 1a). Although not all participants exhibited strict selective influence for our saliency manipulation, those who did not significantly violate the assumption were retained for further analysis. Upon visual inspection, their survivor functions were appropriately ordered. We posit that our failure to detect strict dominance for these participants is due more to the limitations of null hypothesis testing than real violations of selective influence. The Supplemental Materials include summary tables of individual processing architectures for all participants.

Chinese Individual SIC functions of Chinese processing are shown in Fig. 5. The visual inspection suggests that participants presented positive SIC functions consistent with parallel, first-terminating processing mechanisms depicted in Fig. 2. To be more specific, in the case of Chinese character processing, six participants were categorized using Parallel-OR processing. In contrast, one participant used Parallel-AND processing for the same judgments. All five interpretable participants were categorized using Parallel-OR processing for the different judgments. For pseudo-character processing, two participants were categorized as using Parallel-AND processing for the same judgments and Parallel-OR processing for the different judgments. The remaining five participants were categorized as using Parallel-OR for both judgments. In the case of non-character processing, all participants exhibited Parallel-OR processing.

English Individual SIC functions of English are shown in Fig. 6. The visual inspection suggested that participants presented similar processing patterns as in Chinese processing. In English word processing, five participants were categorized as using Parallel-OR processing and two participants as using Serial-OR processing for the same judgments. All six interpretable participants were categorized as using Parallel-OR processing for the different judgments. In pseudoword processing, five participants were categorized as using Parallel-OR processing, and one participant as using Coactive processing for the same judgments. All seven participants were categorized as using Parallel-OR processing for the different judgments. For non-word judgments, all participants were categorized as using Parallel-OR processing.

2.3. Discussion

In Experiment 1, where the second test stimulus was either the same or entirely different (for both left and right comments) from the first study stimulus, we expected participants to employ an "OR" decision (self-terminating stopping rule) for "different" judgments, and an "AND" decision (exhaustive stopping rule) when making "same" judgments. Consistent with our hypotheses, most participants displayed clear and consistent evidence against serial processing of the parts of either Chinese characters or English words, as revealed by the MIC and SIC. The positive MIC results indicated a parallel self-terminating or coactive process. SIC results displayed

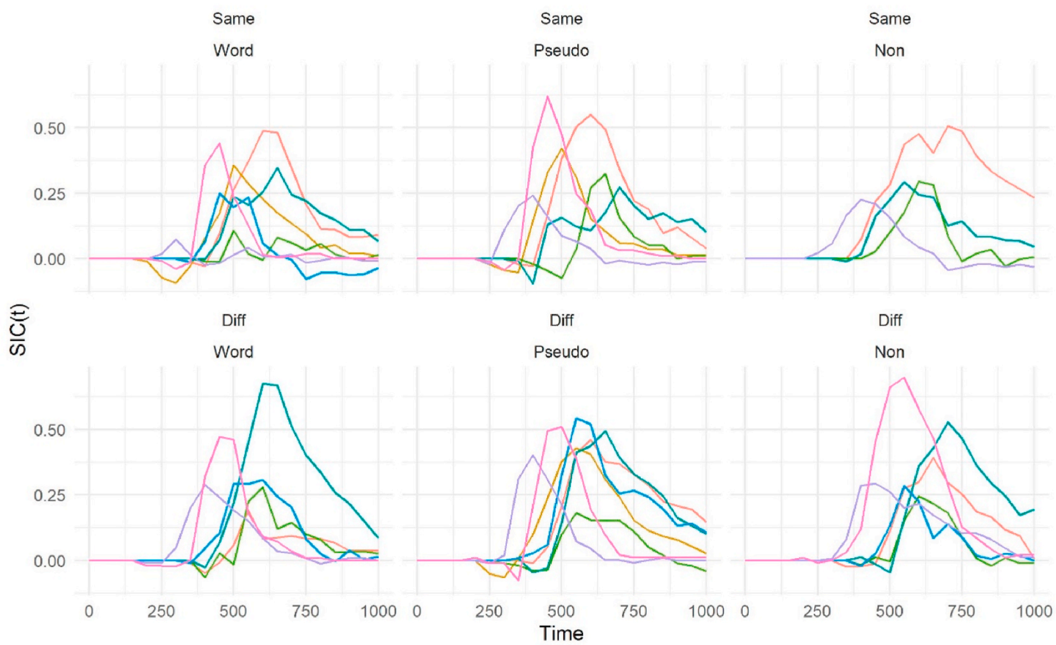

Fig. 6. Survivor interaction contrasts with Experiment 1 in English processing for the same (top panel) and different (bottom panel) comparisons. Each line represents a single participant.

