Acta Psychologica 143 (2013) 7–13

Contents lists available at SciVerse ScienceDirect

Acta Psychologica

journal homepage: www.elsevier.com/ locate/actpsy

Asymmetry of congruency effects in spatial Stroop tasks can be eliminated

Chunming Luo [a,*], Robert W. Proctor [b]

[a] Key Laboratory of Behavioral Science, Institute of Psychology, Chinese Academy of Sciences, China
[b] Department of Psychological Sciences, Purdue University, West Lafayette, IN, USA

ARTICLE INFO

Article history:
Received 8 August 2012
Received in revised form 22 January 2013
Accepted 29 January 2013
Available online 20 March 2013

PsycINFO classification:
2340 Cognitive Processes
2346 Attention

Keywords:
Interference asymmetry
Simon effect
Spatial Stroop task
Stroop effect

ABSTRACT

Three experiments examined whether asymmetry in interference can be eliminated in spatial Stroop tasks. In Experiment 1, responding to arrows or location words written in Chinese and to their locations created spatial Stroop effects of similar sizes. In Experiment 2, responding to a location word embedded in an outline drawing of arrow did not yield a spatial Stroop effect, but responding to the arrow's direction did yield an effect. In Experiment 3, responding to a location word flanked by an arrow and to the arrow rather than the word produced similar sizes of spatial Stroop effects. These results show that asymmetry in spatial Stroop interference can be eliminated in some situations. Although aspects of the results are consistent with predictions of translation and dimensional overlap models, they are in closest agreement overall with an account in terms of the relative strengths of the relevant and irrelevant stimulus–response associations.

1. Introduction

Human behavior in many situations is influenced by task-irrelevant information. Many studies have examined how and why irrelevant information affects performance by using two-dimensional stimuli, with one dimension designated as task-relevant and the other as irrelevant (e.g., Lu & Proctor, 2001). One of the most widely investigated phenomena of this type is the Stroop effect (e.g., MacLeod, 1991). In the Stroop color-naming task, the irrelevant color word affects the time to name the relevant dimension of stimulus color. However, when stimulus color is irrelevant, it does not affect the time to read the color word (e.g., Dunbar & MacLeod, 1984; Glaser & Glaser, 1982; Stroop, 1935), indicating that the direction of effect for the stimulus dimensions is asymmetric. An asymmetric relation has also been found in a spatial variant of the Stroop task (see Lu & Proctor, 1995, for review), in which an irrelevant location word affects the time to name the relevant stimulus location, but irrelevant stimulus location exerts little influence on naming the location word (e.g., O'Leary & Barber, 1993; Seymour, 1973; Virzi & Egeth, 1985). This asymmetric relation in the spatial Stroop task is reversed for keypress responses, with irrelevant stimulus location affecting the time to respond to the word but not vice versa (Logan, 1980; Logan & Zbrodoff, 1979; O'Leary & Barber, 1993; Virzi & Egeth, 1985).

Closely related to the spatial Stroop effect is the Simon effect, which refers to the finding that, for tasks in which stimulus location is defined as irrelevant and a non-spatial dimension (e.g., stimulus color) as relevant, responses are still faster and more accurate when the stimulus appears in the same relative location as the response (see Lu & Proctor, 1995, for review; Treccani, Umiltà, & Tagliabue, 2006). In the Simon task, when stimulus location is irrelevant it influences reaction time (RT) to the relevant dimension, but when stimulus location is relevant the irrelevant non-spatial dimension has no influence on RT (e.g., Umiltà & Nicoletti, 1990).

Although the congruency effect for irrelevant information is asymmetric in the Simon task and in the color and spatial Stroop tasks, it is bi-directional and symmetric in some versions of Stroop-like tasks. For instance, when participants are to respond to color Stroop stimuli with keypresses, the irrelevant dimension influences performance irrespective of whether it is the color or color word (e.g., Melara & Mounts, 1993; Simon & Berbaum, 1990). Thus, any model intended to explain performance in tasks for which one stimulus dimension is irrelevant and another relevant must be able to produce the asymmetric effect patterns found for the Simon and basic Stroop tasks, as well as the symmetric effect pattern found for some versions of Stroop-like tasks.

1.1. Explanations of interference asymmetry in the spatial Stroop task

Several accounts have been offered to explain asymmetry in the spatial Stroop task. According to Virzi and Egeth's (1985) translation model, an irrelevant dimension affects performance whenever a

* Corresponding author at: Key Laboratory of Behavioral Science, Institute of Psychology, Chinese Academy of Sciences, 4A Datun Road, Chaoyang District, Beijing 100101, China. Tel.: +86 10 6487 6719.
E-mail address: luocm@psych.ac.cn (C. Luo).

0001-6918/$ – see front matter
http://dx.doi.org/10.1016/j.actpsy.2013.01.016

translation between systems is needed to respond correctly to the target. That is, words and physical locations are assumed to be processed in separate systems, each of which operates on its own codes. For a participant to make a keypress to the word, the verbal code must engage a translation module so as to be converted into a physical location code. Engaging the translation module causes interference. For a participant to respond to the location by keypress, no translation is necessary because the stimulus location is already in the location code. Consequently, there is no spatial Stroop effect.

Kornblum (1992) and Kornblum, Hasbroucq, and Osman (1990) proposed that dimensional overlap can be used as a criterion for categorizing tasks and explaining congruency effects in the Simon, Stroop, and spatial Stroop tasks. According to Kornblum's (1992) dimensional overlap model, an irrelevant stimulus dimension affects performance only when it overlaps with the relevant stimulus dimension [stimulus–stimulus (S–S) overlap], the response dimension (irrelevant S–R overlap), or both. For S–S overlap, identity codes are created for both dimensions. If these identity codes conflict, this conflict must be resolved by determining which code is relevant. For irrelevant stimulus–response (S–R) overlap, the irrelevant attribute automatically activates its corresponding response. If this primed response conflicts with the response identified for the relevant stimulus dimension, then it must be inhibited and the correct response programmed and executed. Because dimensional overlap can vary in degree, the size of the S–S and S–R congruency effects will vary according to the amount of overlap (Oliver & Kornblum, 1991). Also, when both S–S and irrelevant S–R overlap are present, their effects will be additive.

