The effect of flanker category on crowding is modulated by processing time

Yiyang Yu

The Graduate School of Natural Science and Technology,
Okayama University, Japan
Email: pj5v3xw3@s.okayama-u.ac.jp

Qiong Wu*

School of Education,
Suzhou University of Science and Technology,
Suzhou, China
and
Graduate School of Interdisciplinary Science and Engineering in Health Systems,
Okayama University, Japan
Email: wuqiong@usts.edu.cn
*Corresponding author

Qi Dai, Jiajia Yang, Satoshi Takahashi, Yoshimichi Ejima and Jinglong Wu

Graduate School of Interdisciplinary Science and Engineering in Health Systems,
Okayama University, Japan
Email: pjs06t9b@s.okayama-u.ac.jp
Email: yang@okayama-u.ac.jp
Email: takaha-s@okayama-u.ac.jp
Email: ejima.yoshimichi.86w@st.kyoto-u.ac.jp
Email: wu@mech.okayama-u.ac.jp

Abstract: When the human visual system processes complex scenes, crowding is considered a bottleneck in interpreting visual information. Several studies have reported that visual crowding seems to occur in the early stage of visual possessing. After that, extensive evidence suggested that high-level visual information has a major effect on crowding, which showed substantial interest in the impact of high-level visual information on crowding. However, the temporal property of high-level crowding is not well understood. Here, we performed a series of behavioural experiments to show how flanker category information and exposure time affected crowding's intensity. We found that as the category's effect becomes stronger, the intensity of crowding will be reduced in longer exposure time. The peak of this effect occurs at the time window of 100 ms–150 ms after the stimulus appears. We propose that exposure time may modulate high-level information processing depth, which can adjust multi-level crowding.

Keywords: multi-level crowding; flanker category effect; temporal property; behavioural experiment.

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Biographical notes: Yiyang Yu is a PhD student in the Graduate School of Natural Science and Technology, Okayama University. His research interests include visual perception and language processing.

Qiong Wu is an Associate Professor from the Suzhou University of Science and Technology. He received his PhD from the Okayama University. His research interests include attention visual perception, function MRI data analysis and visuospatial attention mechanism.

Qi Dai is a PhD student in the Cognitive Neuroscience Laboratory in Graduate School of Interdisciplinary Science and Engineering in Health Systems from Okayama University. His research interests include unconscious information processing and attention mechanism.

Jiajia Yang is an Assistant Professor in the Cognitive Neuroscience Laboratory in Graduate School of Interdisciplinary Science and Engineering in Health Systems from Okayama University. He received his PhD from the Kagawa University. His research interests include cross-modal perception processing and the human somatosensory system.

Satoshi Takahashi is an Associate Professor in the Cognitive Neuroscience Laboratory in Graduate School of Interdisciplinary Science and Engineering in Health Systems from Okayama University. He received his PhD from the Okayama University. His research interests include the brain-machine interface and rehabilitation.

Yoshimichi Ejima is a Guest Professor in the Cognitive Neuroscience Laboratory in Graduate School of Interdisciplinary Science and Engineering in Health Systems from Okayama University. His research areas include human visual information processing, integration of binocular information and perception integration process.

Jinglong Wu is a Professor in the Cognitive Neuroscience Laboratory in Graduate School of Interdisciplinary Science and Engineering in Health Systems from Okayama University. He received his PhD from the Kyoto University. His research areas include biomedical engineering and cognitive memory brain function network.

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1 Introduction

Crowding is a visual perception phenomenon, which can break our identification ability when a target is surrounded by flankers in peripheral vision (Bouma, 1973; Huckauf and Heller, 2004; Pelli et al., 2004; Whitney and Levi, 2011). For example, it is difficult for people to glimpse a face in a crowd. In the same way, it is also difficult to read a message on the navigator when people concentrate on driving. In these examples, face and message in peripheral vision are more difficult to be identified because of the impact of crowding. In the real world, objects typically do not appear alone. Most of the objects are surrounded by other objects in the complex visual scenes. The crowding mechanism is the key point to know how humans can efficiently identify objects in complex scenes (Doerig et al., 2019).

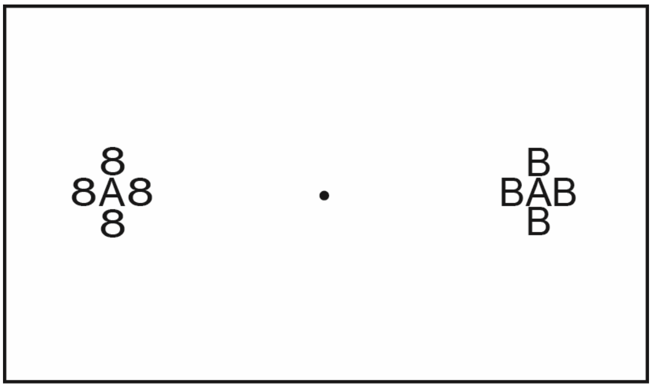
Scientists have been interested in the existence of crowding effect since the 1970s. From a spatial domain perspective, extensive research has shown that crowding is typically thought to manifest as a kind of contextual modulation caused by the inhibitory interaction between the target and the flankers. Following experimental research, researchers believe the reason for crowding is the failures of feature integration, segmentation, and coarse resolution of spatial attention. From a temporal domain perspective, it is widely accepted that crowding occurs in the identification stage of visual processing (Millin et al., 2014).

In some studies, crowding is thought to occur in the early stage, which means that the factors to affect crowding originate from the low-level visual information (Poder and Wagemans, 2007; Nandy and Tjan, 2007; Hanus and Vul, 2013). Nevertheless, there is extensive evidence that high-level visual information has a major effect on crowding.

