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Stimulus–Response Compatibility With Pure and Mixed Mappings in a Flight Task Environment

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The present study examined the stimulus–response compatibility (SRC) effect in a simulated flight environment. Experiments 1 and 2 tested the effect with pure and mixed mappings in flight tasks by using attitude displays with inside–out and outside–in formats, whereas Experiments 3 and 4 used a simplified display and tasks. The SRC effect was obtained with mixed mappings when responses were turns of a flight yoke (Experiments 1–3). In contrast, the SRC effect was absent with mixed mappings when they were buttonpresses (Experiment 4). Analyses of sequential effects suggest that the reduction in Experiments 1–3 can be attributed to reduction in the frequency of trials for which the congruent mapping repeats, but the elimination in Experiment 4 cannot be. Implications of the findings are discussed in the context of aviation cockpit design.

Keywords: stimulus-response compatibility, response selection, mixing cost, sequential effect, interface design

Stimulus–response compatibility (SRC) is widely acknowledged to be an important aspect of interface design (e.g., Wickens, Lee, Liu, & Becker, 2004), and considerable effort has been devoted to basic empirical and theoretical research that has increased understanding of SRC effects (Proctor & Vu, 2006). Yet, the link between the basic research and application remains weak. For this link to be strengthened, it is essential that the basic findings and principles be extended to tasks that more closely approximate the properties of those performed in operational environments. The present study takes a step in this direction by examining performance of tasks with pure or mixed congruent and incongruent mappings in a simulated flight environment.

Definition and Model of SRC

SRC effects refer to differences in speed and accuracy of responding as a function of the mapping of stimuli to responses. For manual responses to visual stimuli that appear in different locations, performance is better when the stimulus and response locations correspond than when they do not (Fitts & Deininger, 1954). In two-choice tasks for which a left or right key is to be pressed in response to a left or right stimulus, response time (RT) is typically 50–100 ms shorter when the left key is mapped to the left stimulus and the right key to the right stimulus (*congruent mapping*) than when the mapping is reversed (*incongruent mapping*). The advantage for the congruent mapping has been attributed to response selection being faster when the spatially corresponding response can be made than when it cannot be (e.g., Fitts & Deininger, 1954; Hasbroucq, Guiard, & Ottomani, 1990; Reeve & Proctor, 1990).

Most accounts of the SRC effect are based on the idea that stimuli and responses are represented by spatial codes (e.g., Heister, Schroeder-Heister, & Ehrenstein, 1990; Kornblum, Hasbroucq, & Osman, 1990; Reeve & Proctor, 1990; Umiltà & Nicoletti, 1990). Spatial codes are implicated because RT is mainly a function of the mapping of stimuli to response locations and not to left–right effectors (e.g., Roswarski & Proctor, 2000; Wallace, 1971). According to coding accounts, for the cognitive system to produce a response, it must encode a stimulus and transform it into the assigned response code. The SRC effect occurs when the response codes are similar to, or overlap with, the stimulus codes. For instance, when a member of the response set is coded as left in relation to the other member, the stimulus–response (S–R) transformation occurs more rapidly to the member of the stimulus set that is also coded as left than to the member that is coded as right. Also, it has been suggested that the speed of S–R transformation is a function of salient features of the S–R sets (Cho & Proctor, 2003; Proctor & Reeve, 1986). According to this salient-feature coding account, stimuli and responses are encoded in terms of their salient features, and S–R transformation is faster when salient features of stimulus and response correspond than when they do not.

SRC effects have been shown to be robust, occurring for a variety of stimulus and response sets that convey spatial information (Proctor & Wang, 1997a) and for tasks in which the spatial dimension of stimuli is not relevant (Simon & Rudell, 1967). In Simon and Rudell's (1967) study, the task was to press left and

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right keys, respectively, to spoken words “left” and “right” presented to the left or the right ear. Responses were faster when the key location corresponded to the side of the ear to which a stimulus was presented than when it did not. This finding of an SRC effect based on an irrelevant spatial stimulus dimension is termed the *Simon effect*; it typically ranges from 20 ms to 50 ms (see Lu & Proctor, 1995, for a review). The Simon effect has led many researchers to incorporate an automatic, or unconditional, component into their models of the SRC effect in addition to the intentional, or conditional, S–R translation component (De Jong, Liang, & Lauber, 1994; Hommel & Prinz, 1997; Kornblum et al., 1990; Zorzi & Umiltà, 1995). These models differ in their details, but we call this type of model a *dual-route model* in the subsequent discussions.

Dual-route models state that activation of the response corresponding to the stimulus is produced through a direct route. This direct activation is often conceptualized as an automatic process, which facilitates responding when the mapping is congruent and interferes when the mapping is incongruent, giving rise to the Simon effect even when the spatial dimension is irrelevant. Activation of the assigned response is produced by way of an indirect, or intentional translation, route. Although activation typically occurs more slowly along this route than along the direct route, the intentional activation will be quicker when the mapping is congruent than when it is incongruent. This advantage for the congruent mapping over the incongruent mapping in the indirect route is attributed to differences in efficiency of the translation process for those mapping rules, consistent with a mechanism that is provided by coding accounts.

Kornblum et al.’s (1990) dimensional overlap model assumes that the automatic activation is actively inhibited at a response-verification stage, in which a response activated automatically through the direct route is compared with the response activated through the indirect route (Stürmer, Leuthold, Soetens, Schröter, & Sommer, 2002; Wühr, 2005). The activated response is produced when they match (on corresponding trials) and is inhibited when they do not (on noncorresponding trials). Other dual-route models incorporate strategic suppression of the direct route (De Jong, 1995; Stoffels, 1996a, 1996b), passive decay of irrelevant response codes activated via the direct route (De Jong et al., 1994; Hommel, 1994), or interference in the process of response code or mapping rule activation (De Jong, 1995; Hommel, Proctor, & Vu, 2004).

Elimination of Spatial SRC Effect

Though SRC effects have been shown to be robust, especially for tasks in which the spatial dimension is relevant, Shaffer (1965) reported an exception to the robustness of the task-relevant SRC effect. In his method, a horizontal or vertical line was presented simultaneously with the imperative stimulus, serving as a mapping signal. This signal indicated whether the corresponding or noncorresponding response was to be made to the imperative stimulus (a left or a right circle) on each trial. RT for this mixed mapping condition was compared with that for a pure mapping condition in which only one mapping was in effect for a block of trials. Responses were slower for the mixed mapping condition than for the pure mapping condition, indicating a mixing cost. More important, the SRC effect was eliminated in the mixed mapping condition, with the spatially congruent mapping showing no RT benefit over the spatially incongruent mapping. Although this elimination of the SRC effect with mixed mappings has not received much notice, it has been replicated in several subsequent studies (Heister & Schroeder-Heister, 1994; Vu & Proctor, 2004; see Proctor & Vu, 2002, for a review).

De Jong (1995) proposed that elimination/reduction of the SRC effect with mixed mappings is attributable to strategic suppression of the direct route, an account known as the *suppression hypothesis*. He noted that the corresponding response activated via the direct route would be incorrect on those trials for which the mapping was incongruent. To prevent a high error rate on the incongruent trials, the direct route is suppressed, resulting in elimination of the advantage for the congruent mapping.

It has been also shown that when sufficient time is allowed to prepare the congruent mapping, suppression of the direct route can be released. De Jong (1995) varied the interval between onset of the mapping signal (a high- or a low-pitch tone) and the imperative stimulus (a left- or a right-pointing arrow, mapped to left–right keypresses). He found that the SRC effect was eliminated when the interval between the mapping signal and the imperative stimulus was less than 200 ms but was apparent when the interval was 600 ms. Shaffer (1965) also found reinstatement of the SRC effect when the mapping signal preceded the imperative stimulus by 333 ms.

In addition, the suppression hypothesis involves an assumption that, in the mixed mapping condition, corresponding and noncorresponding responses are produced in the indirect route with equal difficulty. This assumption is needed because both coding accounts and dual-route models state that S–R translation in the indirect route is more efficient with the congruent mapping than the incongruent mapping. That is, even with suppression of the direct route, the SRC effect based on the efficiency of translation rules in the indirect route should still be apparent (Vu & Proctor, 2004). Consequently, the SRC effect can be reduced but should not be eliminated or reversed with mixed mappings. This equal-difficulty assumption is reasonable, given that mixing costs still appear with a long cue-stimulus interval (e.g., De Jong, 1995; Shaffer, 1965), in which one could prepare for a specific mapping in advance as in the pure mapping condition. Thus, it may be argued that this finding indicates an altered response-selection process in the indirect route, probably due to having to maintain multiple mapping rules even with a long cue-stimulus interval.