Lu and Proctor (2001) also put forward an S–R association strength account for the size of congruency effects for irrelevant information in Stroop-like tasks. According to this account, whether congruent effect patterns are symmetric or asymmetric is determined by the relative strengths of the relevant and irrelevant S–R associations, as specified by the criteria of conceptual similarity and mode similarity (also sometimes called perceptual similarity, e.g., Proctor, Wang, & Vu, 2002). Conceptual similarity exists when the members of the S–R set refer to the same concepts (e.g., the words "left"–"right" mapped to left–right keypresses). Mode similarity exists when the stimulus code (e.g., verbal, spatial) corresponds to the response modality (e.g., spoken "left"–"right" responses have higher perceptual similarity with the words "left"–"right" than do left–right keypresses). The size of the congruency effect is also a function of the temporal overlap of the resulting response activation, that is, the temporal distance between the coding of the relevant stimulus and the coding of the irrelevant location information, which is determined primarily by mode similarity.

Besides the three accounts described above, there are other models that are mainly used to explain the color–word Stroop effects. On the dominant automaticity view, reading the word is fast, ballistic, and obligatory, whereas naming the color is slower, voluntary and effortful. Consequently, the Stroop effect is due to people's efforts to inhibit their automatic tendencies to read the word when responding to the colors. Modern theories of automatic activation (e.g., Cohen, Dunbar, & McClelland, 1990; Logan, 1980) assert that automaticity is a continuum (rather than being all-or-none) and that evidence increases continuously toward alternative responses until a threshold is reached, allowing for color and word interaction to occur throughout the course of processing. The three-layer network of Cohen et al. (1990) works by accumulating evidence forward along the color and word pathways so that the total activation received by the output units (color, word) determine which will first cross its threshold for responding.

Other theories of the Stroop effect (e.g., Phaf, Van der Heijden, & Hudson, 1990; Roelofs, 2003) share a common assumption that color–word interaction occurs at some stage of processing. Typically, the interaction is governed by the automatic dominance of word over color when the two clash within the semantic conflict engendered by the specific makeup of the Stroop (incongruent) stimulus. Different from the above Stroop-effect models, the tectonic theory of Melara and Algom (2003) minimizes the role of automatic activation and semantic conflict in creating the Stroop effect. Those authors assert that the Stroop effect is mutable, molded through the confluence of contexts. Slight stimulus manipulations (e.g., making the color more salient than the word, reducing the correlation over trials between word and color, presenting more colors than words) can eliminate or reverse the Stroop effect (Melara & Algom, 2003; Melara & Mounts, 1993; Sabri, Melara, & Algom, 2001). This plastic, contextual basis of the Stroop phenomenon is incompatible with strong automaticity.

1.2. The purpose and main manipulation

The main purpose of the current study was to examine whether the three accounts of the spatial Stroop effect described in the first part of Section 1.1 can predict the relative size of the congruency effect created by an irrelevant stimulus dimension in spatial Stroop tasks that combine physical locations and location words written in Chinese or arrows in Experiment 1, and arrows and location words written in Chinese in Experiments 2 and 3. We also consider implications of these results for the other theories developed mainly for the color–word Stroop effect in the General discussion.

Different from the prior studies using left–right keypresses paired with left and right stimulus information, in the current study, left–right keypresses were paired with up and down stimulus dimensions. This manipulation allowed measurement of a relatively pure S–S spatial congruency or spatial Stroop effect, given that the responding hand (whether left or right) was orthogonal to the location and direction of the arrow (up/down) and the meaning of the word (up/down) (e.g., Luo, Lupiáñez, Fu, & Weng, 2010; Lupiáñez & Funes, 2005; but see Cho, Proctor, & Yamaguchi, 2008, and Nishimura & Yokosawa, 2006, for Simon effects occurring when the spatial stimulus dimension is orthogonal to the response dimension). Moreover, in the current study, the location words were 上 (up) and 下 (down), two simple Chinese characters that can function as single words.

2. Experiment 1

Using a version of spatial Stroop task that combines location words and physical locations (e.g., the words RIGHT or LEFT appear to the right or left of a central fixation sign), some studies found that reading the location word is little influenced by a conflicting physical location, but naming the location occupied by the word is slowed if a conflicting location word appears in that location (e.g., O'Leary & Barber, 1993; Seymour, 1973; Virzi & Egeth, 1985). However, this asymmetric relation is reversed when the responses are keypresses (e.g., Logan, 1980; Logan & Zbrodoff, 1979; O'Leary & Barber, 1993; Palef & Olson, 1975; Virzi & Egeth, 1985).

By contrast, few studies have investigated whether an asymmetric relation also exists in the spatial Stroop task that combines arrows with physical locations (e.g., an up or down pointing arrow appearing above or below the central fixation cross). Some studies, though, have found that specifying the direction in which an arrow points with a keypress is affected by a conflicting spatial location (e.g., Danziger, Kingstone, & Ward, 2001; Luo et al., 2010; Luo, Lupiáñez, Funes, & Fu, 2010; Luo, Lupiáñez, Funes, & Fu, 2011; Lupiáñez & Funes, 2005). Others have shown that specifying the physical location of an arrow relative to the central fixation cross also is affected by a conflicting pointing direction with both keypresses (e.g., Clark & Brownell, 1975; Shimamura, 1987) and vocal responses (e.g., Shimamura, 1987).

In Experiment 1 we examined performance patterns for keypress versions of spatial Stroop tasks, with the word and arrow or the physical location of the stimulus defined as the relevant dimension. The translation model predicts that response to physical location will create a smaller spatial Stroop effect than response to arrow or word, because response to arrow or word needs to engage a translation, but response to location need not do so. Kornblum's (1992) dimensional overlap model predicts that the spatial Stroop effect will be no different regardless of whether the responses are made to word and arrow or location, because there is the same degree of S–S overlap (but no S–R overlap) in each case, given that the responding hand (left or right) was orthogonal to the location and direction of the arrow (up/down) and the meaning of the word (up/down) (e.g., Luo et al., 2010; Lupiáñez & Funes, 2005).