Central to this debate is the role of high-level visual information. In the low-level crowding view, the existing body of vision research suggests that visual crowding is a bottom-up process (Poder and Wagemans, 2007; Nandy and Tjan, 2007; Hanus and Vul, 2013). When low-level features are combined, crowding destroys the integrity of information and reduces the utilisation rate of high-level information, which leads to difficulties in identification. In the high-level crowding view, the researchers suggest that crowding may involve multiple levels of visual processing (Manassi and Whitney, 2018). The property of high-level concepts may counteract the crowding. There are many kinds of high-level information that will not be affected by crowding, and high-level information can affect crowding at several stages, which shows the importance of top-down process. To date, there has been little agreement regarding the impact of high-level visual information on crowding. Accordingly, the mechanism of multi-level crowding has become a hot research topic in recent years.

Researchers adjust the target-flanker similarity to explore the properties of crowding in previous studies. In studies of multi-level crowding, the target-flanker difference usually originates from high-level visual information. These differences include the following levels, such as shape composition, integrity, object configuration and dynamic configuration. There is much evidence to show that the property of high-level information plays a vital role in order to know the mechanism of multi-level crowding. Researchers used several identification tasks with letter, number, or symbol flanker. They found that the category property of flankers can adjust the intensity of crowding. Moreover, in order to explain this observation, the flanker category effect was proposed. In this study, the letter flankers reduced the crowding intensity in the number identification task, even if the visual characteristics of letters and numbers have been unified. Flanker category effect is vital in multi-level crowding research, and the paradigm provided a way to study the function of high-level information above low-level visual characteristics under crowding (Reuther and Chakravarthi, 2014).

Figure 1 Demonstration of flanker category effect



Notes: Left stimulus: examples of flanker category effect. Right stimulus: examples of normal crowding.

In support of low-level crowding view, the importance of temporal factor is widely studied (Chakravarthi and Cavanagh, 2007; Lev and Polat, 2015; Yeshurun et al., 2015; Chung, 2016). Despite the importance of temporal factor, there remains a paucity of evidence on the role of temporal factor in multi-level crowding. According to the object recognition theory, the processing time will affect the depth of target processing, and the processing depth is an important factor to adjust the influence of the high-level information. Processing time might be an important factor that can affect the occurrence of flanker category effect.

This paper aims to prove the importance of processing time on flanking category effect. The central question in this dissertation asks how to determine the time frame of flanker category effect. The behavioural experiments were used to explore the flanker category effect in different processing times. This investigation used two experiments to achieve research purposes.

In Experiment 1, by using the QUEST method, the critical spacing under different temporal and category conditions was calculated. We used psychophysical methods to prove that the flanker category effect is related to temporal factors. In Experiments 2, 3 and 4, we discussed the relationship between flanker category effect and processing time. The threshold of critical spacing is replaced by accuracy in this experiment because we want to investigate the results in strong crowding. Further, the visual masking method was used in this experiment to ensure accurate processing time. We adjusted the interstimulus interval (ISI) between the stimulus and the masking to discuss the effect of processing time with short and long exposure time. This investigation will enhance our understanding of the role of processing time in multi-level crowding and provided a foundation for imaging and electrophysiological studies.

2 General methods

First, we will introduce the methodological information commonly used in all experiments.

2.1 Observers

Sixteen observers aged 24 to 33 years took part in this study. All had a normal or corrected-to-normal vision. Ten participated in Experiment 1, four in Experiments 2 and 3 and six in Experiment 4. All observers signed informed consent. Ethics was granted from Okayama University.