significantly positive SIC deviations and nonsignificant negative deviations, supporting the MIC findings and indicating that a coactive model was less likely than purely parallel self-terminating processing.

The detailed analysis found no evidence of a speed-accuracy tradeoff between conditions, implying the relative ease of the judgment task. In addition, there was a main effect of experience level – participants responded slower to non-words/characters – and an interaction effect between the experience level and salience. The low-salience condition disproportionately influenced non-word/character comparisons, while experience levels disproportionately affected English comparisons.

We found no substantial difference between the two structural types (same vs. different), indicating that participants quickly learned to only use a single component before deciding. This contradicted our hypothesis that participants would employ different stopping rules based on the contextual “same” or “different” judgments, as they need information from both components to make a “yes, same” decision. Rather than indicating an inherent property of the system, the self-terminating rule might have been due to the information constraints in the task. Consequently, we introduced additional uncertainty in Experiment 2 by changing only one component at a time, which necessitated participants to compare both components exhaustively before reaching a decision.

3. Experiment 2

Our first experiment aimed to investigate the mental architecture and stopping rule of participants' processing of characters and words. Nevertheless, because Experiment 1 allowed for judgment completion without necessitating the exhaustive processing of both components on every trial, it remains unknown whether participants would alter their strategy when in the presence of potential response conflicts.

Experiment 2 explored whether processing strategies shifted when participants responded to word/character halves presenting congruent changes (as in Experiment 1) or conflicting changes (e.g., 睛 – 請). This resulted in four possible structural types: both-same, both-different, left-different, and right-different. The left-different and right-different conditions resulted in conflicting responses, analogous to the incongruent condition in the composite task (e.g., Ref. [14]). By presenting all possible structural types in a randomized order, participants were obliged to process both components before determining whether any two stimuli were the same or different.

3.1. Methods

3.1.1. Participants

Eight students aged between 20 and 29 ($M_{age} = 22.88$ years, $SD_{age} = 2.82$, Female = 3) from the same subject pool as Experiment 1 completed the study. Similar to our exclusion criteria in Experiment 1, two participants were excluded from data analysis for low accuracy performance (not within the 3.5 SD of the group), leaving six participants in the final data analysis.

3.1.2. Materials and design

The design and materials of the study were the same as in Experiment 1, except for the addition of two structural types which necessitated that participants process all components before reaching a judgment decision. The study consisted of a 2 (language condition: English/Chinese) × 3 (experience level: character/word, pseudo-character/word, non-character/word) × 4 (structural type: both-same, left-different, right-different, both-different) within-subjects factorial design (Table 3). Each character/word comparison type included an additional manipulation of *high* and *low* salience (see Table 4).

3.1.3. Procedure

The entire task consisted of 20 sessions, each lasting approximately 1 h. Sessions were equally split between English and Chinese stimuli. Participants were allowed to complete no more than two sessions per day. Each session began with 24 practice trials and included 5 blocks of 144 trials (5 × 144 trials = 720 trials per session). There were 150 trials for each possible combination, resulting in 14400 trials in total for the within-subjects factorial design. The trial procedure remained the same as in Experiment 1.

3.2. Results

The analysis of Experiment 2 was the same as Experiment 1. Responses that fell within the time range between 150 ms and 1500 ms

Table 3
Full set of stimuli used in Experiment 2.

	Type	Stimuli			
		Same	Left-Diff	Right-Diff	Both-Diff
Chinese	Character	目青	言青	目登	言登
	Pseudo	彳召	巠召	彳頁	扌頁
	Non	力糸	易糸	力其	斤車
English	Word	crew	stew	crop	stop
	Pseudo	lerb	narb	lemf	namf
	Non	rlkf	vtkf	rljk	vtjk

Table 4
The salience manipulation for example stimuli in Experiment 2
Note. H: High salience manipulation, L: Low salience manipulation.