According to the S–R association strength account of Lu and Proctor (2001), conceptual similarity should be identical for either word or arrow combined with physical location, because their meanings all refer to up and down. With regard to mode similarity, as implied by the findings of previous studies (e.g., Logan, 1980; Logan & Zbrodoff, 1979; O'Leary & Barber, 1993; Palef & Olson, 1975), the association of the stimulus dimension with the corresponding keypress response is stronger for physical location (both are spatial) than for location word (i.e., the stimulus dimension is verbal and the response is non-verbal). However, no difference exists in the association of the stimulus dimension with the corresponding keypress response for physical location and arrows, because the compatibility of arrows with keypresses is higher than that of words with keypresses (Lu & Proctor, 2001; Wang & Proctor, 1996) and arrows tend to directly activate their corresponding keypress responses much as do stimuli presented in distinct physical locations (Eimer, 1995; but see Miles & Proctor, 2012, for evidence that irrelevant arrows are sometimes coded more like location words). This association strength account predicts that the spatial Stroop effect should be smaller for responses to physical location than to location word, but it should be no different for responses to physical location and arrow conditions.

2.1. Method

2.1.1. Participants

Twenty participants (8 males), aged from 19 to 22 years, took part in this experiment. All had normal or corrected-to-normal vision and were naive to the purpose of the experiment.

2.1.2. Apparatus, stimuli, procedure, design

Stimuli were presented in white on a super VGA high-resolution color monitor with black background. A Lenovo-compatible computer, running E-Prime 1.1 software, controlled the presentation of stimuli, timing operations, and data collection. Participants rested their heads on a chinrest and viewed the monitor from a distance of 57 cm in a dimly lit room.

The stimuli were created by presenting a Chinese character [上 (up) or 下 (down)] or an arrow [🡅 (up-pointing) or 🡇 (down-pointing)] in an above or below location on the screen. The two locations were symmetric to the horizontal middle line of the screen, separated by 8 cm. The visual angle for each arrow or Chinese character was 1.2°×1.4°.

Each participant took part in two sessions of trials. Half of the participants first performed session A and then session B, and vice versa for the other half, with a rest interval of 5 min between them. In session A, the task was to respond on each trial to a word [上 (up) or 下 (down)] or to an arrow pointing up or down. In session B, the task was to respond to the location occupied by each word or arrow.

For each task, every participant received two blocks of trials for words and two for arrows, the orders of which were randomized. Each block had 72 test trials preceded by 12 practice trials, which were excluded from the analyses. A trial began with onset of a central fixation cross (0.4°×0.4°). After 1 s, a word or arrow in white appeared and remained visible until the participant responded or for 1500 ms if no response was made. Then the next trial began. The interval between trials was 1 s, and the screen remained black throughout this interval.

Responses were made by pressing a left key (C) or right key (M) on the computer keyboard with the left or right index finger. The response keys and computer screen were aligned such that the fixation point and the midway point between the two response keys were on the participant's sagittal midline. Participants were instructed to maintain fixation and to respond to the targets as quickly and accurately as possible.

For the task of responding to the meaning of location words and arrows, participants were to press the C key for up and the M key for down in one block of trials for words and to use the reverse mapping in the other block, as was also true for up and down pointing arrows. For the task in response to physical locations occupied by location words and arrows, both mappings of physical locations to responses were used in different trial blocks for both words and arrows, except that the task was to judge the location occupied by words or arrows relative to the center of screen by keypress.

This experiment had a 2 (task type: respond to stimulus, respond to location)×2 (stimulus type: word, arrow)×2 (spatial Stroop: congruent, incongruent) design, with 72 observations per experimental condition.

2.2. Results

Mean correct response times (RTs) and percent errors (PEs) are presented in Table 1. An analysis of variance (ANOVA) was performed separately on RT and PE, with task type (response to stimulus vs. response to location), stimulus type (word vs. arrow) and spatial Stroop (congruent vs. incongruent relevant and irrelevant stimulus dimensions) as within-participant variables.

The analysis of RT revealed two main effects, spatial Stroop, $F(1, 19)=92.11$, $p<.001$, $MSE=344$, $\eta_p^2=.829$, for which the overall Stroop effect was 28 ms, and task type, $F(1, 19)=90.88$, $p<.001$, $MSE=3343$, $\eta_p^2=.827$, with slower responses to the words and arrows ($M=$ 501 ms) than to their locations ($M=435$ ms). The main effect of stimulus type did not attain the .05 level, $F(1, 34)=3.06$, $p=.096$, $MSE=704$, $\eta_p^2=.139$. The stimulus type×spatial Stroop interaction also was not significant, $F(1, 19)=1.85$, $p=.189$, $MSE=1495$, $\eta_p^2=.089$, nor was the other interactions ($Fs<1$).

The analysis of PE showed two main effects, spatial Stroop, $F(1, 19)=$ 21.52, $p<.001$, $MSE=.001$, $\eta_p^2=.531$, indicating an overall Stroop effect of 1.6%, and task type, $F(1, 19)=8.91$, $p=.008$, $MSE=.001$, $\eta_p^2=.319$, with more errors when responding to arrows and words ($M=3.3\%$) than to locations ($M=2.1\%$). The main effect of stimulus type was not significant, $F(1, 19)=2.60$, $p=.123$, $MSE=.001$, $\eta_p^2=.120$. The three-way interaction was not reliable, $F(1, 19)=2.29$, $p=.147$, $MSE=$ .00004, $\eta_p^2=.107$, nor was the remaining two-way interactions ($Fs<1$).

2.3. Discussion

The spatial Stroop effect in response to arrows was not statistically different from that in response to locations occupied by arrows, indicating that no significant asymmetry relation occurred for arrows. This

Table 1
Mean reaction time (in ms), percent error and their separate standard error (in parentheses) as a function of task type, stimulus type and spatial Stroop in Experiment 1, respectively. Effect size = incongruent–congruent.