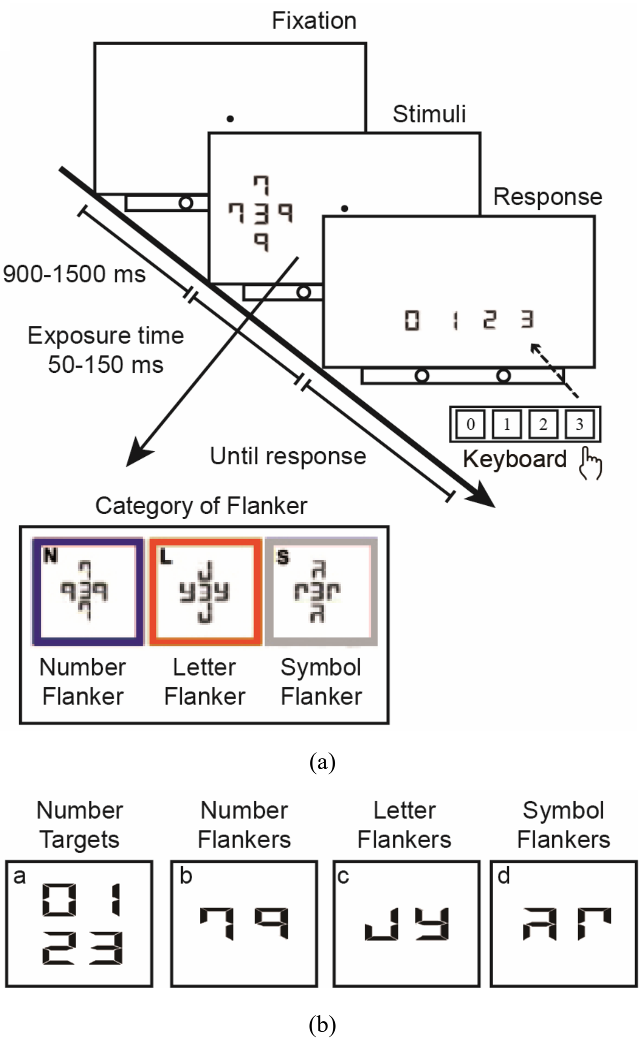
2.2 Material and stimuli

The experimental program is built by PTB based on MATLAB 2014a and presented on a Display++ LCD monitor (Cambridge Research System) with a frame rate of 100 Hz and resolution of 1,920 × 1,080 pixels (Brainard, 1997). Viewing distance was set to 57 cm secured using a chinrest. Eye movements were monitored using LiveTrack Lightning. This device is used to ensure that the observers are always looking at the centre of the screen. Stimuli were black (Lv1/4 0.25 cd/m^2) on white background (Lv1/4 91.5 cd/m^2) with a high contrast (Cmichelson1/4 0.99). A black fixation (0.3 deg diameter) was located in the centre of the screen. The target was presented 15 deg from the fixation on the horizontal meridian randomly either in the left or the right visual field in Experiment 1. Moreover, the target was presented 10 deg from the fixation on the horizontal meridian randomly either on the left or the right in Experiment 2, Experiment 3 and Experiment 4.

All experiment was started with a key press. A fixation mark appeared at the centre of the screen and stayed on the throughout block. Target and flankers were randomly displayed in the left or right visual field after varying onset times (0.9–1.5 s after trial onset) for 50 or 150 ms, ensuring that no eye movements could be made. After the stimuli disappeared, all possible target stimuli were displayed on the screen for keyboard response. The next trial started after the observer's response, and the program provided audio feedback.

The font, which previous researchers designed, consisted of only seven straight lines like a calculator font. The targets were always numbers, 0–3. The letters J and Y and the numbers 7 and 9 were served as flankers since they shared the same features (in the designed font). Note that 9 and Y did not share the exact same feature set but had the same number of vertical and horizontal elements, with one horizontal element displaced in position. Meaningless flankers (symbols) were rotations or mirror images of the used letter flankers (Reuther and Chakravarthi, 2014). The size of visual stimuli in all experiments was 2.1 deg. The spacing between the target and the flanker is adaptive, and the value is determined by the quest toolbox in Experiment 1. The spacing between the target and the flanker is 5 deg in Experiments 2, 3 and 4.

Figure 2 Experiment procedure and stimuli (see online version for colours)



Notes: The general procedure is shown in Figure 2(a). Several target surround by four flankers is shown randomly in the right or left on the screen. Exposure time was changed in different experiments. The flanker type conditions are the same in all experiments, including number flanker, letter flanker, and symbol flanker. Figure 2(b) shows an example of the experimental stimulation used for all experiments: (a) are the number targets, (b) are the number flankers, (c) are the letter flankers and (d) are the symbol flankers.

3 Experiment 1: flanker category effect modulated by exposure time

Experiment 1 was aimed to extend the results of previous study (Reuther and Chakravarthi, 2014). We extended that approach with a two (exposure time: 50 ms, 150 ms) by three (flanker: numbers, letters and symbols) factorial design. To test that exposure time was involved in the effect of flanker category or not. This introduced the temporal property into the flanker category effect for the first time. If we can adjust the intensity of the category effect by manipulating the exposure time, it shows that the category effect is a dynamic process related to the processing depth of the target and the flanker.

3.1 Method

The QUEST algorithm was used to determine the critical spacing when the recognition accuracy rate is 82% (Watson and Pelli, 1983). The critical spacing was used as a measure of crowding intensity. Six blocks were classified according to conditions. Each block included about 50 trials, and it was decided to use the QUEST algorithm. The experiment was repeated five times, and the data were averaged.

3.2 Results and discussion

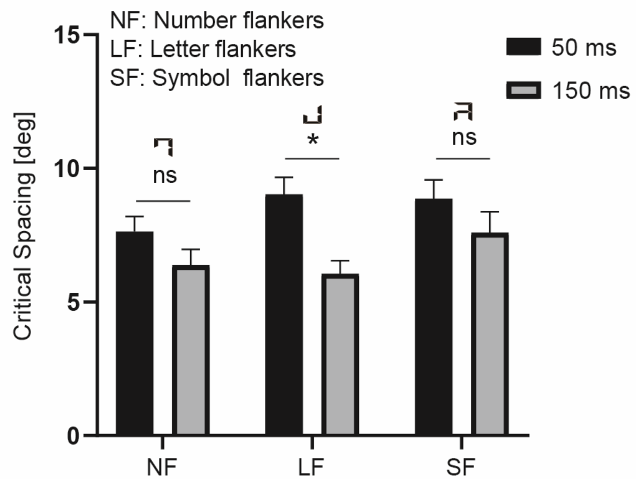
The performance of the task was calculated by the degree of critical spacing. The results are presented in Figure 3(a) and Figure 3(b). A two-way repeated measure analysis of variance (ANOVA) uncovered a significant effect of exposure time [$F(1, 9) = 8.984$, $P = .015$] and the type of flankers [$F(1.708, 15.375) = 8.239$, $P = .005$]. There is a significant interaction effect between exposure time and type of flankers [$F(1.600, 14.402) = 9.363$, $P = .004$]. Greenhouse-Geisser corrections were applied. Simple effects analyses were performed to uncover the relationship between two factors. The results are given in Table 1. Pairwise t-tests showed that longer exposure time could significantly reduce crowding under the condition of letter flanker. The effect of exposure time was not significant under the other two conditions. When the exposure time is 150 ms, all the experimental conditions are consistent with the previous study, and we obtained consistent results with previous researchers. When the exposure time becomes shorter, the crowding intensity of letter flankers is significantly higher than that of number flankers, and the crowding intensity of letter flankers is the same as that of symbol flankers.