	Right	Same		Different	
Left		H	L	H	L
Same	H	HH 	HL 	HH 	HL 
	L	LH 	LL 	LH 	LL 
Different	H	HH 	HL 	HH 	HL 
	L	LH 	LL 	LH 	LL 

were included in further analysis. Behavioral analyses were reported using repeated measures ANOVA with JASP [22], and MIC and SIC analyses were conducted using the SFT package [23] in R [24]. As in Experiment 1, only correct responses were included in the RTs and mental architecture/stopping rule analyses.

3.2.1. *Capacity-resilience*

As reported in our previous study [18], the inclusion of distracting information (left-different, right-different) in Experiment 2 allows for the calculation of capacity-resilience [25]:

$$R(t) = \frac{H_{whole}(t)}{H_{part(1),X}(t) + H_{Y,part(2)}(t)}$$

Where the numerator refers to the processing time of the target information such as "睛"; whereas the denominator refers to the

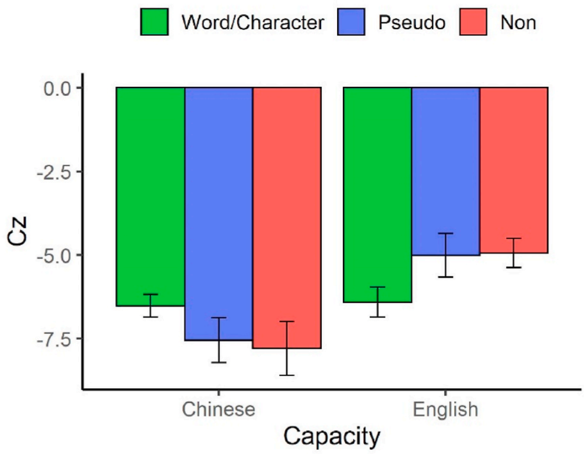

Fig. 7. Mean Cz values for the Resilience) functions indicating limited processing efficiency in Experiment 2. Error bars display ± one standard error.

processing time of the stimuli "請" and "瞪" in which each decomposition of target "目" and "青" is in the present with another distractor component. Therefore, participants with high processing efficiency, represented by the super capacity of R(t), should be capable of easily decomposing the target information "睛" into parts "目" and "青", with no interference with distracting information on the other side.

The resilience function, R(t), indicates that the processing was limited capacity for both Chinese and English stimuli (i.e., Cz < 0). This suggests the exisitence of distracting information slowed the processing of the target component (Fig. 7). Repeated-measures ANOVA results (Table 5) display a main effect of language, as participants were more efficient at English ($M = -5.45$, $SD = 1.38$) than Chinese processing ($M = -7.28$, $SD = 1.57$), $t(11) = 4.83$, $p = .005$, $d = 1.29$. In addition, there was an interaction between language and experience. Post-hoc analyses indicate participants processed English nonwords more efficiently than Chinese non-characters, given the same experience level ($t(5) = 4.04$, $p = .016$, $d = 2.01$). Meanwhile, English pseudowords were processed more efficiently than Chinese pseudo-characters ($t(5) = 3.60$, $p = .04$, $d = 1.79$). No difference was observed between Chinese characters and English words.

3.2.2. Accuracy

Fig. 8 depicts the mean accuracy for saliency manipulation and experience level combinations in each language condition. As illustrated in Fig. 8, participants exhibited the lowest accuracy when responding to Chinese characters ($M = 0.93$, $SD = 0.08$), as compared to pseudo-characters ($M = 0.98$, $SD = 0.03$) and non-characters ($M = 0.97$, $SD = 0.05$). However, when responding in English, the lowest accuracy was observed for non-words ($M = 0.97$, $SD = 0.03$), as compared to words ($M = 0.99$, $SD = 0.02$) and pseudowords ($M = 0.98$, $SD = 0.03$).