SRC in Flight Task Environment

One of the task environments that can benefit from application of SRC principles is flight operation. For instance, a recent trend within the aviation community is represented by the concept of “free flight,” a redistribution of currently centralized air traffic management and decision making to the aircraft operators (Ballin, Hoekstra, Wing, & Lohr, 2002; Johnson et al., 2005; Lee et al., 2003). It has been suggested that success of the free flight concept depends heavily on operational aids that minimize workload without compromising the safety and efficiency of the air traffic (Johnson, Bilimoria, Thomas, Lee, & Battiste, 2003). In support of this paradigm, development of advanced flight deck displays, such as cockpit situation display (CSD), has been advocated (Granada, Dao, Wong, Johnson, & Battiste, 2005; Johnson, Battiste, & Holland, 2000).

CSD provides an automated alerting system to make pilots aware of those conflicts, in response to which the pilots are to change the current flight path to ensure restricted separation distances. This type of situation is one of the most straightforward links with the spatial SRC tasks that have been used in previous laboratory studies. This display technology enables the pilots to decide whether to turn toward or away from an intruder on the path of the pilot's aircraft depending on the color code. Thus, it gives rise to issues concerning the SRC effect with mixed mappings, similar to the task conditions that were first tested by Shaffer (1965) and subsequently by other researchers (De Jong, 1995; Heister & Schroeder-Heister, 1994; Vu & Proctor, 2004) in basic two-choice reaction tasks.

Yet, in these studies, elimination of the spatial SRC effect with mixed mappings has been reported exclusively for tasks that require responding on each trial to one of several possible spatial stimuli mapped to keypress responses (Heister & Schroeder-Heister, 1994; Shaffer, 1965; Vu & Proctor, 2004), a response mode that is not commonly used, if ever, to navigate aircraft. Also, those studies presented the imperative stimulus in isolation on a screen, whereas operational environments normally consist of complex displays. Thus, it is more informative from an applied perspective if the effect of mixed mappings is tested in tasks that involve a response mode and complex visual display that have more ecological validity, such as operating a flight yoke while monitoring the attitude display. In fact, there are several studies that give rise to the question of whether patterns of SRC effects demonstrated in laboratory studies would be replicated in such tasks.

For instance, it has been shown that when responses are made with a steering wheel, factors come into play in SRC that are not involved with keypress responses (Proctor, Wang, & Pick, 2004). Proctor et al. (2004) showed that when participants placed both hands at the bottom of the steering wheel, wheel rotation could provide two different frames of reference, one based on the left–right movement of the top of the wheel (or wheel turn) and another based on the left–right movement of their hands (or the bottom of the wheel). Because these reference frames involved in wheel rotation moved opposite to each other (the top moves to the left when the hands move to the right or vice versa), the direction of the SRC effect varied depending on whether participants chose the wheel-referenced code or hand-referenced code to represent their responses (Guiard, 1983; D.-Y. D. Wang, Proctor, & Pick, 2003). Furthermore, when a visual object was presented on the screen and moved in response to the wheel rotation, the direction of the SRC effect was consistent with the direction of object movement, even when the hands were placed on the bottom of the wheel (Proctor et al., 2004).

Also, Vu and Proctor (2004) found that when responses were the spoken utterances "left" and "right" mapped to the left and right circles, the SRC effect was not eliminated with mixed presentation. Vu and Proctor interpreted their results as suggesting that suppression of the direct route with mixed mappings is limited primarily to situations in which the stimulus and response sets are perceptually similar and thus of high compatibility (i.e., for visual–spatial stimuli paired with keypresses and location words paired with vocal responses; but see Hazeltine, Ruthruff, & Remington, 2006; Stelzel, Schumacher, Schubert, & D'Esposito, 2005, for a possible distinction of modality-specific pathways from SRC).

Hence, although the previous studies have shown consistent results with mixed mappings for left–right locational stimuli mapped to left–right keypresses, it is possible to obtain results different from those provided by the previous studies when response modes other than keypresses are used. Further, use of a complex display may provide a frame of reference that is not found in simple displays of the type used previously to study the SRC effect with mixed mappings. Moreover, complexity of the display may reduce the relative salience of spatial information conveyed by the imperative stimuli and lead to a decrease of SRC. These considerations are particularly important for successful application of the SRC principles to dynamic task settings, such as flight operation.

Present Study

As discussed above, SRC is an important aspect of flight operations (e.g., responding to an automated alerting system or turning the aircraft in accordance with the color-coded visual objects in a display). However, these operational environments involve complex displays and various types of manual response modes, factors that may modulate SRC effects. Therefore, the main purpose of the present study is to test the SRC effect in tasks that are similar to those of a real-time flight task environment. A total of four experiments were conducted.

In Experiments 1 and 2, the apparatus consisted of a glass cockpit display on a computer screen, housed in a general aviation flight simulator (see Figure 1). A glass cockpit is an instrument for the flight deck that has been widely adopted for commercial and military aircraft since the 1980s (Jukes, 2004). Its standard format consists of the primary flight display (PFD) and the navigation display (ND; see Figure 2, top and bottom, respectively). PFD presents the roll (or bank) and pitch of the aircraft by using a combination of the roll index pointer, bank angle markings, and

Figure 1. The flight simulator consisted of four display screens, controlled by two computers. Two screens were located on the upper row and the other two on the lower row. The left screen on the lower row was used, and the remaining screens were turned off. A pilot seat was located in front of the screen, and the yoke was placed between the screen and the seat.

Figure 2. The inside-out format of the glass cockpit frame used in Experiment 1. The artificial horizon and the bank angle markings rotated to the left or to the right in the direction opposite to the yoke turn, whereas the aircraft symbol and the roll pointer were stable. The imperative stimulus appeared at the left or the right upper corner (a right stimulus is shown in the current figure).

artificial horizon. Experiments 1 and 2 use different formats for the PFD.

Participants in those experiments monitored the attitude of the aircraft (i.e., roll angle) through the simulated glass cockpit display. The task was to roll the simulated aircraft 45° to the left or to the right by turning the yoke in response to the imperative stimuli that occurred on the left- or right-upper corner of the screen. The color of the stimuli (red or green) signaled whether to roll the aircraft toward or away from the stimulus location. In one condition, the imperative stimuli consistently appeared in one of the two colors (i.e., pure mapping condition), whereas in another condition, they could appear in both colors (i.e., mixed mapping condition). That is, those experiments compared performance with pure and mixed congruent and incongruent mappings by using a simulated flight environment.

Experiment 3 examines whether the complex displays used in the preceding two experiments had contributed to the SRC effect with pure and mixed mapping conditions by using the identical stimuli and yoke-turn responses but removing the flight visual display. In Experiment 4, effects of response mode on the SRC effect in those conditions are examined, replacing the yoke-turn responses of Experiments 1–3 with buttonpress responses, similar to the keypress responses used in previous studies (De Jong, 1995; Heister & Schroeder-Heister, 1994; Shaffer, 1965; Vu & Proctor, 2004).

Finally, sequential effects on the SRC effect were examined. It has been shown that the Simon effect (correspondence effect for irrelevant stimulus location and responses) is present on trials following a corresponding trial but is absent on trials following a noncorresponding trial (e.g., Hommel, Proctor, & Vu, 2004; Proctor, Vu, & Marble, 2003; Stürmer et al., 2002; Wühr, 2005). One explanation of the sequential effects in the Simon tasks, the *transient gating/release account* (Stürmer et al., 2002; Wühr, 2005), proposes that the direct response-selection route is suppressed after a noncorresponding trial but is released after a corresponding trial. In SRC tasks with mixed mappings, each trial is preceded by a congruent or incongruent trial. Consequently, it is possible that reduction/elimination of the SRC effect with mixed mappings is due to a transient gating/release mechanism of the direct route. Hence, to examine this possibility, supplemental analyses of sequential effects for the four experiments were conducted; they are reported immediately after Experiment 4.

Experiment 1

The purpose of Experiment 1 is to determine whether the SRC effect would be eliminated under mixed mapping conditions for a more dynamic task than those used in previous studies. As indicated, the apparatus was a flight simulator, in which the participants monitored the attitude of the aircraft through the simulated glass cockpit display. Their task was to roll the aircraft 45° to the left or right according to a stimulus presented on the left- or the right-upper corner of the screen. Hence, it was a spatial SRC task, where responses were made by turning the yoke. The SRC effect for the mixed mapping condition was compared with that for pure congruent and incongruent mapping conditions.