Table 1 Results of simple effects analysis

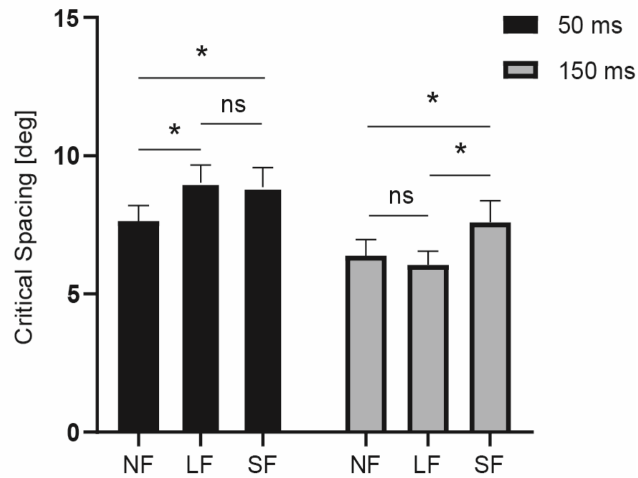
Pair of factors	*Paired differences*	*t value*	*Sig.*
NF 50–NF 150	1.25	1.99	0.08
LF 50–LF 150	2.98	4.37	0.01
SF 50–SF 150	1.27	1.84	0.10
NF 50–LF 50	–1.39	–3.00	0.02
NF 50–SF 50	–1.23	–3.73	0.01
LF 50–SF 50	0.16	0.40	0.70
NF 150–LF 150	0.34	1.28	0.23
NF 150–SF 150	–1.21	–3.63	0.01
LF 150–SF 150	–1.55	–3.50	0.01

As mentioned in the previous study, flanker category effect was significant on the condition of 150 ms exposure time. This result suggests that crowding oculars at the object classification stage. However, when the exposure time was reduced, the observers could not complete the classification of letter flankers. This result may have led to an increase in the intensity of crowding. However, according to the results of this experiment, the trend of flanker category effect changing with the exposure time cannot be understood. For exposure time, we have defined only two levels. The current experimental design cannot rule out the possibility that the significant effect is simply caused by the change of difficulty.

Figure 3 Results for Experiment 1



(a)



(b)

Notes: Number flanker is abbreviated as NF, letter flanker is abbreviated as LF and symbol flanker is abbreviated as SF. Error bars represent SEM. Black – 50 ms exposure time and grey – 150 ms exposure time. The symbol * means there was a significant difference, $p < 0.05$, ns means no significant difference in this pair.

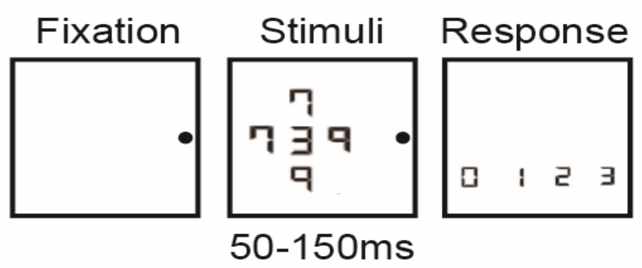
4 Experiment 2: the relationship between category index and exposure time

In Experiment 2, we chose six kinds of exposure time to explore the temporal property of category effect. Two experimental conditions were generated using a factorial design: six exposure time (50, 70, 90, 110, 130 and 150 ms) × three types of flanker.

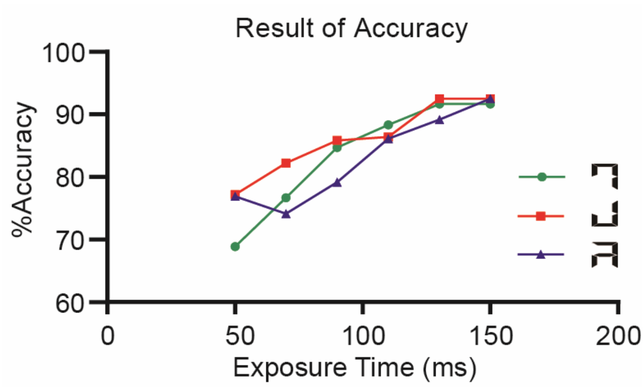
4.1 Method

Experiment 2 consisted of two conditions: three levels in flanker category and six exposure time levels. In contrast to the design of Experiment 1, the accuracy was used to measure identification performance in Experiment 2. This change aimed to define a certain distance to create a high crowding intensity throughout the experiment. There were 18 levels (six kinds of exposure time × three kinds of flankers) in this experiment. Each level consisted of 75 trials. The trials were arranged randomly. The experiment of each condition was performed individually, and all the trials were divided into nine blocks. The experiment was repeated three times, and the data were averaged. The procedure was the same as Experiment 1. The procedure of experiments was presented in Figure 4(a).

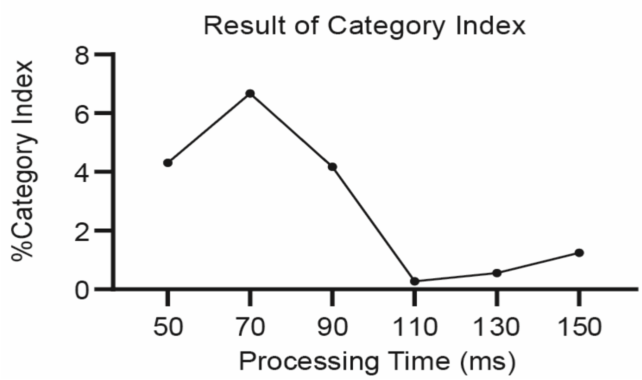
Figure 4 Procedure and results for Experiment 2 (see online version for colours)



(a)



(b)



(c)

Note: Figure 4(a) shows the schematic of experimental flow in Experiment 2.