	Response to word and arrow		Response to location	
	Word	Arrow	Word	Arrow
Congruent				
RT	502(16)	516(17)	421(19)	420(18)
PE	1.6(.004)	3.2(.008)	1.4(.004)	1.3(.003)
Incongruent				
RT	527(15)	544(17)	451(24)	449(21)
PE	4.1(.008)	4.4(.009)	2.5(.007)	3.0(.007)
Effect size				
RT	25(4)	28(5)	30(5)	29(5)
PE	2.5(.179)	1.2(.200)	1.1(.161)	1.7(.185)

outcome is in agreement with evidence suggesting that arrows tend to activate their corresponding keypress responses much as do stimuli presented in distinct physical locations (Eimer, 1995) and have higher compatibility with keypresses than do location words (e.g., Wang & Proctor, 1996). Similarly, the spatial Stroop effect in response to location words also was not statistically different from that in response to locations occupied by location words, indicating no significant asymmetry relation occurred for location words. This symmetric relation for location words had not occurred in previous studies using left–right keypresses paired with the words "left" and "right" (e.g., Logan, 1980; Logan & Zbrodoff, 1979; O'Leary & Barber, 1993; Palef & Olson, 1975), all of which obtained an asymmetric relation for location words. This disparity might be because the location words [上 (up) and 下 (down)] still maintain the rudiments of the original pictograph and are formed via logographic orthography, in a similar way to which arrows are, which may result in the absence of asymmetric relation. For instance, previous studies found that the logographic characteristics of stimuli could affect the magnitude of spatial Stroop effect (e.g., Moriguchi & Morikawa, 1998; Morikawa, 1981; Shimamura, 1987). Phonetic symbols (e.g., English words or Kana words in Japanese) produced less Stroop or reverse Stroop interference in a color-naming task (e.g., Moriguchi & Morikawa, 1998; Morikawa, 1981; Shimamura, 1987) and less spatial Stroop interference in a spatial location task than logographic symbols (e.g., Kanji words in Japanese, Shimamura, 1987). Moreover, conflicting arrows and Kanji words created similar interference, which was more than that for conflicting Kana words, in a spatial location task.

The findings of the present experiment are inconsistent with predictions of the translation model, but fit with predictions of the dimensional overlap model because the amount of S–S overlap is similar regardless of which dimension is relevant to responding. The S–R association strength account can easily explain the results for the arrows, but it has more difficulty with the results for the words. However, it can explain them as well if it is assumed that the logographic characteristics of the location words (上 and 下) cause temporal overlap between the coding of the words and the coding of location information, and making the words like the arrows.

3. Experiment 2

Shor (1970) conducted experiments using a spatial and pictorial analog to the standard Stroop task in which the location word up, down, left, or right was embedded within an outline drawing of an arrow pointing in one of the four directions. Naming the direction in which the arrow pointed took longer than naming the location word. Moreover, naming the direction of the arrow was slowed when the location word was incongruent, but naming the location word was not slowed by an incongruent arrow direction. Shor, Hatch, Hudson, Landrigan, and Shaffer (1972) showed that the spatial Stroop effect for naming the arrow direction persisted even after extended practice. Aarts, Roelofs, and Van Turennout (2009) used a similar paradigm, in which the location word left or right was embedded within an outline drawing of a left or right arrow. In contrast to the results of Shor (1970) and Shor et al. (1972), Aarts et al. (2009) observed that responding to either the location word or the direction of the arrow manually created spatial Stroop interference, although the size of the effect of the former was larger than of the latter.

In this experiment, location words [上 (up) and 下 (down)] were used as Stroop stimuli, one of them was embedded within an outline drawing of an arrow pointing up or down for each trial. The task was to respond to the meaning of location word or the direction of the arrow by keypress, and the responding hand (whether left or right) was orthogonal to the location and direction of the arrow (up/down) and the meaning of the word (up/down).

As noted, prior studies have suggested that arrows tend to activate their corresponding keypress responses similarly to stimuli presented in distinct physical locations (Eimer, 1995), and that they have higher compatibility than words with keypresses (Lu & Proctor, 2001; Wang & Proctor, 1996). Therefore, the translation model predicts that response to location words will create a larger spatial Stroop effect than response to arrows, because response to words needs to engage a translation. Kornblum's (1992) dimensional overlap model predicts that the spatial Stroop effect will be no different regardless of responses to word or arrow, because only S–S overlap exists for each task, given that the responding hand (whether left or right) was orthogonal to the location and direction of the arrow (up/down) and the meaning of the word (up/down). According to the S–R association strength account, conceptual similarity is identical for response to either word or arrow, because their meanings all refer to up and down. As to mode similarity, the association of the stimulus dimension with the corresponding keypress response is stronger for arrow than for location word, as the compatibility of arrows with keypresses was higher than that of words and the arrows were larger than the words. This account predicts a smaller spatial Stroop effect for response to arrow than to location word.

3.1. Method

3.1.1. Participants

Twenty undergraduate students (10 males), aged from 18 to 23 years took part in the experiment for payment. All had normal or corrected-to-normal vision.

3.1.2. Apparatus, stimuli, procedure and design

The apparatus was identical to Experiment 1. The stimuli were white and the background was black. Each trial began with a fixation cross ($0.4° \times 0.4°$) that was presented for 1 s. When it went off the main display appeared on the center of screen, and it remained visible until the participant responded or for 1500 ms if no response was emitted. Then the next trial began. The interval between trials was 1 s, and the screen remained black throughout this interval. When the task was to identify the word, the main display included a word 上 (up) or 下 (down) embedded within an outline drawing of an arrow pointing up or down or of a rectangle that served as a neutral condition. When the task was to identify the direction of the arrow, the main display included a word 上 (up) or 下 (down) or 口 (mouth) embedded within an outline drawing of an arrow pointing up or down. The word 口 (mouth) condition functioned as a neutral one. The visual angle of each word was $1.2° \times 1.4°$ and of each arrow or rectangle was $2.3° \times 3.6°$. The word and the outline drawing were presented on the center of screen.

Each participant took part in two sessions of trials. Half of the participants first performed session A and then session B, and vice versa for the other half, with a rest interval of 30 min between them. In session A, the task was to respond to a word 上 (up) or 下 (down). In session B, the task was to respond to an arrow pointing up or down. Each session included two blocks of trials and their order was randomized for each participant. Each block included 108 test trials preceded by 12 practice trials that were excluded from the analysis.