Previous studies have reported that the SRC effect is eliminated with mixed mappings (Heister & Schroeder-Heister, 1994; Shaffer, 1965; Vu & Proctor, 2004). However, Vu and Proctor's (2004) experiments demonstrate that the SRC effect is not always eliminated under mixed mapping conditions. Vu and Proctor concluded that for complete elimination to occur, stimulus and response sets must be of very high compatibility or perceptually similar. Though it is typically considered that similarity between stimulus and response modalities is one of the most apparent determinants of their compatibility, different response modes within the same modality (e.g., unimanual movements to target locations versus bimanual keypresses) can produce different magnitudes of SRC effect, implying different degrees of compatibility for those response modes with the identical stimulus set (Proctor & Wang, 1997a, 1997b).

Also, incompatibility between movements of response and visual objects may modulate compatibility between the stimulus and response sets. Proctor et al. (2004) showed that when a visually displayed object moved in response to a wheel rotation, the direction of the SRC effect was determined by the direction of object movement rather than that of the wheel rotation. The visual display in the present experiment used a conventional *inside–out* frame of reference, which simulated the roll of an aircraft by rotating the artificial horizon in the direction opposite to the aircraft's roll. This means that the actual movement of the display object was incompatible with the direction of responses, though it simulated the movement of the aircraft compatible to the responses. Hence, if this incompatible movement of the visual object affects task performance, SRC can be reduced and elimination would not occur.

Moreover, if responses are delayed long enough in the mixed mapping conditions, the SRC effect could be reinstated, much like when the mapping is precued (De Jong, 1995; Shaffer, 1965). This could occur in the current task because of the task requirement involving a type of step-tracking, in which responses are concerned not only with the response direction (left or right) but also with the response precision (aligning the pointer and a target mark).

Taking these factors into account, three alternative hypotheses can be generated: The SRC effect in the mixed mappings should be (a) comparable with the effect in the pure mapping condition, (b) reduced relative to the effect in the pure mapping condition but still evident, or (c) absent (eliminated). If the results support the first or second hypothesis, further examinations will be required to isolate the critical factors, including the frame of reference, display and task complexities, and response mode. Additionally, it was expected that responses would be slower in the mixed mapping condition than the pure mapping condition, indicating mixing costs. As is typical in the SRC literature, the hypotheses are examined primarily for RT, with supplementary results in terms of percentage errors (PE).

Method

Participants. Twenty-eight undergraduate students (5 female, 23 male) enrolled in the introductory psychology course at Purdue University participated for credit toward a course requirement. All reported having normal or corrected-to-normal visual acuity and color vision. Two male participants reported having received formal flight training or education prior to the experiment. A male participant was replaced with a newly recruited male student from the same subject pool because he had difficulty following the instructions (see the *Task and procedure* section below). Another male participant was replaced with a newly recruited male participant for having an error rate greater than 10%.

Apparatus and stimuli. The flight simulator, described in detail in Proctor et al. (2005), was composed of two personal computers (Pentium 4, 3-GHz CPU; 2 GB RAM) and four computer screens (17-in. [43.2-cm] color monitors; see Figure 1). Two screens were placed next to a control panel between them. A throttle box was located below the control panel. The other two screens were mounted above the first two screens. The upper screens were connected to one computer and the lower screens to the other computer. Commercial flight simulator software (X-Plane, Laminar Research, Columbia, SC) displayed a glass cockpit frame in the left lower screen. The remaining computer screens were not used in the experiment. A custom computer application was constructed, which communicated with the simulator software to control the experiment.

The cockpit display was composed of the PFD and ND (upper and lower portions, respectively; see Figure 2). Because ND was irrelevant to the current task, its details are not described here. We refer to the PFD simply as *the display* in the following descriptions.

The display consisted of the artificial horizon and a set of objects superimposed on the horizon. These objects included the aircraft symbol, roll index pointer, bank angle markings, altitude tape meter, and vertical speed meter. The artificial horizon was a horizontal line bisecting the display. The upper portion of the horizon was colored in a graduation of blue (representing the sky), whereas the lower portion was in a graduation of brown (representing the ground). The artificial horizon rotated correspondingly to the bank of the aircraft, simulating the view from the cockpit window. The horizon also moved downward or upward relative to the aircraft symbol, indicating the pitch of the aircraft. A downward movement indicated climbing of the aircraft; an upward movement descending.

The aircraft symbol was composed of a set of black and white solid lines that were located on the center of the display and stable at the position. Above the aircraft symbol was a white isosceles triangle, or the roll index pointer, pointing to the top of the screen. The roll pointer indicated the current bank angle of the aircraft. The height and the width of the bottom side of the pointer were 1.4 cm. The roll pointer was also stable at the distance of 9 cm from the center of the screen.

The bank angle markings consisted of a series of short and long graduations lined along an imaginary semicircle. The markings rotated either to the left or right as the aircraft rolled. The movement of the markings was consistent with the rotation of the artificial horizon. The circumference of the semicircle was graduated at points corresponding to 10°, 20°, 30°, and 60° of the aircraft's roll to the right and to the left, respectively. Inverted white triangles pointing to the center of the aircraft symbol were located at three points corresponding to 0° and 45° of the rotation to the left and to the right. The rotation angle of 0° indicated that the aircraft was parallel to the ground. The triangle at 0° (center mark) served as a fixation point of the roll pointer at the beginning of each trial. The other two triangles served as the target positions at which the participants fixated the roll pointer in response to the imperative stimulus. The altitude meter was a tape positioned next to the bank markings, orthogonal to the artificial horizon at the roll angle of 0°. It was stationary on the display. There was a window located at the middle of the altitude meter, in which the altitude of the aircraft was numerically displayed.

An imperative stimulus consisted of a rectangle (3.8 cm along the diagonal) colored either green or red. It could appear on the left- or the right-upper corner of the screen. The position was approximately 27 cm from the midline of the screen to the left or right. The imperative stimulus was presented by a custom computer application, which also monitored and recorded response time and accuracy. A response was made by turning the yoke placed 28 cm in front of the screen. The distance between the left and right grips of the yoke was approximately 28 cm. The participants were instructed to hold the left and the right grips with their left and right hands, respectively, and to operate the yoke with both hands. They were also told to place their thumbs on the thumb rests equipped on the grips. They sat in front of the screen with an unrestricted viewing distance of approximately 60–70 cm.

Task and procedure. All participants performed four trial blocks, one with a pure congruent mapping, another with a pure incongruent mapping, and two with mixed congruent and incongruent mappings. In the congruent mapping block, only green stimuli were presented. The participants were to respond to the imperative stimulus by aligning the pointer with the target mark located on the same side as the stimulus location. In the pure incongruent mapping block, only red stimuli were used, and participants were to align the roll pointer with a target mark on the side opposite to the stimulus location. In the mixed mapping blocks, both green and red stimuli could appear, and the participants were told to set the pointer at a target triangle on the same side when it was green and on the opposite side when it was red.

The experiment was conducted individually for each participant. A session lasted less than 1 hr per participant. The experimenter first described the relevant objects in the display while demonstrating the task. The participant then sat in the cockpit of the flight simulator and read written instructions on the computer screen. The instructions emphasized that the participant was to respond to a stimulus as fast as possible.

The participants were also informed that when the aircraft descended to an altitude below 7,000 ft, the program would suspend the trial and the experimenter would set the altitude at an appropriate level (above 9,000 ft). This ensured a relatively constant flight condition across participants. However, a preliminary study suggested that participants who had had little or no training for flight operation had great difficulty maintaining the altitude; attempts to do so tended to result in a loss of control. Hence, the experimenter told the participants not to try to maintain or control the altitude. One participant did not follow this instruction and demonstrated apparent difficulty focusing on the task throughout the entire session. Hence, the participant was replaced with a newly recruited participant. Four of the remaining participants descended to an altitude below 7,000 ft at least once during the experiment, requiring the altitude to be reset.

After the instructions, the participants performed 12 trials of practice for the mixed mapping condition, followed by one of the three test conditions. A block in each pure condition consisted of 68 trials. The first block in the mixed condition consisted of 72 trials, whereas the second block had 64 trials, in which the numbers of green and red cue trials were equated (a total of 68 trials for each stimulus color). The order of conditions was counterbalanced in the way that half the participants performed two pure conditions first and then two blocks of the mixed condition, and the other half performed two mixed conditions followed by two pure conditions. Similarly, the order of the pure conditions was counterbalanced in the way that one-half of the participants in each group performed the congruent mapping condition first and then the incongruent mapping condition; the other one-half performed the conditions in the reverse order.