4.2 Results and discussion

4.2.1 Accuracy

The performance of the task was calculated by accuracy. The results are presented in Figure 4(b). A two-way repeated measure ANOVA uncovered a significant effect of exposure time [F(1.411, 4.234) = 45.570, P < .001] and the type of flankers [F(1.870, 5.609) = 8.915, P = .019]. There is no significant interaction effect between exposure time and type of flankers [F(1.970, 5.911) = 9.363, P=.146]. Greenhouse-Geisser corrections were applied.

4.2.2 Linear fitting

One of this experiment's purposes was to know the effect of exposure time on the accuracy of number identification tasks in different category flankers. We used correlation analyses to identify the relationship between exposure time and accuracy. The accuracy of all the three category flankers was significantly associated with expose time. The Pearson correlation coefficient close to 0.9 under various conditions (number flanker: 0.90**, letter flanker: 0.95** and symbol flanker: 0.90**).

4.2.3 Category index

To describe the intensity of the flanker category effect, we introduce the category index concept, which refers to the change of accuracy from different categories of flankers. It can be seen in Figure 4(c).

$$Category\ index = Acc_{letter} - \left(Acc_{number} + Acc_{symbol}\right)/2$$

According to the results, we found a significant effect of flanker type condition and exposure time condition, but no significant interaction effect existed between flanker type and exposure time. Furthermore, the accuracy was increased linearly with exposure time. Analysis of the results found that the condition with letter flanker performance was higher than other conditions. Subsequently, the category index was used to measure the advantage of letter flanker condition. We found that the category index changed in an inverted U shape with exposure time, which predicted that the relationship between category effect and exposure time might be more complicated.

Interestingly, the results of 50 ms exposure time showed a fluctuation. Conversely, the results of 150 ms exposure time became more concentrated. This phenomenon could be originated in the change of the target-flanker-gap. In Experiment 2, the target-flanker-gap was 5 deg, so the target was always in a strong crowding. This layout might lead to difficulty in identification. Besides, the accuracy's sensitivity is also lower when the exposure time is long enough than the critical spacing. Overall, this experiment further explored the temporal property of flanker category effect, and the result consistent with the finding in Experiment 1.

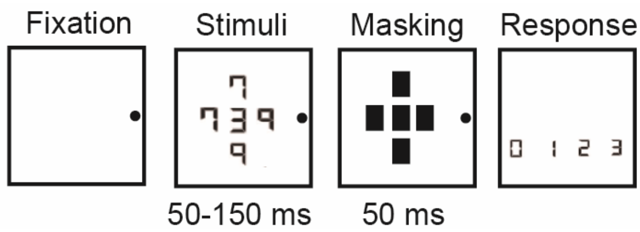
5 Experiment 3: the relationship between category index and exposure time with masking

To further test the role of processing depth in category effect, a masking stimulus was displayed when the target and the flankers disappeared in this experiment.

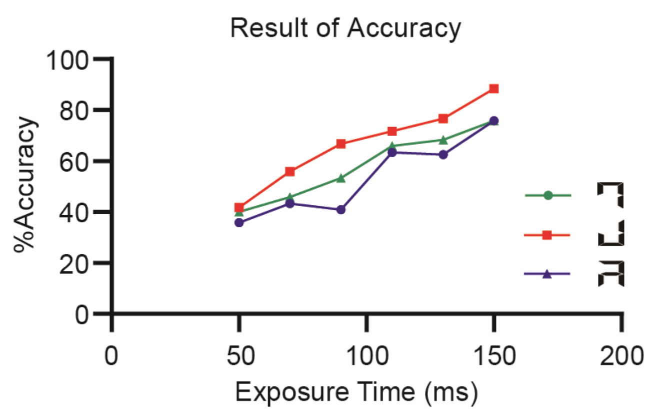
5.1 Method

Experiments 3 used the same procedures as Experiment 2. The only difference was a masking stimulus displayed in 50 ms after the target stimulus disappeared.

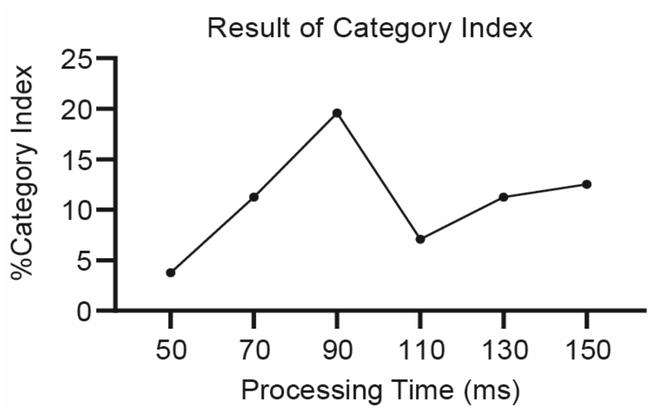
Figure 5 Procedure and results for Experiment 3 (see online version for colours)



(a)



(b)



(c)

Note: Figure 5(a) shows the schematic of experimental flow in Experiment 3.

Experiment 3 consisted of two conditions: three levels in flanker category and six levels in exposure time. There were 18 levels (six kinds of exposure time × three kinds of flanker) in this experiment. Each level consisted of 75 trials. The trials were arranged randomly. The experiment of each condition was performed individually; it was divided into nine blocks. The experiment was repeated three times, and the data were averaged. The procedure of experiments was presented in Figure 5(a).

5.2 *Results and discussion*

5.2.1 *Accuracy*

The performance of the task was calculated by accuracy. The results are presented in Figure 5(b). A two-way repeated measure ANOVA uncovered a significant effect of exposure time [$F(2.367, 7.102) = 34.883$, $P < .001$] and the type of flankers [$F(1.454, 4.361) = 28.991$, $P = .004$]. There is no significant interaction effect between exposure time and type of flankers [$F(2.333, 7.000) = 1.030$, $P = .418$]. Greenhouse-Geisser corrections were applied.