As in Experiment 1, responses were made by pressing a left key (C) or right key (M) on the computer keyboard with the left or right index finger, and participants were instructed to maintain fixation and to respond to the targets as quickly and accurately as possible. For session A, in one block of trials, the task was to press the C key when the word is 上 (up), and to press the M key when the word is 下 (down), regardless of the arrow's direction, vice versa for the other block of trials. For session B, in one block of trials, the task was to press the C key when the arrow pointed up, and to press the M key when the arrow pointed down, regardless of the meaning of the word, vice versa for the other block of trials.

This experiment had a 2 (response task: response to word, response to arrow) × 3 (spatial Stroop: congruent, neutral, incongruent) design, with 72 observations per experimental condition.

3.2. Results and discussion

Mean correct RTs and PEs are presented in Table 2. The ANOVA on RTs revealed the main effects of response task, $F(1, 19) = 14.53$, $MSE = 8651$, $p < .001$, $\eta_p^2 = .433$, and spatial Stroop, $F(2, 38) = 30.93$, $MSE = 276$, $p < .001$, $\eta_p^2 = .619$, and their interaction, $F(2, 38) = 26.53$, $MSE = 304$, $p < .001$, $\eta_p^2 = .583$. Further analyses showed that the spatial Stroop effect was significant for responses to words, $F(2, 38) = 68.14$, $MSE = 243$, $p < .001$, $\eta_p^2 = .782$, but not for responses to arrows ($F < 1$). In the former case, RT was longer for incongruent than congruent, $t(19) = 9.02$, $p < .001$, and neutral conditions, $t(19) = 8.48$, $p < .001$, and for neutral than congruent conditions, $t(19) = 2.44$, $p = .009$.

The ANOVA on PEs revealed a main effect of spatial Stroop, $F(2, 38) = 9.63$, $MSE = .001$, $p < .001$, $\eta_p^2 = .336$, but the main effect of response task was not significant, $F(1, 19) = 2.93$, $MSE = .001$, $p = .103$, $\eta_p^2 = .134$. The interaction between response task and spatial Stroop was significant, $F(2, 38) = 12.68$, $MSE = .001$, $p < .001$, $\eta_p^2 = .400$. As for RT, further analyses showed that spatial Stroop was not significant for responses to arrows, $F(2, 38) = 2.03$, $MSE = .001$, $p = .170$, $\eta_p^2 = .097$, whereas it was for responses to words, $F(2, 38) = 15.33$, $MSE = .001$, $p < .001$, $\eta_p^2 = .447$. For words, more errors were made for incongruent than neutral, $t(19) = 4.00$, $p = .001$, and congruent conditions, $t(19) = 4.42$, $p < .001$, and the neutral condition tended to show a higher error rate than did the congruent condition, $t(19) = 1.89$, $p = .069$.

In this experiment, we observed that the keypress response to word was interfered with by the direction of the arrow, whereas the keypress response to arrow was not interfered with by meaning of the word, indicating an asymmetry relation. These findings are somewhat different from those in Aarts et al. (2009), which might arise from our manipulation with left–right keypresses paired with up and down stimulus dimensions. The findings of Experiment 2 are consistent with predictions of the translation model and the S–R association strength account, but are inconsistent with predictions of the dimensional overlap model.

4. Experiment 3

Some previous studies used a similar paradigm as in Experiment 3, but with a location word left or right flanked by a left or right-pointing arrow responded to by pressing a left key or right key (e.g., Baldo, Shimamura, & Prinzmetal, 1998; Lu & Proctor, 2001; Roelofs, Van Turennout, & Coles, 2006). Those studies also found that response to the location word was slowed when the direction of the arrow was incongruent, but response to the arrow direction was not slowed, or was less slowed, when the meaning of the location word was incongruent.

In Experiment 3, location words [上 (up) and 下 (down)] were used as Stroop stimuli, one of them being flanked by an up- or down-pointing arrow for each trial. The task was to respond to the words or arrows by keypress, and the responding hand (whether left or right) was orthogonal to the location and direction of the arrow (up/down) and the meaning of the word (up/down). The predictions of results by the translation model and the dimensional overlap model were identical to Experiment 2. According to the S–R association strength account, the association of the stimulus dimension with the corresponding keypress response is stronger for arrow than for location word, as the compatibility of arrows with keypresses is higher than that of words. But, the strength of association would be reduced relative to that in Experiment 2, as the size of arrows was equal to that of the words in Experiment 2. Consequently, this account predicts the difference of spatial Stroop effects for response to arrow and to location word should be reduced and even disappeared.

4.1. Method

4.1.1. Participants

Twenty undergraduate students (10 males), aged from 18 to 21 years took part in the experiment for payment. All had normal or corrected-to-normal vision.

4.1.2. Apparatus, stimuli, procedure and design

The apparatus, procedure and design were identical to Experiment 2. In this experiment, the main stimuli were white and the background was black, as presented in Table 3. When the task was to identify the word, the main display included a word 上 (up) or 下 (down) and a flanker that was an up- or down-pointing arrow or a rectangle (0.4° × 1.2°) that served as a neutral stimulus. When the task was to identify the direction of the arrow, the main display included an up- or down-pointing arrow and a word, which was 上 (up) or 下 (down) or 口 (mouth), which functioned as a neutral stimulus. The visual angle for each arrow or word was 1.2° × 1.4°. The task-relevant word or arrow and its flanker were randomly presented at two locations in the middle of the screen. They were separated by 0.2° of visual angle, with each being 0.1° from the center of the screen.

4.2. Results and discussion

Mean correct RTs and PEs are presented in Table 2. The ANOVA on RTs revealed a main effect of spatial Stroop, $F(2, 38) = 35.30$, $MSE = 363$, $p < .001$, $\eta_p^2 = .650$, with slower response in incongruent than

Table 2
Mean reaction time (in ms), percent error and their separate standard error (in parentheses) as a function of task type and spatial Stroop in Experiments 2 and 3, respectively. RW = response to word, RA = response to arrow and effect size = incongruent–congruent.