At the beginning of each trial, the participant was to set the roll pointer at the center mark for 3 s, which then triggered the imperative stimulus to appear. The offset of the stimulus was established when the pointer stayed at the appropriate target position for 1 s. The next stimulus appeared when the participant set the pointer at the center mark for 3 s, which served as the minimum length of intertrial interval (ITI). A long interval was expected to reduce the possible variance of the yoke position at the beginning of each trial; that is, the participant had to stabilize the yoke horizontally before the imperative stimulus appeared.

RT was measured as the interval between the onset of the imperative stimulus and turning of the yoke approximately 20° to the left or the right. A response was considered an error if the yoke was turned to the direction opposite to the cued side to the same degree. Although the participants were told that RT for each trial was recorded, they were not informed exactly at which point it was counted.

Results

Trials for which RT was less than 100 ms or greater than 1,500 ms were removed from the subsequent analyses (0.4% of all trials). Also, the first four trials in the two pure mapping conditions and the first eight trials in the first mixed block (i.e., four trials for each of the two mappings) were considered as warm-up trials and were thus discarded. With the remaining trials (64 trials for each of the pure conditions, 128 trials for the mixed condition, and a total of 256 trials), the mean RT for correct responses and PE were computed for each participant (see Table 1). The overall error rate was 3.0%.

A 2 (condition: pure, mixed) × 2 (mapping: congruent, incongruent) repeated-measures ANOVA was conducted for RT and PE. The alpha level for this and subsequent analyses was .05. Effect sizes (ES) were estimated using Cohen's *f*, with the criterion values of .25 for a medium effect and .4 for a large effect (J. Cohen, 1988). ES greater than 1.5 was considered as an extremely large effect. Cohen's *d* was computed to examine simple main effects, with criterion values of .5 for a medium effect and .8 for a large effect.

For RT (see Table 2), the main effect of mapping was significant, indicating an overall advantage for the congruent mapping (M = 574.0 ms, SD = 89.3 ms) over the incongruent mapping (M = 643.0 ms, SD = 103.6 ms). ES was extremely large. The interaction between mapping and condition did not achieve statistical significance, but ES was a medium to large size, indicating an apparent reduction of the SRC effect in the mixed mapping condition. SRC effects of 82 ms (SD = 52.2 ms; Cohen's d = 1.57) and 57 ms (SD = 37.0 ms; Cohen's d = 1.53) were observed for RT in the pure and mixed mapping conditions, respectively, showing large ESs for both conditions.

The main effect of condition was also significant. RT was shorter in the pure condition (M = 549.0 ms, SD = 99.7 ms) than in the mixed condition (M = 668.0 ms, SD = 101.6 ms), with an extremely large ES, indicating a mixing cost.

The PE data (see Table 3) also revealed a significant main effect of mapping (M = 1.4%, SD = 1.8% for congruent; M = 4.6%, SD = 3.8% for incongruent), with a large ES. The interaction was not significant, with ES being very small. The SRC effects for PE were 3.3% (SD = 4.9%; Cohen's d = 0.59) for the pure condition and 3.0% (SD = 3.8%; Cohen's d = 0.78) for the mixed condition, ESs being medium for both conditions. Thus, the SRC effect in the mixed mapping was comparable to the effect in the pure mapping condition. The main effect of condition (M = 2.2%, SD = 2.6% for pure; M = 3.7%, SD = 2.8% for mixed) was also significant, and ES was large, indicating a mixing cost.

Discussion

Responses were slower and less accurate overall for the mixed mapping condition than for the pure mapping condition, indicating the expected cost of mixing congruent and incongruent mappings. The overall SRC effect was significant for both RT and PE. SRC effects of 82 ms and 57 ms, and 3.3% and 3.0%, were observed for

Table 1
Mean Response Times (RT) and Percentage Errors (PE) as a Function of Mapping and Condition, and the Stimulus–Response Compatibility (SRC) Effects in Experiments 1–4

Experiment and condition	Congruent				Incongruent				SRC effect			
	RT		PE		RT		PE		RT		PE	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
1												
Pure	508	92.6	0.6	1.0	590	112.5	3.9	4.9	82	52.2	3.3	4.9
Mixed	639	97.5	2.2	2.0	696	108.8	5.2	4.3	57	37.0	3.0	3.8
2												
Pure	510	89.3	0.3	0.7	601	133.6	2.7	2.4	91	59.6	2.4	2.3
Mixed	673	128.1	3.2	3.0	714	139.6	7.3	6.8	41	59.8	4.1	6.5
3												
Pure	422	65.5	0.3	0.8	471	70.5	1.6	1.8	49	31.5	1.3	1.7
Mixed	569	93.3	3.4	3.2	601	95.9	3.3	2.5	32	38.1	−0.1	3.4
4												
Pure	307	44.5	0.2	0.6	364	54.9	1.8	1.9	57	38.7	1.6	1.7
Mixed	525	73.9	4.7	4.6	516	65.0	2.3	2.5	−10	35.7	−2.4	4.6

Table 2
Analysis of Variance for Response Times in Experiments 1–2

Source	$F(1, 27)$	Cohen's f
Experiment 1		
Condition	100.84*	1.93
MSE	3,932.88	
Mapping	161.96*	2.45
MSE	828.75	
Condition × Mapping	3.69	0.37
MSE	1,215.47	
Experiment 2		
Condition	132.72*	2.22
MSE	4,012.44	
Mapping	48.99*	1.35
MSE	2,476.01	
Condition × Mapping	15.97*	0.77
MSE	1,085.23	

* $p < .05$.

the pure and mixed mapping conditions, respectively. Thus, there was a reduction of the SRC effect with mixed mappings for RT, as indicated by ES for the interaction effect, but not for PE. Conversely, the SRC effect was still apparent in the mixed mapping condition. In contrast to its absence found in studies that used left–right visual stimuli mapped to keypresses (e.g., Shaffer, 1965; Vu & Proctor, 2004), the results of the present experiment support the hypothesis that the SRC effect in the current task was reduced but not eliminated with mixed mappings. Thus, in Experiment 2 we proceeded to examine a factor that was not involved in previous studies.

Experiment 2

A factor involved in Experiment 1 that differed from previous studies is use of a complex flight display. More specifically, the glass cockpit display in Experiment 1 provided an inside–out frame of reference, in which the artificial horizon moved in response to yoke turn, as opposed to an *outside–in* frame of reference, in which the aircraft symbol moves with the artificial horizon being stationary. This could have invited what Wickens, Andre, and Haskell (1990) call stimulus-central processing incompatibility, in which a stimulus presentation is incompatible with the cognitive representation or meaning of the display quantity.

According to previous aviation research, an outside-in format is generally superior to an inside-out format for attitude displays (e.g., Previc & Ercoline, 1999). For instance, novice pilots tend to take longer to train with an inside-out format display than with an outside-in display. Also, pilots spent 25% less time monitoring the attitude display when an outside-in format was used than when an inside-out format was, indicating greater attentional demands with the latter to monitor the display. Previc and Ercoline (1999) proposed that the mental representation of space relies on the most distant static surround of one's visual field, such as the horizon. Thus, a stationary representation of the horizon in an outside-in display provides a more intuitive concept of the attitude of the aircraft than a moving one in an inside-out display. One needs to switch from the "natural" reference frame to adapt to an inside-out display but not for an outside-in display (D. Cohen, Otakeno, Previc, & Ercoline, 2001).

Vu and Proctor (2004) suggested that the SRC effect is eliminated only for pairs of S–R sets that are of sufficiently high compatibility. Thus, the cognitively unnatural inside-out format display that provides display-response incompatibility may have modulated compatibility between the stimulus and response sets, resulting in the occurrence of the SRC effect with mixed mappings in Experiment 1. To investigate this possibility, Experiment 2 replaced the inside-out frame of reference of Experiment 1 with an outside-in frame of reference (see Figure 3). This was accomplished by moving the roll index pointer in relation to the artificial horizon, which was now stable on the display. Because the outside-in frame of reference provides a direct link between the movement of visual objects and the direction of yoke response, the display may increase compatibility of the S–R sets relative to the inside-out format display.

Hence, three alternative hypotheses were again derived for Experiment 2: The SRC effect with mixed mappings should be (a) comparable to the effect with pure mappings, (b) reduced relative to the effect with pure mappings but still evident, or (c) absent. Also, we again expected that mixing costs would be apparent in the mixed condition.