There was a main effect of the experience level, $F(2,10) = 4.66$, $p = .037$, $\eta_p^2 = 0.48$. On average, participants demonstrated higher accuracy in processing pseudo-words/characters ($M = 0.98$, $SD = 0.03$) than words/characters ($M = 0.96$, $SD = 0.06$), $t(47) = 3.05$, $d = 0.46$. There was also a main effect of the saliency, $F(3,15) = 3.57$, $p = .04$, $\eta_p^2 = 0.42$. However, no further significant differences were found among any two levels in the post-hoc analysis, according to Bonferroni-adjusted p-values. In addition, the results indicated a significant interaction between the language and experience level, $F(2,10) = 7.84$, $p = .009$, $\eta_p^2 = 0.42$; and an interaction between language and saliency, $F(3,15) = 3.31$, $p = .049$, $\eta_p^2 = 0.40$.

Post-hoc analysis on the interaction between the language and experience level further revealed that Chinese characters were processed with lower accuracy ($M = 0.94$, $SD = 0.08$) compared to Chinese non-characters ($M = 0.97$, $SD = 0.05$; $t(23) = 3.36$, $p = .049$, $d = 0.80$) and pseudo-characters ($M = 0.98$, $SD = 0.03$; $t(23) = 4.77$, $p = .002$, $d = 1.14$). However, no such difference was not found among different English experience levels. Post-hoc analysis on the interaction between language and saliency revealed that Chinese characters with high saliency (HH; $M = 0.99$, $SD = 0.008$) were processed with higher accuracy compared to those with low saliency (LL; $M = 0.94$, $SD = 0.086$; $t(17) = 4.01$, $p = .02$, $d = 1.30$).

3.2.3. RT

Fig. 9 displays the mean RT indicates that participants responded more slowly to Chinese characters ($M = 560.64$, $SD = 77.17$) compared to pseudo-characters ($M = 539.01$, $SD = 78.08$) and non-characters ($M = 550.96$, $SD = 82.53$). However, in the English comparisons, participants were slower in responding to English nonwords ($M = 562.59$, $SD = 77.97$) than pseudowords ($M = 530.03$, $SD = 78.08$) and words ($M = 526.11$, $SD = 80.50$).

Further ANOVA analysis on response times indicates that there was a main effect of the experience level, $F(2,10) = 7.84$, $p = .009$, $\eta_p^2 = 0.61$. Non-word/character ($M = 556.77$, $SD = 79.64$) processing was slower compared to pseudo-word/character processing ($M = 534.52$, $SD = 75.38$), $t(47) = 3.93$, $p < .001$, $d = 1.15$. There was also a main effect of saliency, $F(3,15) = 165.31$, $p < .001$, $\eta_p^2 = 0.97$.

Post-hoc analysis revealed an ordered relationship between the saliency levels: stimuli with HH saliency resulted in the fastest responses ($M_{\text{HL-HH difference}} = 74.39$, $t = 12.08$, $d = 1.15$, $p < .001$; $M_{\text{LH-HH difference}} = 74.30$, $t(35) = 12.06$, $d = 1.15$, $p < .001$; $M_{\text{LL-HH difference}} = 136.90$, $t(35) = 22.23$, $d = 2.11$, $p < .001$) and stimuli with LL saliency resulted in the slowest responses ($M_{\text{LL-HL difference}} = 62.51$, $t(35) = 10.15$, $d = 0.97$, $p < .001$; $M_{\text{LL-LH difference}} = 62.61$, $t(35) = 10.17$, $d = 0.97$, $p < .001$). Moreover, the analysis indicated an interaction between the language and experience level, $F(2,10) = 5.22$, $p = .03$, $\eta_p^2 = 0.51$. Post-hoc analysis on this interaction revealed that English nonwords were processed significantly slower compared to pseudowords ($t(23) = 3.57$, $p = .031$, $d = 0.50$) and nonwords ($t(23) = 4.00$, $p = .012$, $d = 0.56$). In contrast, such differences in experience level failed to be found in Chinese comparisons.

3.2.4. Architecture and stopping rule

As in Experiment 1, we employed a series of Kolmogorov-Smirnov tests to verify the selective influence assumption. Similarly, we

Table 5
Repeated measures ANOVA results for Cz comparisons in Experiment 1.