5.2.2 *Linear fitting*

In Experiment 3, we used the same analysis method as Experiment 2. The Pearson correlation coefficient close to 0.9 under various conditions (number flanker: 0.89**, letter flanker: 0.97** and symbol flanker: 0.98**).

5.2.3 *Category index*

Figure 5(c) shows that the category index is above 5%, and the highest index occurred when the processing time was 90 ms.

In Experiment 3, we used a visual masking method to provide precise temporal courses. The experimental results' trend is consistent with Experiment 2. We found a significant effect of flanker type condition and exposure time condition, but no interaction between flanker and time.

6 Experiment 4: the relationship between category index and ISI

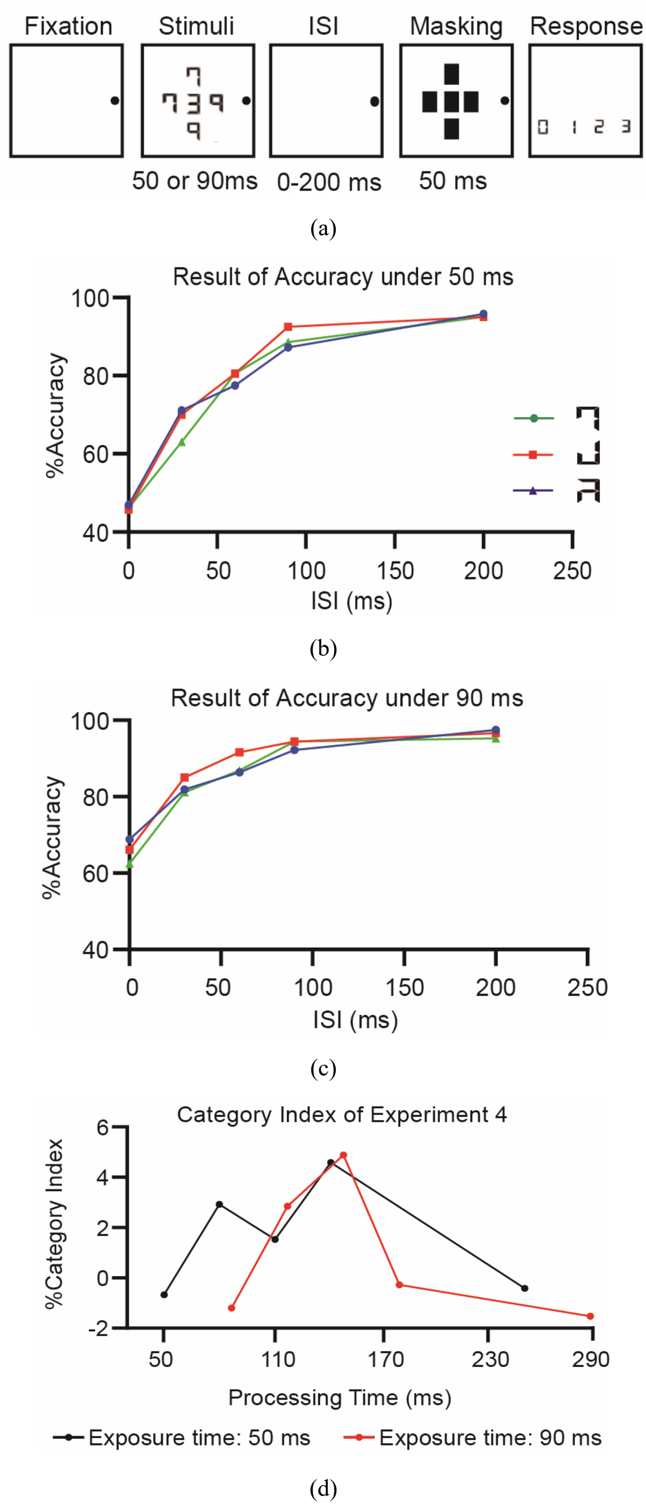
In Experiment 4, we introduce the concept of ISI. ISI is the time between stimulus presentations. Here, ISI is used to describe the interval between the target stimulus and masking. In this experiment, ISI is used to study the occurrence time of flanker category effect.

6.1 *Method*

Experiment 4 consisted of three conditions, included three levels in flanker category (number, letter and symbol flanker), two exposure time (50 ms and 90 ms), and five levels in the ISI (0, 30, 60, 90 and 200 ms), totally 30 levels. Each level consisted of 75 trials, which were arranged randomly. Experiment 4 was divided into 15 blocks. Each block included 150 trials in all experiments.

Experiments 4 used the same procedures as Experiment 3, except for an ISI for 0–200 ms displayed between target stimuli and masking stimuli. The experiment was repeated five times, and the data were averaged. The procedure of experiments was presented in Figure 6(a).

Figure 6 Procedure and results for Experiment 4 (see online version for colours)



Note: Figure 6(a) shows the schematic of experimental flow in Experiment 4.

6.2 Results and discussion

6.2.1 Accuracy

The performance of the task was calculated by accuracy. The results are presented in Figures 6(b) and 6(c). A repeated measure ANOVA uncovered a significant effect of exposure time [$F(1, 5) = 103.924$, $P < .001$] and ISI [$F(1.563, 7.813) = 8.915$, $P < .001$]. There is a marginally significant of category [$F(1.588, 7.813) = 7.941$, $P = .107$]. The interaction test was significant between exposure time and ISI [$F(2.039, 10.197) = 6.348$, $P = .016$]. However, no significant differences were found in other conditions. Greenhouse-Geisser corrections were applied.

6.2.2 Linear fitting

We conducted linear fitting to assess the effect of ISI. Figure 6(b) presented the accuracy under three conditions when exposure time is 50 ms. The Pearson correlation coefficient close to 0.7 under various conditions (number flanker: 0.76, letter flanker: 0.68 and symbol flanker: 0.75). There was no significant linear correlation between ISI and accuracy.