Method

Participants. Twenty-eight undergraduate students (12 female, 16 male) from the same subject pool as Experiment 1 participated. None of the participants had taken part in Experiment 1, and all reported having normal or corrected-to-normal visual acuity and color vision. Five male participants reported having had some experience of flight training or education prior to the experiment. A female participant was replaced with a newly recruited male participant for having an error rate greater than 10%.

Apparatus, stimuli, and procedure. The apparatus and procedure closely followed those used in Experiment 1, but several changes were made. First, the stimuli were presented by using a custom computer application that replicated the artificial horizon, bank angle markings,

Table 3
Analysis of Variance for Percentage Errors in Experiments 1–2

Source	$F(1, 27)$	Cohen's f
Experiment 1		
Condition	8.01*	0.54
MSE	7.70	
Mapping	25.21*	0.97
MSE	11.22	
Condition × Mapping	0.13	$F < 1$
MSE	8.03	
Experiment 2		
Condition	27.88*	1.02
MSE	14.04	
Mapping	24.15*	0.95
MSE	12.15	
Condition × Mapping	1.92	0.27
MSE	11.54	

* $p < .05$.

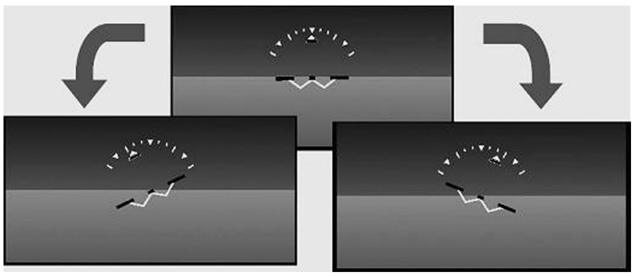

Figure 3. The outside-in format of the glass cockpit display used in Experiment 2, which replicated the primary flight display of Experiment 1. The altitude meter and other objects in the display were removed, except the artificial horizon, bank angle markings, roll pointer, and aircraft symbol. In contrast to the cockpit display in Experiment 1, the roll pointer and the aircraft symbol rotated to the left or to the right in response to the yoke, whereas the artificial horizon and the bank angle markings were stable. The imperative stimuli were presented at the same locations as in Experiment 1.

aircraft symbol, and roll pointer presented on the display in Experiment 1 (see Figure 3). Other display items irrelevant to the task were eliminated from the screen. The altitude meter was not presented in the display, nor was the upward or downward movement of the horizon. In contrast to the previous display, in which the horizon and the markings moved in response to the yoke, the roll pointer and aircraft symbol rotated to the left or to the right according to responses, whereas the horizon and markings were stationary. The imperative stimuli were identical with those used in Experiment 1, appearing in green or red and at the right or left upper corner of the screen.

The task was the same as that in Experiment 1; the participants set the roll pointer at an appropriate target triangle in response to the imperative stimulus by turning the yoke and returned to the center mark after the stimulus went off. The same instructions as in Experiment 1 were used, but no mention about altitude control was made. Experiment 2 was identical to Experiment 1 in other respects. The experimental session lasted less than 1 hr for each participant.

Results

The same criteria as those in Experiment 1 were used to exclude outliers (0.30% of all trials). The mean RT and PE were computed (see Table 1) and analyzed in the same manner as in Experiment 1. The overall error rate was 3.30%.

For RT (see Table 2), the main effect of mapping was significant, and ES for the mapping effect was extremely large. Responses were faster with a congruent mapping (M = 592.0 ms, SD = 104.1 ms) than with an incongruent mapping (M = 658.0 ms, SD = 132.2 ms). However, this was modified by its significant interaction with condition with a large ES. The SRC effects were 91 ms (SD = 59.6 ms; Cohen's d = 1.52) for the pure mapping condition and 41 ms (SD = 59.8 ms; Cohen's d = 0.68) for the mixed mapping condition. These results indicate that the SRC effect was significantly reduced, but not eliminated, in the mixed mapping condition. In addition, the main effect of condition was significant for RT, indicating a mixing cost. Responses were faster for the pure mapping condition (M = 556.0 ms, SD = 109.7) than for the mixed mapping condition (M = 694.0 ms, SD = 130.6 ms).

For PE (see Table 3), a significant main effect of mapping was found, with a large ES. Responses were more accurate for the congruent mapping (M = 1.8%, SD = 1.5%) than for the incongruent mapping (M = 5.0%, SD = 3.9%). The interaction between mapping and condition was not significant. ES for the interaction was slightly above a medium size. The SRC effect was 2.4% (SD = 2.3%; Cohen's d = 1.0) for the pure condition and 4.1% (SD = 6.5%; Cohen's d = 0.64) for the mixed condition, with standard errors being medium for the former and large for the latter. Thus, the SRC effect was still apparent in the pure and the mixed mapping conditions. A main effect of condition for PE was also significant, responses being more accurate for the pure condition (M = 1.5%, SD = 1.3%) than for the mixed condition (M = 5.2%, SD = 4.8%). ES was large for this variable.

Discussion

An overall SRC effect was also observed in Experiment 2. However, in the mixed condition, the effect for RT was reduced compared with the pure mapping condition, but not for PE, consistent with the results of Experiment 1. That is, the SRC effect was apparent for both pure and mixed mapping conditions. These outcomes support the hypothesis that the SRC effect was reduced but still evident with mixed mappings, as in Experiment 1. Thus, the continued presence of the SRC effect with mixed mappings in Experiment 1 was not due to the inside-out frame of reference used for the PFD. However, it still remains unclear why the SRC effect was present with mixed mappings in both Experiments 1 and 2.

Experiment 3

Another unique factor of Experiments 1 and 2 is that the response requirement was complex compared with that of previous studies. In those studies, elimination of the SRC effect was observed when responses were discrete keypresses. In contrast, Experiments 1 and 2 used a task in which participants were required to align the pointer and a target mark in response to the imperative stimuli. That is, the task involved more continuous control and was concerned with response precision as well as response direction.

According to the suppression hypothesis, the suppression of the direct route is released when participants are allowed sufficient time to prepare for signaled congruent mappings. This reflects the finding that a substantial SRC effect was obtained when the mapping signal preceded the onset of the imperative stimulus for approximately 300–600 ms but not for less than 200 ms (De Jong, 1995; Shaffer, 1965). It is possible that the complexity of the task used in Experiments 1 and 2 slowed responding long enough to allow the occurrence of the SRC effect with mixed mappings. Therefore, in Experiment 3, the glass cockpit display was removed, making the task essentially a basic two-choice reaction task.

Hence, in the present experiment, the participants' task was simply to turn the yoke in the direction signaled by the imperative stimuli. This modification also allows elimination of the complexity of the display as well as the complexity of the task requirement. Because the preceding two experiments consistently showed reduction of the SRC effect with mixed mappings, we derived only two alternative hypotheses for the current experiment: The SRC effect in the mixed mapping condition should be (a) reduced relative to that in the pure mapping condition but still evident or

(b) absent. In addition, we again expected that mixing costs would be present in the mixed mapping condition.

Method

Participants. Twenty-eight undergraduate students (9 female, 19 male) were recruited from the same subject pool as Experiments 1 and 2. None of the participants took part in Experiments 1 and 2. They reported having normal or corrected-to-normal visual acuity and normal color vision. One of the male participants reported having some experience of formal flight training prior to the experiment.

Apparatus and stimuli. The same flight simulator as in Experiments 1 and 2 was used. However, the display consisted of a blank screen with a white fixation cross (composed of 1.3 cm horizontal and vertical lines) on the black background. The bank markings, roll pointer, artificial horizon, and all other visual objects displayed in Experiments 1 and 2 were removed from the screen. The imperative stimuli were identical with those in the previous experiments, appearing at the same locations on the screen.

Task and procedure. The participants' task was to respond to the imperative stimulus by turning the yoke to the left or right. They were asked to keep the yoke on the appropriate side in response to a stimulus until the offset of the stimulus (for 1 s), instead of moving a visual object on the screen. The onset of a stimulus was triggered by holding the yoke straight for 3 s. During the ITI, the message *Center the yoke!* appeared above the fixation cross when the yoke was still turned to either side. The message went off when the yoke was set at the straight position. The procedure was identical with those in Experiments 1 and 2. RTs and accuracy on each trial were measured in the same way as in the preceding experiments. An experimental session lasted less than 30 min for each participant.