Variable	F ratio	df	η_p^2
Language (L)	23.35**	1,5	.824
Experience (E)	0.04	2,10	.007
L × E	4.25*	2,10	.459

Note. *$p < .05$, **$p < .01$, ***$p < .001$.

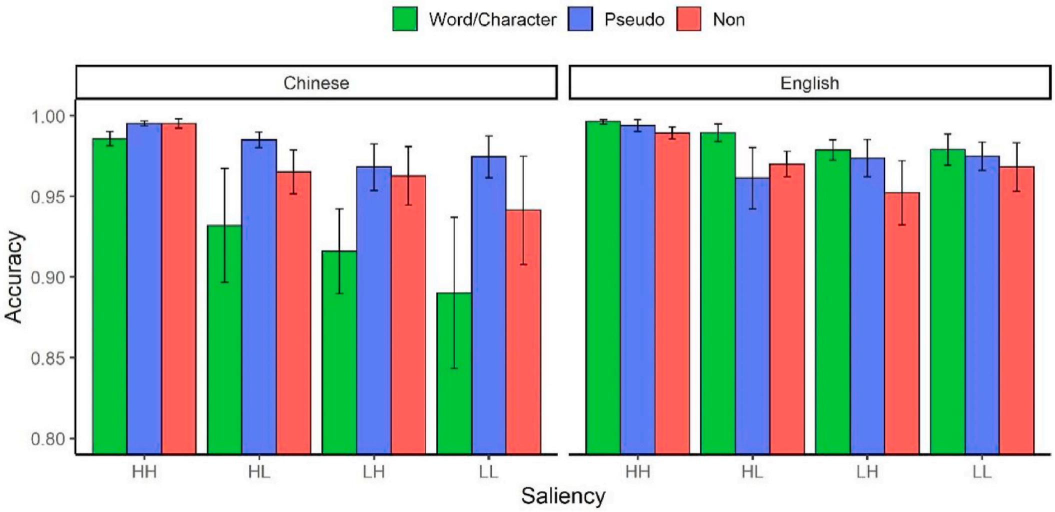

Fig. 8. Mean accuracy across conditions of saliency type (High-High, High-Low, Low-High, Low-Low) and experience level for Chinese (left panel) and English (right panel) comparisons. Error bars display ± one standard error.

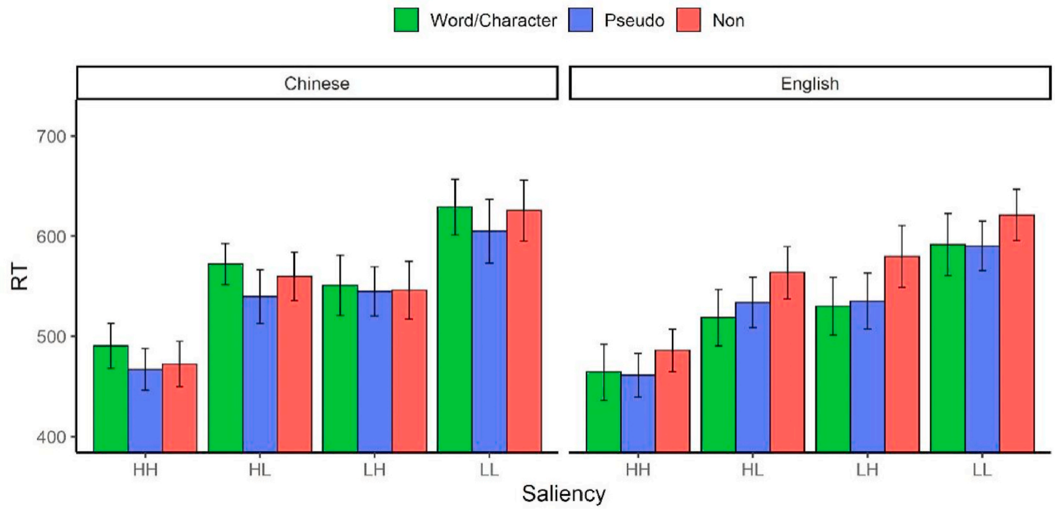

Fig. 9. Mean response times across conditions of saliency type (High-High, High-Low, Low-High, Low-Low) and experience level for Chinese (left panel) and English (right panel) comparisons. Error bars display ± one standard error.

interpreted participants' processing architecture and stopping rule only for those participants who passed the selective influence check (Supplementary Material Table 2a). A comprehensive table detailing the processing architecture of all participants can be found in the Supplemental Material.