	Experiment 2		Experiment 3	
	RW	RA	RW	RA
Congruent				
RT	509(19)	464(19)	500(12)	499(11)
PE	1.7(.005)	3.6(.007)	2.2(.004)	3.0(.006)
Incongruent				
RT	563(19)	465(17)	532(16)	527(13)
PE	6.9(.012)	2.7(.007)	6.4(.012)	5.4(.010)
Neutral				
RT	518(18)	466(20)	494(13)	501(13)
PE	3.3(.010)	2.4(.005)	2.3(.005)	2.8(.006)
Effect size				
RT	54(5)	1(5)	32(5)	28(4)
PE	5.2(.228)	−.9(.190)	4.2(.233)	2.4(.181)

Table 3
The main stimuli used in Experiment 3. The left half represents response to arrow condition, and the right half represents response to word condition.

Response to arrow			Response to word		
Congruent	Incongruent	Neutral	Congruent	Incongruent	Neutral
↑上	↑下	↑口	↑上	↑下	下▮
上↑	下↑	口↑	上↑	下↑	▮下
↓下	↓上	↓口	↓下	↓上	上▮
下↓	上↓	口↓	下↓	上↓	▮上

neutral, $t(19)=6.23$, $p<.001$, and congruent conditions, $t(19)=7.11$, $p<.001$, for which there was no difference, $t(19)=.600$, $p=.558$. The main effect of response task was not significant ($F<1$), nor was the interaction, $F(2, 38)=1.26$, $MSE=239$, $p=.295$, $\eta_p^2=.062$, with the Stroop effect being 32 ms for responses to words and 28 ms for responses to arrows.

The ANOVA on PEs revealed a main effect of spatial Stroop, $F(2, 38)=14.30$, $MSE=.001$, $p<.001$, $\eta_p^2=.429$, with more errors in incongruent than neutral, $t(19)=4.13$, $p<.001$, and congruent conditions, $t(19)=4.12$, $p=.001$, but no significant difference between neutral than congruent conditions, $t(19)<1.0$. The main effect of response task was not significant ($F<1$), and neither was the interaction, $F(2, 38)=1.28$, $MSE=.001$, $p=.291$, $\eta_p^2=.063$.

In this experiment, we observed that the keypress response to word was interfered with by the direction of the arrow and the keypress response to arrow was also interfered with by meaning of the word: The Stroop effect was not significantly larger for responses to words than to arrows, indicating no asymmetry relation. These results are somewhat inconsistent with those observed in the previous studies (e.g., Baldo et al., 1998; Lu & Proctor, 2001; Roelofs et al., 2006) that observed asymmetry relation, although responding to words also received some interference from the direction of the arrows, which might arise from our pairing of left–right keypresses with up and down stimulus dimensions. Moreover, these findings are different from those in Experiment 2, which might be because the arrows were smaller in Experiment 3 and not centered in the display, which would reduce their discriminability. Also, this disparity might be because the arrows were global and the words local in Experiment 2, which resulted in more ready identification of the global feature, that is, the arrow direction, because of global precedence (Navon, 1977), whereas they were at the same level in Experiment 3. These results also are compatible with findings for the Stroop color-naming task by Melara and Mounts (1993), in which varying the relative discriminability of the color and word dimensions could eliminate and even reverse the Stroop asymmetry, and the more discriminable of two dimensions always interfered with judgments of the less discriminable dimension.

The findings of Experiment 3 are inconsistent with predictions of the translation model, but are in agreement with predictions of dimensional overlap model and the S–R association strength account.

5. General discussion

The current study examined whether asymmetry in Stroop interference can be eliminated in spatial Stroop tasks. It also considered whether the translation model, dimensional overlap model, and S–R association strength account could predict the size of the congruency effect created by an irrelevant stimulus dimension in spatial Stroop tasks that combined physical locations and location words written in Chinese, arrows and physical locations, and arrows and location words written in Chinese, respectively. In Experiment 1, responding to location words or to up- or down-pointing arrows above or below the center of screen and to their locations resulted in similar sized spatial Stroop effects. In Experiment 2, when a location word was embedded in an outline drawing of an arrow, responding to arrow direction did not create a spatial Stroop effect but responding to word meaning did. In Experiment 3, when a location word was flanked by an arrow, spatial Stroop effects of similar size were obtained when responding to location words and to arrows.

As described in the Introduction, there are three main accounts of the asymmetric and symmetric relations in spatial Stroop tasks. According to the translation model (e.g., Virzi & Egeth, 1985), location words, arrows and physical locations are separately processed in linguistic, symbolic, and spatial systems, each of which operates in its own code. The linguistic system encodes word meaning, which is particularly suited to vocal responses. The spatial system encodes spatial relations, which is particularly suited to manual responses. For a participant to make a keypress response in the context of the spatial Stroop task, the codes of the location words and arrows must engage a translation module so as to be converted into a location code. Engaging the translation module can cause interference. Thus, when a participant responds to the location words and arrows by keypress, the irrelevant physical location would interfere with the performance, as observed in Experiment 1. However, this account cannot explain the occurrence of the spatial Stroop effects for responses to locations in Experiment 1, in which no translation would have been engaged because the spatial system is particularly suited to manual responses.

The translation account also does not predict the dissociation of the results of Experiments 2 and 3. Instead, it predicts that responding to arrows and location words will produce similar size of interference because both stimuli are symbolic. This account also cannot explain other findings. O'Leary and Barber (1993) replicated the pattern of results in Virzi and Egeth (1985) for simultaneous presence of verbal and nonverbal spatial information but observed that the Stroop effect (11 ms) was statistically reliable in the vocal-response-to-word meaning condition. Similarly, the keypress-response-to-location condition also tended to show a small Stroop effect (8 ms) in Virzi and Egeth's study and (7 ms) in O'Leary and Barber's study, although it was not significant in both cases. Because irrelevant location words influence keypress responses and irrelevant locations influence vocal responses, to at least some extent, translation of irrelevant information into activation of response codes is best viewed as varying in degree, as O'Leary and Barber (1993) suggested, rather than being all-or-none. Also, the translation account cannot explain some findings when the irrelevant location word and arrow are displayed simultaneously. For example, Baldo et al. (1998) observed a significant Stroop effect of 10 ms for vocal response to word meaning and 14 ms for keypresses to left or right pointing arrows (also see Aarts & Roelofs, 2011; Aarts et al., 2009; Roelofs et al., 2006).