Figure 6(c) presented the accuracy when exposure time is 90 ms. The Pearson correlation coefficient close to 0.7 under various conditions (number flanker: 0.79*, letter flanker: 0.58 and symbol flanker: 0.63).

6.2.3 Category index

The results of category index are displayed in Figure 6(d). Processing time is the sum of exposure time and interval time. The peak of category index was found when processing time ranged from 100 ms to 150 ms.

Table 2 The parameters for logistic curve fitting

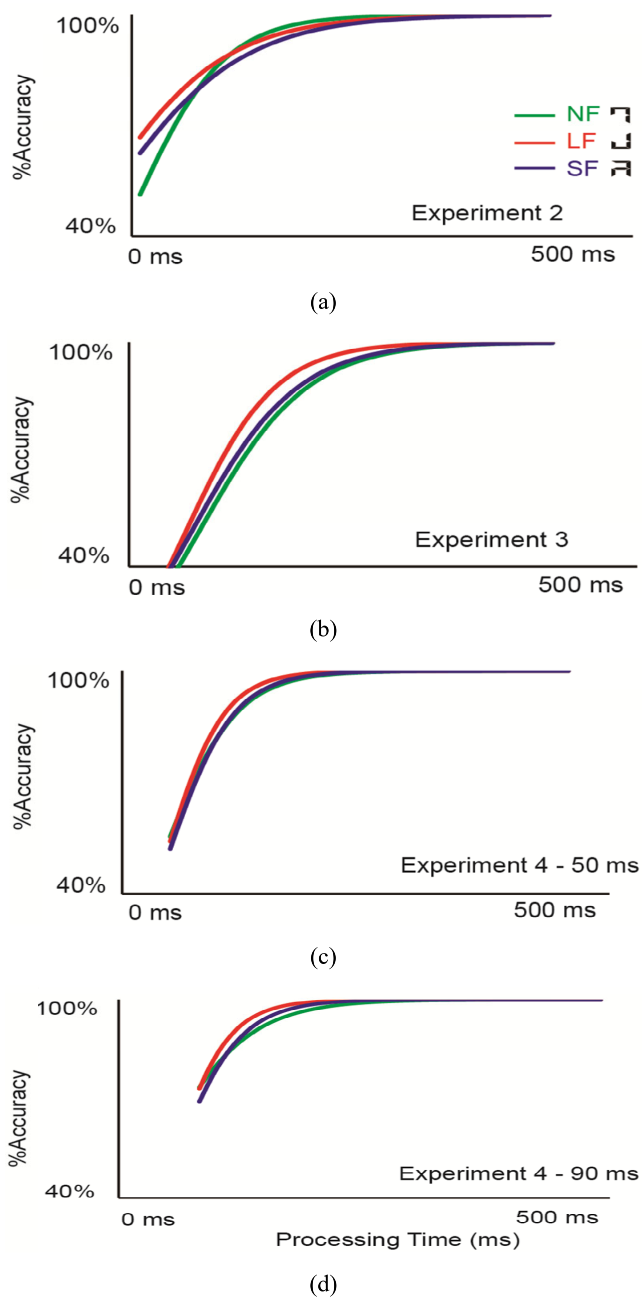
Experiment	*Parameter*	*NF*	*LF*	*SF*
Experiment 2	*a*	1	1	1
	b	1.15	0.57	0.68
	c	19.25	13.3	12.55
Experiment 3	*a*	1	1	1
	b	3.78	3.71	3.37
	c	15.79	19.14	16.1
Experiment 4 by 50 ms	*a*	1	1	1
	b	1.01	1.13	1.18
	c	22.54	28.09	24.76
Experiment 4 by 90 ms	*a*	1	1	1
	b	0.43	0.49	0.57
	c	18.2	29.04	24.91

6.2.4 Curve fitting

It was found out that the linear model is not good for Experiment 4. To compare the three experiments included Experiment 2, Experiment 3 and Experiment 4. The processing time and accuracy were analysed by curve-fitting analysis. The curve was generated by logistic law. The results of the fits are shown in Figure 7, and the fitting parameters are listed in Table 2.

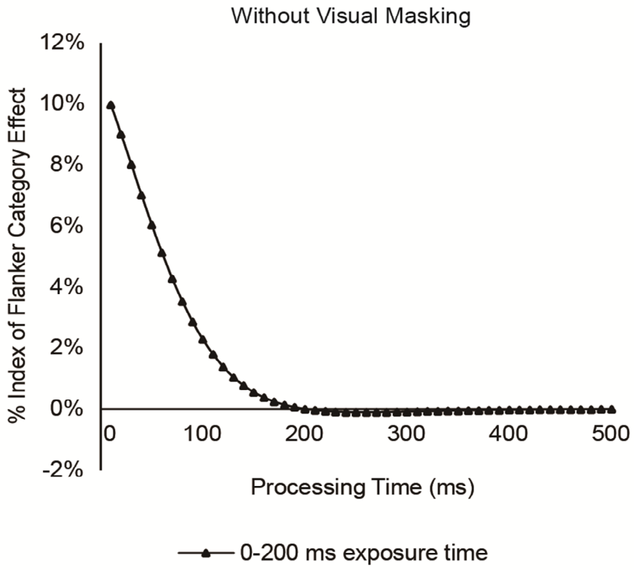
$$Acc = a / \left[1 + b \times \exp(-c \times processing\ time)\right]$$

Figure 7 Relationship between processing time and accuracy (see online version for colours)