Chinese Individual SIC functions of Chinese processing in Experiment 2 are shown in Fig. 10. As the figure illustrates, the same judgments generally resulted in negative SIC functions, corresponding to parallel, exhaustive systems. In contrast, the different judgments led to all negative or first-negative-then-positive SIC functions. To further examine these visual inspections, the SIC and MIC functions indicated that in the case of Chinese character processing, all four interpretable participants were categorized as using Parallel-AND processing for the same judgments. However, for differing judgments, three participants were categorized as using Parallel-AND processing, while the remaining three used Parallel-OR, Serial-AND, and Coactive processing, respectively. For pseudo-character processing, all six participants used Parallel-AND processing for the same judgments. Four participants used Parallel-AND processing for the different judgments, and two used Coactive processing. A consistent trend of Parallel-AND processing for non-character processing was observed for the same judgments. For different judgments, three participants employed Parallel-AND processing, and one each used Serial-OR, Coactive, and Serial-AND processing.

English Individual SIC functions of English processing in Experiment 2 are shown in Fig. 11. Likewise, the SIC and MIC functions indicated that in the case of English word processing, all interpretable participants uniformly employed Parallel-AND processing for

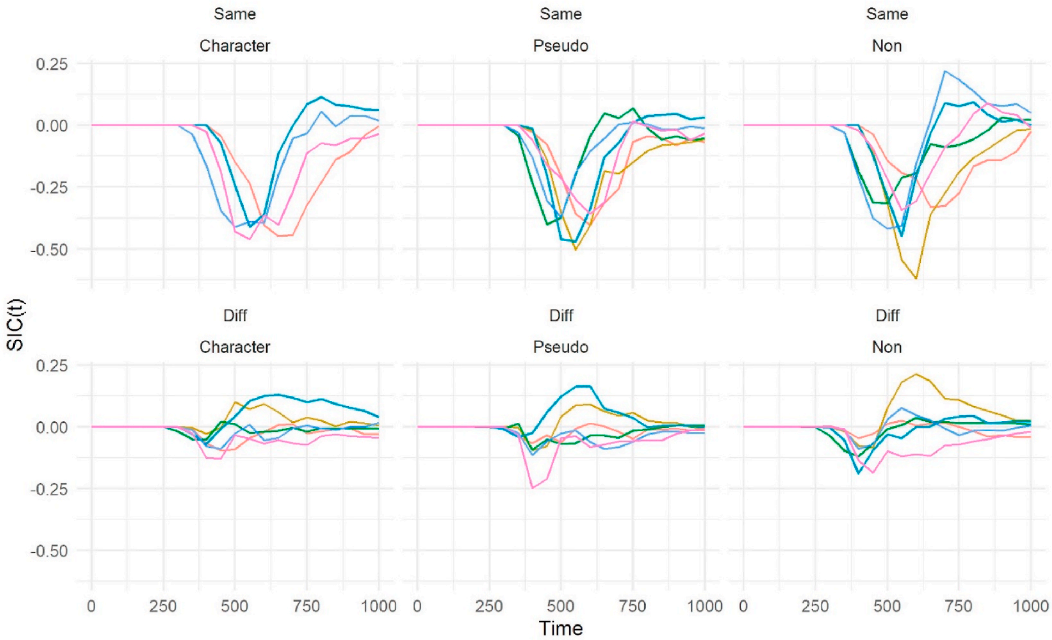

Fig. 10. Survivor interaction contrasts for Experiment 2 in Chinese processing for the same (top panel) and different (bottom panel) comparisons. Each line represents a single participant.

the same judgments. For the different judgments, three participants were categorized as using Coactive processing, with one each categorized as using Serial-OR, Parallel-AND, and Serial-AND processing. All five interpretable participants were categorized as using Parallel-AND processing for the same judgments in pseudoword processing. Five participants were categorized as using Parallel-AND processing and one as Coactive for the different judgments. For the nonword same judgments, all five interpretable participants used Parallel-AND processing. By contrast, four participants employed Parallel-AND processing, and two used Serial-AND processing for the different judgments.