Kornblum's (1992) dimensional overlap model predicts that the spatial Stroop effect should be no different regardless of whether the responses are made to word and arrow or location, because there is the same degree of S–S overlap (but no S–R overlap) in each case, given that the responding hand (whether left or right) was orthogonal to the location and direction of the arrow (up/down) and the meaning of the word (up/down) (e.g., Luo et al., 2010; Lupiáñez & Funes, 2005). This account could explain well the results of Experiments 1 and 3, but not the results of Experiment 2.

According to the account of the relative strengths of the relevant and irrelevant S–R associations, conceptual similarity of location words [i.e., 上 (up) and 下 (down)] and arrows (i.e., up or down pointing) is the same as stimulus locations (i.e., up and down), as they refer to the same concepts, up or down. At the same time, location words, arrows and physical locations will not overlap with response locations, which refer to different concepts, left and right. Accordingly, conceptual similarity is identical in these two conditions. Therefore, in Experiments 1 to 3, conceptual similarity is the same for arrows and words, regardless of whether the response is made to location words, arrows or the physical locations occupied by them. With respect to mode similarity, mode similarity of arrow direction with keypresses is higher than that of location words (for which the stimulus dimension is verbal and the response is non-verbal; Lu & Proctor, 2001; Wang & Proctor, 1996), but both would be lower than that of physical locations with keypresses. Therefore, the association of physical locations with keypress responses is the strongest, and the association of arrow directions with the corresponding keypress responses would be stronger than the association of location words with the corresponding keypress responses. This account could easily explain the results of Experiments 1, 2 and 3.

As described in the Introduction, there are other theories that have been used to explain the findings in Stroop-like tasks. The automaticity view may explain the results in Experiments 1 and 3, if it is assumed that the keypress response to the location word written in Chinese, arrow or location has comparable automatic level. Also, this view may explain the results in Experiment 2, if the stimuli display that the arrows were global and the words local in Experiment 2 affected the relative level of automaticity in response to the arrows and location words because of global precedence. The tectonic theory by Melara and Algom (2003) can explain the results in the present study, if we assume that the relative discriminabilities of the location words, arrows and locations in Experiments 1 and 3 are almost identical, leading to the absence of the spatial Stroop asymmetry, whereas in Experiment 2 the arrow's direction is more discriminable than the location word because of global precedence, leading to the occurrence of the spatial Stroop asymmetry.

6. Conclusion

Asymmetry in Stroop interference can be eliminated in spatial Stroop tasks. The elimination of asymmetry of the spatial Stroop effect cannot be explained by the translation account but it can be explained by the dimensional overlap model and the account in terms of relative strengths of the relevant and irrelevant S–R associations. However, the dimensional overlap model cannot explain asymmetry of spatial Stroop effect, whereas the translation account and association-strength accounts can. Therefore, the latter account is in closest accord with the entire set of results obtained in the current study.

Acknowledgments

This research was supported in part by grants from the Knowledge Innovation Program of the CAS (KSCX2-YW-BR-6), China Postdoctoral Science Foundation funded project (grant # 201003171) and the Young Scientist Project of IPCAS (grant # Y1CX262005). We wish to thank Juan Lupiáñez and Xinshan Li for their helpful comments on the manuscript.

References

Aarts, E., & Roelofs, A. (2011). Attentional control in anterior cingulate cortex based on probabilistic cueing. *Journal of Cognitive Neuroscience*, *23*, 716–727.

Aarts, E., Roelofs, A., & Van Turennout, M. (2009). Attentional control of task and response in lateral and medial frontal cortex: Brain activity and reaction time distributions. *Neuropsychologia*, *47*, 2089–2099.

Baldo, J. V., Shimamura, A. P., & Prinzmetal, W. (1998). Mapping symbols to response modalities: Interference effects on Stroop-like tasks. *Perception & Psychophysics*, *60*, 427–437.

Cho, Y. S., Proctor, R. W., & Yamaguchi, M. (2008). Influences of response position and hand posture on the orthogonal Simon effect. *The Quarterly Journal of Experimental Psychology*, *61*, 1020–1035.

Clark, H. H., & Brownell, H. H. (1975). Judging up and down. *Journal of Experimental Psychology. Human Perception and Performance*, *1*, 339–352.

Cohen, J. D., Dunbar, K., & McClelland, J. L. (1990). On the control of automatic processes: A parallel distributed processing account of the Stroop effect. *Psychological Review*, *97*, 332–361.

Danziger, S., Kingstone, A., & Ward, R. (2001). Environmentally defined frames of reference: Their sensitivity to spatial cues and attention, and their time course. *Journal of Experimental Psychology. Human Perception and Performance*, *27*, 494–503.

Dunbar, K. N., & MacLeod, C. M. (1984). A horse race of a different color: Stroop interference patterns with transformed words. *Journal of Experimental Psychology. Human Perception and Performance*, *10*, 622–639.

Eimer, M. (1995). Stimulus–response compatibility and automatic response activation: Evidence from psychophysiological studies. *Journal of Experimental Psychology. Human Perception and Performance*, *21*, 837–854.

Glaser, M. O., & Glaser, W. R. (1982). Time course analysis of the Stroop phenomenon. *Journal of Experimental Psychology. Human Perception and Performance*, *8*, 875–894.

Kornblum, S. (1992). Dimensional overlap and dimensional relevance in stimulus–response and stimulus–stimulus compatibility. In G. E. Stelmach, & J. Requin (Eds.), *Tutorials in motor behavior II* (pp. 743–747). Amsterdam: North–Holland.

Kornblum, S., Hasbroucq, T., & Osman, A. (1990). Dimensional overlap: Cognitive basis for stimulus–response compatibility — A model and taxonomy. *Psychological Review*, *97*, 253–270.

Logan, G. D. (1980). Attention and automaticity in Stroop and priming tasks: Theory and data. *Cognitive Psychology*, *12*, 523–553.

Logan, G. D., & Zbrodoff, N. J. (1979). When it helps to be misled: Facilitative effects of increasing the frequency of conflicting stimuli in a Stroop-like task. *Memory & Cognition*, *7*, 166–174.