Results

The percentage of discarded trials, following the criteria used in Experiments 1 and 2, was 0.1%. After excluding the first four trials in the pure congruent and incongruent mapping blocks and the first eight trials for the first mixed block, the mean RT for correct responses and PE were computed for each participant (see Table 1) and submitted to a repeated-measures ANOVA as a function of mapping (congruent, incongruent) and condition (pure, mixed). The overall error rate was 0.9%.

For the RT data (see Table 4), the main effect of mapping was significant, yielding an overall advantage for the congruent mapping (M = 495.0 ms; SD = 76.4 ms) over the incongruent mapping (M = 536.0 ms, SD = 81.9 ms). ES was extremely large for this variable. This was modified by the significant interaction between mapping and condition, with a large ES. The SRC effect was 49 ms (SD = 31.5 ms; Cohen's d = 1.56) for the pure mapping condition and 32 ms (SD = 38.1 ms; Cohen's d = 0.83) for the mixed mapping condition, ES being large for both conditions. These outcomes suggest that the SRC effect was reduced but still present in the mixed mapping condition as well as in the pure mapping condition. The main effect of condition was also significant, indicating a mixing cost. Responses were faster for the pure condition (M = 446.0 ms, SD = 66.1 ms) than for the mixed condition (M = 585.ms, SD = 92.70 ms). An extremely large ES was obtained for this variable.

The PE data (see Table 5) showed that the main effect of mapping was not significant (M = 1.8%, SD = 1.8% for congruent; M = 2.5%, SD = 1.7% for incongruent), although ES was a medium size. Mapping interacted with condition, indicating a large ES. There was a positive SRC effect for the pure condition (M = 1.3%, SD = 1.7%; Cohen's d = 0.77) but not for the mixed condition (M = −0.1%, SD = 3.4%; Cohen's d = 0.03). The main effect of condition remained significant (M = 1.0%, SD = 1.1% for pure; M = 3.4%, SD = 2.3% for mixed), with a large ES, indicating a mixing cost for PE.

Table 4
Analysis of Variance for Response Times in Experiments 3–4

Source	$F(1, 27)$	Cohen's f
	Experiment 3	
Condition	333.13*	3.51
MSE	1,613.51	
Mapping	60.62*	1.50
MSE	754.78	
Condition × Mapping	4.52*	0.41
MSE	465.36	
	Experiment 4	
Condition	297.42*	3.32
MSE	3,230.46	
Mapping	19.91*	0.86
MSE	781.57	
Condition × Mapping	50.55*	1.37
MSE	606.10	

* $p < .05$.

Discussion

The present experiment removed the complexity of the display and task requirements involved in Experiments 1 and 2. The SRC effect was significantly reduced in the mixed mapping condition compared with the pure mapping condition. However, the SRC effect was still present for RT in the mixed condition, although the effect was absent for PE. The presence of the SRC effect for RT supports the hypothesis that the SRC effect was reduced with mixed mappings in the current task. Hence, removal of the complex display and task requirement was not sufficient to replicate the results of previous studies that showed elimination of the SRC effect. Moreover, because the current task was much simpler than those in Experiments 1 and 2, it is unlikely that the presence of the SRC effect in the mixed conditions of the first two experiments is attributable to the duration of response preparation.

Experiment 4

A consistent factor across Experiments 1–3 is the response mode, that of turning a yoke to the left or to the right. This response mode differed from that of keypresses used for the studies in which the SRC effect was eliminated under mixed mapping conditions (Heister & Schroeder-Heister, 1994; Shaffer, 1965; Vu & Proctor, 2004). Although the responses used in Experiments 1–3 are manual, as are keypresses, different types of manual responses may lead to differences in SRC (Proctor & Wang, 1997b; Wang & Proctor, 1996). If that is the case, no significant SRC effect should occur under conditions similar to

Table 5
Analysis of Variance for Percentage Errors in Experiments 3–4

Source	$F(1, 27)$	Cohen's f
Experiment 3		
Condition	31.40*	1.08
MSE	5.27	
Mapping	2.79	0.32
MSE	4.08	
Condition × Mapping	4.43*	0.41
MSE	3.10	
Experiment 4		
Condition	24.51*	0.95
MSE	7.20	
Mapping	0.70	$F < 1$
MSE	6.08	
Condition × Mapping	19.93*	0.86
MSE	5.67	

* $p < .05$.

those of Experiment 3 when the yoke responses are replaced with buttonpresses.

The method used in Experiment 4 replaced the yoke responses with buttonpress responses. The participants responded to a stimulus by pressing a button equipped on each grip of the yoke, and the experiment followed Experiment 3 as much as possible in other respects. With buttonpresses, we expected that the SRC effect would be absent in the mixed mapping condition. Again, we also expected that mixing costs would be obtained in the mixed mapping condition.

Method

Participants. A new group of 28 undergraduate students (10 female, 18 male) from the same subject pool as in Experiments 1–3 participated for partial fulfillment of a course requirement. All reported having normal or corrected-to-normal visual acuity and color vision. One male participant and 1 female participant were replaced with 2 newly recruited male participants (the former for a technical problem, and the latter for not completing all trials). Two of the male participants reported that they had had formal flight training prior to the experiment. No participant showed an overall error rate greater than 10%.

Apparatus, stimuli, task, and procedure. The apparatus and stimuli were identical with those of Experiment 3. However, instead of turning the yoke, the participants pressed buttons equipped on the grips of the yoke in response to the imperative stimuli. The left and right buttons were located on the left and right grips of the yoke, respectively. The buttons were located on the back of the grips, facing toward the computer screen. The participants were instructed to place their left and right index fingers on the left and right buttons, respectively, and to maintain the positions throughout the experiment. They were also told not to turn the yoke and to keep it straight throughout the experiment.

To maintain an interval between trials similar to that in Experiment 3, a relatively long ITI was used (3 s). An offset of the imperative stimulus was triggered when a button was pressed. When an incorrect response was made, the word *ERROR* was presented, which remained for 1 s on the screen. The procedure closely followed the previous experiments in other respects. Response time was recorded as the interval between the stimulus onset and depression of a button. An experimental session lasted less than 30 min for each participant.

Results

Mean RT and PE were computed in the same way as in the previous experiments (Table 1). The discarded trials counted 0.01% of all trials, and the mean error rate was 2.3%.

An ANOVA for the RT data (see Table 4) revealed a significant main effect of mapping. RT was 416 ms (SD = 48.8 ms) for the congruent mapping and 440 ms (SD = 55.2 ms) for the incongruent mapping. Mapping also interacted with condition, with ES being large. The SRC effect for the pure condition was 57 ms (SD = 38.7 ms; Cohen's d =1.46). However, for the mixed condition, the SRC effect was −9 ms (SD = 35.7 ms; Cohen's d = 0.27), indicating elimination, if not reversal, of the SRC effect. The main effect of condition was also significant, with a large ES. RTs were 335 ms (SD = 46.1 ms) for the pure condition and 521 ms (SD = 67.3 ms) for the mixed condition. Thus, there was a mixing cost.

For PE (see Table 5), the main effect of mapping was not significant (M = 2.5%, SD = 2.3% for congruent; M = 2.1%, SD = 1.3% for incongruent). On the other hand, the interaction between mapping and condition was significant, with a large ES. These results indicated that the SRC effect was positive for the pure condition (1.6%, SD = 1.7%; Cohen's d = 0.97) but was negative for the mixed condition (M = −2.4%, SD = 4.6%; Cohen's d = 0.53). Thus, the advantage of corresponding responses was not obtained; instead, the results favored noncorresponding responses. The main effect of condition was significant with large ES (M = 1.0%, SD = 1.1% for pure; M = 3.5%, SD = 2.9% for mixed), indicating a mixing cost.

Discussion

A sizeable SRC effect was evident for buttonpresses in the pure mapping condition as in the preceding three experiments. In contrast to those experiments, however, the SRC effect was negative for RT and PE in Experiment 4. Thus, it is safe to conclude that the SRC effect was eliminated with mixed mappings, as expected. The method used in Experiment 4 was similar to that of Experiment 3, with the obvious difference being response mode. Responses were made by turning the yoke in Experiment 3 but by pressing buttons in Experiment 4. Thus, the continued presence of the SRC effect with mixed mappings in the first three experiments seems to be due to the yoke responses. This also implies that one type of manual response can establish SRC differently from another type, and the difference is more pronounced with mixed mappings than with pure mappings.