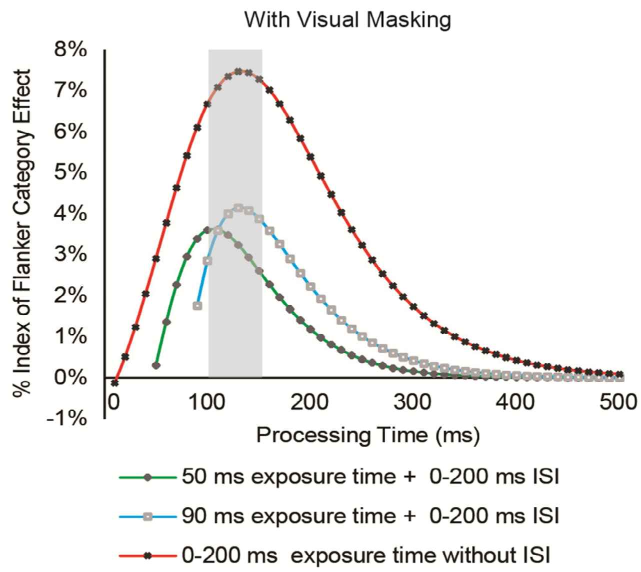


Notes: The curve was generated using a logistic law. Experiment 2 indicated in Figure 7(a), Experiment 3 indicated in Figure 7(b), Experiment 4 indicated in Figures 7(c) and 7(d). Figure 7(e) shows the relationship between processing time and category index with visual masking. Figure 7(f) shows the relationship between processing time and category index with visual masking. The processing time in Experiment 4 is the sum of exposure time and ISI time.

Figure 7 Relationship between processing time and accuracy (continued) (see online version for colours)



(e)



(f)

Notes: The curve was generated using a logistic law. Experiment 2 indicated in Figure 7(a), Experiment 3 indicated in Figure 7(b), Experiment 4 indicated in Figures 7(c) and 7(d). Figure 7(e) shows the relationship between processing time and category index with visual masking. Figure 7(f) shows the relationship between processing time and category index with visual masking. The processing time in Experiment 4 is the sum of exposure time and ISI time.

Using all four fitting results, we calculated the category index again. In this analysis, the two kinds of temporal factors (expose time and ISI) are included in the comparison criteria to discuss the effect of processing time. The trend of category index differences between Experiment 2 (without visual masking) and Experiments 3 and 4 (with visual masking) highlighted in Figures 7(e) and 7(f).

Overall, these results indicate that processing time has a clear effect on category index. The masking stimulus also determines the temporal property of flanker category effect.

7 General discussion

As mentioned in the introduction, processing time might be an important factor influencing multi-level crowding. One of the aims of this study was to explore the effect of high-level information on crowding intensity at different processing times. The core hypothesis is that the effect of flanker category might be modulated by processing time. To test our hypotheses, we designed four experiments.

In Experiment 1, we explored the temporal property of flanker category effect to replicate and extend category effect documented by a previous study (Reuther and Chakravarthi, 2014). The experimental data suggested that flankers' category information cannot reduce crowding when the exposure duration is short. This result may be explained by the fact that the letter flankers were recognised as meaningless clutter. However, the number flankers are easily integrated into one target with a number target. Therefore, the number flanker's crowding is weaker than letter and symbol flanker in short exposure time. Under the condition of long exposure time, the result was consistent with the previous study.

The second question in this study was to know how the influence of category information changes with the processing depth. A series of experiments were performed.

In Experiment 2, we found that the category effect changed in an inverted U shape with exposure time. This finding was unexpected and suggested that the category information's action mechanism might be changed in different exposure times. In Experiment 3, we have further tested the category effect by using visual masking to validate our conclusion. The result is in agreement with Experiments 1 and 2. In Experiment 4, we used processing time to measure category information's role and found the category effect time window.

According to the above experimental results, the most obvious finding emerged from the analysis is that the flanking category effect's peak occurs at the time window of 100–150 ms after the stimulus appears. This result may be explained by object recognition theory (Humphreys et al., 1999; Riddoch and Humphreys, 2001). From the traditional views, the category effect should in the late stage of visual processing. However, from the perspective of occurrence time, flanker category effect starts from the grouping stage. The theory of feedforward and feedback processing might explain this visual phenomenon more clearly (Kafaligonul et al., 2015). Flanking category effect occurs on mid-level vision, and it adopts a short time window to pick out separate objects (Wutz and Melcher, 2014).

Another important finding is that masking stimulus determines the temporal property of flanker category effect. This result is in accord with the previous research, which shows that masking method is a precise paradigm to explore the temporal question (Breitmeyer et al., 2006).

Surprisingly, we used the same parameter of 90 ms exposure time and 0 ms interval in Experiment 3 and Experiment 4, but the category index results were different. There are two likely causes for the differences between masking condition and ISI condition. One of the causes might be that the difficulty of other trials in the experiment affected the cognitive strategies of the observers. Another possibility is that visual memory is used more in ISI experiment, which leads to a decline in the influence of high-level information from flankers. These findings suggest that multi-level crowding is a dynamic process affected by processing time.

These are particularly useful results. These findings might help others to design an experiment of temporal studies using imaging and electrophysiological method.

8 Conclusions

The current study aimed to determine temporal factors for the flanker category effect under visual crowding. The experimental data suggest that the flanking category effect's peak occurs at the time window of 100–150 ms after the stimulus appears. The masking stimulus also determines the temporal property of flanker category effect. This study's contribution has been to confirm that processing depth can adjust the influence of high-level information on crowding. The strengths of the study included an in-depth analysis of category effect under various temporal conditions. Although the study has successfully demonstrated that the category effect is modulated by processing time, it has certain limitations in exploring brain mechanisms. Further electrophysiology studies need to be carried out to validate the temporal property of multi-level crowding.

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