3.3. Discussion

Experiment 2 introduced decisional uncertainty to the second test stimulus, allowing the left or right components to differ. This design forced participants not to rely on a single component when deciding. We expected participants to demonstrate exhaustive stopping rules when making both "same" and "different" judgments. Consistent with our hypotheses, we generally observed clear and compelling evidence favoring parallel exhaustive processing (MIC < 0; SIC(t) < 0) for the "same" judgment task. However, the processing strategies for the "different" judgment task were more varied, suggesting that the specific judgment scenarios influenced processing strategies.

Processing efficiency results – in which participants compared components while dealing with distracting information in the word/character pair – indicated limited capacity in all participants. This finding violates an assumption of parallel exhaustive models that processing channels are independent and unlimited in workload capacity. Instead, these results suggest the presence of an inhibitory process [26], in which additional resources are employed when participants need to decompose conflicting characters or word halves.

Accuracy and response time results indicated that Chinese, but not English characters, were processed with lower accuracy. Moreover, salience disproportionally affected Chinese processing rather than English processing. Chinese high saliency stimuli (HH) were processed more accurately than Chinese low saliency (LL) stimuli. As for response times, the experience level only affected English comparisons, with English nonwords being processed significantly slower than the word and pseudoword conditions.

4. General discussion

Perceptual expertise is often associated with holistic processing (e.g., Ref. [1]). Therefore, one might expect Chinese readers to rely on a holistic strategy when viewing Chinese characters (e.g., Refs. [27–29]). However, previous results have been mixed regarding whether Chinese readers rely on part-based or holistic strategies. One explanation for findings favoring part-based processing is that experts can adapt to the task environment, aligning performance in a selective attention task with part-based processing, even if holistic processes are typically used in a standard reading context. To examine whether holistic or part-based strategies are used in divided attention tasks – those requiring the reader to attend to the entire Chinese character or the whole English word – we deployed a task designed to the specifications of Systems Factorial Technology (SFT) with our results supporting the parallel processing of

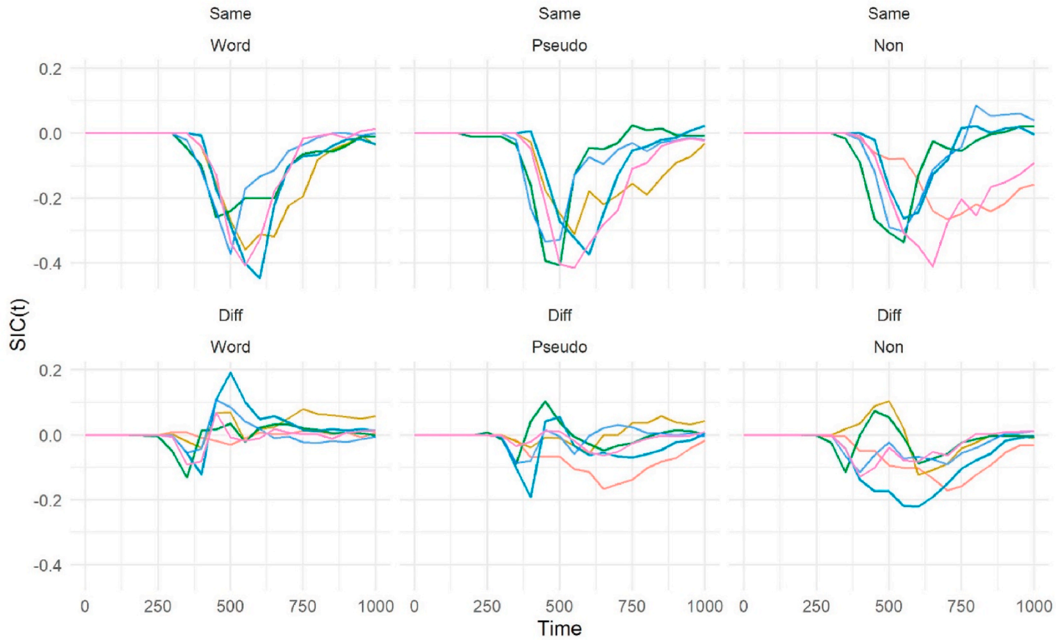

Fig. 11. Survivor interaction contrasts for Experiment 2 in English processing for the same (top panel) and different (bottom panel) comparisons. Each line represents a single participant.

character parts across two experiments.