Experiment 4 also differed from Experiment 3 in that the trials were computer-paced rather than self-paced. In Experiment 3, the participants were required to hold the yoke horizontally straight for 3 s to start each trial. In Experiment 4 there was no such requirement, but the computer automatically initiated each trial after a fixed ITI of 3 s. Adam, Boon, Paas, and Umiltà (1998) proposed differential effects of self- and computer-paced trials for orthogonally oriented stimulus and response sets, arguing that self-paced trials increase the ITI and allow use of a preparation strategy different from one for computer-initiated trials. However, that case showed that the type of trial—computer- or self-paced—was not a significant factor (Cho & Proctor, 2003). Moreover, Heister and Schroeder-Heister (1994) used a warning tone before the presentation of the imperative stimulus in their study of mixed mappings, which would also allow use of such a preparation strategy, yet the SRC effect for keypresses was eliminated. In addition, the 3-s ITI in Experiment 4 of the present study was considerably longer than those typically used for the study of SRC effects and was set to match the interval from yoke centering to stimulus onset in Experiments 1–3. Thus, it is unlikely that computer pacing of trials is responsible for the different results in Experiment 4.

Sequential Effects Analyses

Studies of the Simon effect show that the effect is large for trials that immediately follow a corresponding trial but is eliminated for trials that immediately follow a noncorresponding trial (e.g., Hommel, Proctor, & Vu, 2004; Proctor, Vu, & Marble, 2003; Stürmer et al., 2002; Wühr, 2005). This finding has been attributed by several researchers to a gating–release mechanism of the direct route (e.g., Stürmer et al., 2002; Wühr, 2005). According to the gating account of sequential effects in the Simon task, when the response on a trial does not correspond to the location of the stimulus, the gate of the direct response-selection route is closed. This closure carries over to the next trial, eliminating the advantage that the route would produce when stimulus and response locations correspond. When the response on a trial does correspond with the stimulus location, the gate is opened, resulting in an advantage for correspondence over noncorrespondence on the following trial.

In SRC tasks, all pairwise sequences of trials with a pure congruent mapping are corresponding followed by corresponding. With a pure incongruent mapping, all sequences are noncorresponding followed by noncorresponding. Thus, it could be argued that the direct route would be operational for all trials in the pure congruent mapping block but blocked for all trials in the pure incongruent mapping block, resulting in a substantial SRC effect. With mixed mappings, only 25% of all trials are corresponding followed by corresponding. This reduction in the percentage of corresponding–corresponding trial sequences could account for the reduction and/or elimination of the overall SRC effect.

This possibility raises a theoretically significant issue, which is whether the reduction and/or elimination of the SRC effect is due to trial-by-trial gating of the direct route or global inhibition of the route for the entire block of trials. The transient gating account predicts that the advantage of the corresponding response should occur after a congruent mapping trial but not after an incongruent mapping trial (first hypothesis). On the other hand, global inhibition should result in absence of the advantage of the corresponding response even on trials after a congruent mapping trial (second hypothesis). Therefore, as has been done for the sequential effects analysis of the Simon effect, SRC effects as a function of mapping on the immediately preceding trial were computed for each participant in Experiments 1–4 (see Table 6).

For Experiments 1–3, the SRC effects after the congruent trials were, respectively, 109 ms, 88 ms, and 80 ms (*SD*s = 56.8 ms, 70.09 ms, and 47.52 ms; Cohen's *d*s = 1.91, 1.25, and 1.69), and the SRC effects after the incongruent trials were 7 ms, −5 ms, and −16 ms (*SD*s = 45.82 ms, 76.93 ms, and 57.58 ms; Cohen's *d*s = 0.15, 0.06, and 0.27). Thus, the SRC effect was evident for trials following a congruent trial but not for trials that followed an incongruent trial.

For the mixed condition of Experiment 4, the SRC effects after the congruent and incongruent trials were 22 ms and −39 ms (*SD*s = 47.09 ms and 46.37 ms; Cohen's *d*s = 0.48 and 0.84), respectively. Thus, even in Experiment 4, in which the overall SRC effect was not significant, a small SRC effect was apparent after a congruent trial; but this reversed to favor the incongruent mapping after an incongruent trial. This sequential analysis seems to suggest that reductions of the overall SRC effect in the mixed conditions of the present study may be due to gating of the direct route only after an incongruent trial but release of the route after a congruent trial, supporting the first hypothesis, though this transient gating–release mechanism cannot account for the reversal of the SRC effect for trials after an incongruent trial in Experiment 4.

However, when the SRC effect is analyzed as a function of mapping on the immediately preceding trial, the effect is con-

Table 6
Mean Response Times for the Current Congruent and Incongruent Mappings as a Function of Preceding Mappings in the Pure and Mixed Conditions of Experiments 1–4

Experiment and current mapping	Preceding mapping							
	Pure				Mixed			
	Congruent		Incongruent		Congruent		Incongruent	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
1								
Congruent	508	92.60			606	81.30	670	117.00
Incongruent			590	112.50	714	111.70	677	110.80
2								
Congruent	510	89.30			637	110.30	708	147.60
Incongruent			601	133.60	725	147.00	703	133.20
3								
Congruent	422	65.50			535	83.00	599	102.70
Incongruent			471	70.50	615	100.80	583	93.50
4								
Congruent	307	44.50			505	74.20	540	76.00
Incongruent			364	54.90	527	72.20	501	61.80

founded with the costs of a mapping switch. That is, after a congruent trial, trial sequences are either repetition of the congruent mapping or alternation to the incongruent mapping. Thus, the observed advantage for the congruent trials can be due to the benefits of repeating the congruent mapping trials. Similarly, after an incongruent trial, sequences are either repetition of the incongruent mapping or alternation to the congruent mapping. Thus, the observed disadvantage for the congruent trials can be due to the costs of alternating from incongruent to congruent mapping. That is, because responses are slower on trials in which tasks or mappings switch than those where they are repeated (e.g., Monsell, 2003), the observed patterns in the analysis could be due to entirely switching costs.

To exclude the confounded switching costs, a more appropriate way to analyze the sequential effects in SRC tasks is to compare the repetition and alternation trials of the congruent mapping, with those of the incongruent mapping. Those effects refer to the differences in RT between (a) trials in which the current and preceding mappings are both congruent or both incongruent (repetition trials) and between (b) trials in which the current mapping is congruent but the preceding mapping is incongruent or the current mapping is incongruent but the preceding mapping is congruent (alternation trials; cross-diagonal comparisons under the mixed conditions in Table 6).

For Experiments 1–3, this analysis resulted in SRC effects of 72 ms, 65 ms, and 48 ms (*SD*s = 44.43 ms, 65.47 ms, and 40.81 ms; Cohen's *d*s = 1.61, 1.0, and 1.19) for the repetition trials, and 44 ms, 18 ms, and 16 ms (*SD*s = 47.84 ms, 60.67 ms, and 48.32 ms; Cohen's *d*s = 0.92, 0.29, and 0.33) for the alternation trials, respectively. They support the first hypothesis, suggesting that the reductions in the overall SRC effects in these experiments were due mostly to alternation of congruent and incongruent trials.

For Experiment 4, though, the SRC effects for the repetition and alternation trials were −4 ms and −13 ms (*SD*s = 50.61 ms and 31.81 ms; Cohen's *d*s = 0.08 and 0.4). Thus, little indication of a positive SRC effect for both the repetition and alternation trial sequences for the congruent mapping was found in this experiment, supporting the second hypothesis. This outcome suggests that the failure to find a statistical significance for the overall SRC effect in the mixed mapping condition of Experiment 4 is not accounted for by sequential effects or reduction of the frequency of the repetition trial sequences for the congruent mapping. Rather, the pattern of the SRC effects in Experiment 4 implies that there was an overall inhibition of the corresponding response throughout the entire block of trials, inconsistent with a transient gating–release explanation of the elimination of the SRC effect.

General Discussion

Interpretation of the Results

The present study investigated SRC in a simulated flight environment. In Experiments 1 and 2, the participants were required to align the roll pointer on the attitude display of a simulated glass cockpit with the target mark. This required turning a flight yoke in the direction indicated by an imperative stimulus. Two experiments differed in whether an inside-out or outside-in frame of reference was used for the attitude display. However, the standard SRC effect was obtained with the pure congruent and incongruent mappings in both experiments: Responses toward the imperative stimulus were faster than those away from it. The magnitudes of these effects were within a range of 50 to 100 ms that is typically observed in a laboratory setting. Similarly, for both, the SRC effect was still apparent when the congruent and incongruent mappings were intermixed in a single trial block. These outcomes are in contrast to the elimination with mixed mappings found in previous experiments that used two-choice tasks for which the responses were keypresses.