Lu, C. -H., & Proctor, R. W. (1995). The influence of irrelevant location information on performance: A review of the Simon and spatial Stroop effects. *Psychonomic Bulletin & Review*, *2*, 174–207.

Lu, C. -H., & Proctor, R. W. (2001). Influence of irrelevant information on human performance: Effects of S–R association strength and relative timing. *The Quarterly Journal of Experimental Psychology*, *54*, 95–136.

Luo, C., Lupiáñez, J., Fu, X., & Weng, X. (2010). Spatial Stroop and spatial orienting: The role of onset vs. offset cues. *Psychological Research*, *74*, 277–290.

Luo, C., Lupiáñez, J., Funes, M. J., & Fu, X. (2010). Modulation of spatial Stroop by object-based attention but not by space-based attention. *The Quarterly Journal of Experimental Psychology*, *63*, 516–530.

Luo, C., Lupiáñez, J., Funes, M. J., & Fu, X. (2011). The modulation of spatial congruency by object-based attention: Analysing the "locus" of the modulation. *The Quarterly Journal of Experimental Psychology*, *64*, 2455–2469.

Lupiáñez, J., & Funes, M. J. (2005). Peripheral spatial cues modulate spatial Stroop interference: Analyzing the "locus" of the cueing modulation. *European Journal of Experimental Psychology*, *17*, 727–752.

MacLeod, C. M. (1991). Half a century of research on the Stroop effect: An integrative review. *Psychological Bulletin*, *109*, 163–203.

Melara, R. D., & Algom, D. (2003). Driven by information: A tectonic theory of Stroop effects. *Psychological Review*, *110*, 422–471.

Melara, R. D., & Mounts, J. R. W. (1993). Selective attention to Stroop dimensions: Effects of baseline discriminability, response mode, and practice. *Memory & Cognition*, *21*, 627–645.

Miles, J. D., & Proctor, R. W. (2012). Correlations between spatial compatibility effects: Are arrows more like locations or words? *Psychological Research*, *76*, 777–791.

Moriguchi, K., & Morikawa, Y. (1998). Time course analysis of the reverse-Stroop effect in Japanese kanji. *Perceptual and Motor Skills*, *87*, 163–174.

Morikawa, Y. (1981). Stroop phenomena in the Japanese language: The case of ideographic characters (kanji) and syllabic characters (kana). *Perceptual and Motor Skills*, *53*, 67–77.

Navon, D. (1977). Forest before trees: The precedence of global features in visual perception. *Cognitive Psychology*, *9*, 353–383.

Nishimura, A., & Yokosawa, K. (2006). Orthogonal stimulus–response compatibility effects emerge even when the stimulus position is task-irrelevant. *Quarterly Journal of Experimental Psychology*, *59*, 1021–1032.

O'Leary, M., & Barber, P. (1993). Interference effects in the Stroop and Simon paradigms. *Journal of Experimental Psychology. Human Perception and Performance*, *19*, 830–844.

Oliver, L. M., & Kornblum, S. (1991). Dimensional overlap and population stereotype as joint predictors of S-R compatibility. *Paper presented at the 32nd Annual Meeting of the Psychonomic Society*, San Francisco, CA.

Palef, S. R., & Olson, D. R. (1975). Spatial and verbal rivalry in a Stroop-like task. *Canadian Journal of Psychology*, *29*, 201–209.

Phaf, R. H., Van der Heijden, A. H., & Hudson, P. T. (1990). SLAM: A connectionist model for attention in visual selection tasks. *Cognitive Psychology*, *22*, 273–341.

Proctor, R. W., Wang, H., & Vu, K. -P. L. (2002). Influences of conceptual, physical, and structural similarity on stimulus–response compatibility. *The Quarterly Journal of Experimental Psychology*, *55*, 59–74.

Roelofs, A. (2003). Goal-referenced selection of verbal action: Modeling attentional control in the Stroop task. *Psychological Review*, *110*, 88–125.

Roelofs, A., Van Turennout, M., & Coles, M. G. H. (2006). Anterior cingulate cortex activity can be independent of response conflict in Stroop-like tasks. *Proceedings of the National Academy of Sciences of the United States of America*, *103*, 13884–13889.

Sabri, M., Melara, R. D., & Algom, D. (2001). A confluence of contexts: Asymmetric versus global failures of selective attention to Stroop dimensions. *Journal of Experimental Psychology. Human Perception and Performance*, *27*, 515–537.

Seymour, P. H. K. (1973). Stroop interference in naming and verifying spatial locations. *Perception & Psychophysics*, *14*, 95–100.

Shimamura, A. (1987). Word comprehension and naming: An analysis of English and Japanese orthographies. *The American Journal of Psychology*, *100*, 15–40.

Shor, R. E. (1970). The processing of conceptual information on spatial directions from pictorial and linguistic symbols. *Acta Psychologica*, *32*, 346–365.

Shor, R. E., Hatch, R. P., Hudson, L. J., Landrigan, D. T., & Shaffer, H. J. (1972). Effect of practice on a Stroop-like spatial directions task. *Journal of Experimental Psychology*, *94*, 168–172.

Simon, J. R., & Berbaum, K. (1990). Effect of conflicting cues: The "Stroop effect" vs. the "Simon effect". *Acta Psychologica*, *73*, 159–170.

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology*, *1935*(18), 643–662.

Treccani, B., Umiltà, C., & Tagliabue, M. (2006). Simon effect with and without awareness of the accessory stimulus. *Journal of Experimental Psychology. Human Perception and Performance*, *32*, 268–286.

Umiltà, C., & Nicoletti, R. (1990). Spatial stimulus–response compatibility. In R. W. Proctor, & T. G. Reeve (Eds.), *Stimulus–response compatibility: An integrated perspective* (pp. 89–116). Amsterdam: North–Holland.

Virzi, R. A., & Egeth, H. E. (1985). Toward a translational model of Stroop interference. *Memory & Cognition*, *13*, 304–319.

Wang, H., & Proctor, R. W. (1996). Stimulus–response compatibility as a function of stimulus code and response modality. *Journal of Experimental Psychology. Human Perception and Performance*, *22*, 1201–1217.