Our work sheds light on the previous puzzle of whether Chinese are processed holistically: When native Chinese speakers judged whether consecutively presented characters/words were the same or entirely different (Experiment 1), results generally supported parallel self-terminating processing; When context rules changed and stimulus components could differ by one-half (Experiment 2), processing likewise shifted to parallel exhaustive. The resilience metric, a measure of the degree of interference from distracting information, indicated that target components were affected by distractors. These results suggest that the processing of characters and words may be holistic (coactive) in nature but with inhibitory processing when grouping individual components.

Our initial hypothesis suggested holistic processing would indicate a coactive architecture, where information pools together to reach a single decision ([30,31]). On average, we observed evidence of coactive architectures in Experiment 1 and evidence of a parallel exhaustive process with interference effects in Experiment 2. However, not all participants were aligned with these findings. This suggests that holistic processing strategies depend on the task and presentation contexts. These findings align with Hsiao and Cottrell's study [9], which asserted that the stimuli and task design determine holistic processing.

In addition, we reported that participants processed the "same" and "different" judgments in dissimilar ways. This outcome echoes the "same-fast" effect, wherein the "same" responses differed from the "different" responses in the sameness judgment task [32]. Given that participants in our study may have compared the characters based solely on their visual forms and that a Chinese character can present complex forms in terms of phonetics, shape, and meaning, future research could explore higher-level phonetic and semantic processing of Chinese characters to address this limitation in our current experimental paradigm.

Our current research also investigated whether experience caused differences in processing architecture and stopping rule among participants. We exposed participants to different languages and manipulated experience levels (word/character, pseudo-word/character, non-word/character). Despite variations in accuracy and response times, we did not observe significant discrepancies in participants' processing architecture and stopping rule due to experience. While this discovery is intriguing, we must acknowledge the limitations of the conclusions drawn from this work. It is possible that the consistency of experience was specific to our stimuli and might change with additional practice (as suggested by Refs. [33,34], where holistic processing emerged with practice). Given this limitation, future research could assess the variability of processing architecture across various stimuli and levels of practice further to examine the influence of expertise on visual word processing [35]. In addition, future studies might replicate this work among native English and bilingual speakers to determine whether processing architectures vary with the native language.

To conclude, in the current study, we employed Systems Factorial Technology to examine the processing architectures used in visually processing Chinese characters and English words. In line with our hypotheses, our work suggests that native Chinese speakers as experts can process Chinese characters holistically. Surprisingly, these participants also demonstrated holistic processing of English words. Lastly, we found that the conditions of specific context rules dictate when processing terminates.

Funding

This work is supported by the National Science and Technology Council, Taiwan (NSTC 112-2423-H-038-001-, NSTC 109-2410-H-006 -049 -MY3, NSTC 107-2410-H-006 -055 -MY2, NSTC 105-2410-H-006 -020 -MY2), the Ministry of Education (DP2-TMU-112-N-08), and the National Cheng Kung University (NCKU Rising-Star Top-Notch Project Grant) to C.-T. Yang. H. Zhang would like to acknowledge the support of the Fundamental Research Funds for the Central Universities (CCNU21XJ040, CCNU22QN020).

Author contribution statement

Hanshu Zhang; Paul M. Garrett: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Joseph W. Houpt; Pei-Yi Lin: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data.

Cheng-ta Yang: Conceived and designed the experiments; Performed the experiments; Contributed reagents, materials, analysis tools or data.

Data availability statement

Data associated with this study has been deposited at Open Science Framework (OSF) and can be accessed at https://osf.io/7vbnf/.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2023.e19736.

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