Experiment 3 examined task performance without the glass cockpit display and, consequently, without the requirement to align the roll pointer with a target bank marker. The SRC effect was obtained with the pure congruent and incongruent mappings as in the preceding two experiments. However, though mixing congruent and incongruent mappings reduced the SRC effect, ESs still indicated that the SRC effect occurred in the condition. This outcome suggests that the continued presence of the SRC effect in the mixed mapping conditions of Experiments 1 and 2 was not due to use of a complex visual display or task. Experiment 4 replaced the yoke responses of Experiment 3 with presses of buttons on the yoke grips. With the pure mappings, the SRC effect was again obtained. In contrast, a very small ES was obtained in the opposite direction for the mixed mapping condition of this experiment. These outcomes indicate that the occurrence of the SRC effect with mixed mappings in Experiments 1–3 was most likely due to the use of yoke responses.

A transient gating–release mechanism of the direct route derived from the sequential analysis of the Simon effect predicts the finding that the effect appears on trials immediately following a corresponding trial but not on trials immediately following a noncorresponding trial because the closure of the direct route on a noncorresponding trial carries over to the following trial (Stürmer et al., 2002; Wühr, 2005). This account could also be applied to the reduction–elimination of the SRC effect with mixed mappings.

In the mixed conditions of Experiments 1–3, the SRC effects for the repetition trial sequences were apparent. However, those for the alternation trial sequences were small in Experiments 2 and 3. Thus, it can be claimed that the direct route was suppressed after an incongruent trial but not after a congruent trial. In other words, the overall reduction of the SRC effects with mixed mappings in those experiments can be attributed largely to the reduced frequency of the repetition trial sequences for the congruent mapping.

In contrast, in the mixed condition of Experiment 4, ES of the SRC effect was very small for the repetition trial sequence, and it was less than medium size but in the opposite direction for the alternation trial sequence. That is, a transient gating–release mechanism of the direct route and reduction in frequency of repetition of congruent trials cannot explain this pattern. Rather, it requires global inhibition of the corresponding responses. Therefore, the results of the present study imply that the effect of mixed mappings for the buttonpress responses is qualitatively different from that for the yoke-turn responses.

Vu and Proctor (2004) provided evidence that elimination of the SRC effect occurs mainly for highly compatible S–R sets that are perceptually similar. In their experiments, elimination was observed for mixed mappings of spatial stimuli mapped to keypress responses, but not for mixed mappings of location words mapped to the same keypress responses. The results of the present study are consistent with their assertion. Elimination was observed only for a set of buttonpresses mapped to a set of location stimuli, both of which were located bilaterally on the left or right. For yoke responses, bilaterality was in actions to be made but not in the response device itself. In other words, the response mode is only conceptually, but not perceptually, similar to the stimulus set.

Consistent with this possibility, Proctor and Wang (1997b) obtained data indicating that bimanual responses are relatively more compatible with physical location stimuli than are unimanual responses. They tested SRC effects for pure congruent and incongruent mappings with various types of manual responses. In their Experiment 3, one group of participants responded to stimulus locations or location words by moving the left or right index finger to a left or right key, and another group responded by moving a single index finger to a left or right key. The advantage for the spatial stimuli over verbal stimuli was larger for the bimanual movement condition than for the unimanual movement condition. Proctor and Wang interpreted this and other results as indicating that bimanual responses to spatial stimuli and unimanual responses to verbal stimuli were of higher compatibility than were the other two combinations.

On the basis of these results in the previous studies, a possible explanation for the patterns of the SRC effects in the present study is that yoke-turn responses are analogous to making unimanual responses rather than bimanual ones even when both hands are used. The analogy may be drawn from the fact that a yoke-turn response is cognitively represented as the movement of a single response device, like the movement of a single effector for unimanual responses. Therefore, the degree of compatibility between the stimulus and response sets is not sufficiently high to eliminate the SRC effect with mixed mappings. Because of the high level of compatibility, responses (especially corresponding responses) are prepared rapidly and thus have to be inhibited on each trial regardless of the immediately preceding mapping.

It is also possible that elimination is attributable to simultaneous preparation of two responses for bimanual buttonpress responses. Because the two responses with this response mode are not mutually exclusive, they can be prepared simultaneously. Thus, the readiness to respond is high, and a slight activation of the corresponding response is cumulatively sufficient to produce the response, which results in an incorrect response on incongruent trials. Thus, a global inhibition of the tendency to produce a corresponding response triggered by the onset of an imperative stimulus is required. In contrast, because the two responses with the yoke are mutually exclusive, this response mode does not allow such advance preparation. Consequently, activation of the corresponding response by the direct route does not accumulate to a threshold for actual production of the response. Thus, a global inhibitory process is not required, resulting in continued presence of the SRC effect with mixed mappings.

Regardless of the underlying mechanism, the present study demonstrated that the SRC effects with mixed mappings are qualitatively different between buttonpress and yoke-turn responses. Though the exact factors that contribute to these differences must be specified in more detail by future studies, the results emphasize the importance of response modes used in SRC tasks with mixed mappings.

Practical Implications

The current research was conducted in a flight task environment to test findings provided previously by basic research on SRC. The SRC effect obtained in two-choice reaction tasks typically ranges from 50 to 100 ms, as in the present experiments. At an airspeed for a single-engine general aviation aircraft of about 95 knot (or 9,500 ft/min) this would amount to a distance of approximately 8–16 ft or 2.5–5 m. For a private jet traveling at an airspeed of 300 knot (or 30,000 ft/min), the travel distance would be about 25–50 ft, or 7.5–15 m. The difference in travel distance for congruent and incongruent mappings could be decisive under hazardous conditions. However, one might still want to argue that the SRC effect size of 50–100 ms is not large enough to be of much practical importance. In our opinion, such an argument would be misguided for the following reasons.

The primary significance of the RT difference between congruent and incongruent mappings for practical operational environments is that the difference provides a sensitive measure of SRC. That is, it is not so much the magnitude of the RT difference per se that is important but the variation in relative compatibility for different display-control relationships that the difference signifies. Incompatibility will have a general degrading effect on performance. For example, note that errors of rotating the yoke in the wrong direction were approximately three times more likely with an incongruent mapping as with a congruent mapping in Experiments 1 and 2, which most closely resembled a flight environment. Moreover, both the percentage of incorrect responses and the delay in executing correct responses with the incongruent mapping would be expected to increase under conditions of overload produced by additional task requirements and stress (e.g., Alluisi & Warm, 1990). Thus, the remainder of this section discusses the practical importance of SRC in operational environments and the implications of the findings in the present research in the context of aviation cockpit design.

The relevance of basic research on SRC to cockpit design and issues in the mapping of controls to attitude displays has been noted since the earliest research on SRC, conducted by Paul Fitts and colleagues (Fitts & Seeger, 1953; Fitts & Deininger, 1954). According to Pew (1994), a student of Fitts's,

> [t]he starting point [of Fitts' experiments on SRC] was undoubtedly his early critical incident studies of aircraft cockpit controls and displays. . . . One of the problems they found when examining incidents with aircraft instruments concerned the direction of motion of the artificial horizon. (p. 31)

The significance of SRC research to aviation has continued to be recognized in subsequent years. For example, in a technical report prepared for the National Aeronautic and Space Administration, *Display-Control Compatibility in the Cockpit*, Andre and Wickens (1990) reviewed and analyzed "various underlying mechanisms and common explanatory principles of S–R compatibility effects as these relate to the human factors concerns in the design and placement of displays and controls in the air- or rotor-craft cockpit" (p. 3).

According to a study regarding flight deck automation (Funk et al., 1999), "poorly designed display" is listed as one of the five contributors most often involved in reported accidents. It has also been suggested that incompatibility between the way information is displayed to pilots and the way the pilots understand the information or make actions in response to the information can result in a control-reversal error, an error in which pilots roll the aircraft in the direction opposite to the intended direction (D. Cohen et al., 2001; Previc & Ercoline, 1999). In the present study, making the corresponding response when the mapping was incongruent falls into the category of control-reversal errors. Moreover, as noted, the impact of incompatibility between display and control increases as workload stress and attentional demands increase (Andre & Wickens, 1990). Consequently, neglect and subsequent violations of SRC principles can result in design-induced human errors, which constitute the largest single cause of flight accidents and incidents (O'Hare, 2006; Prinzel, Pope, & Freeman, 2002).

The present study demonstrated that use of mixed congruent and incongruent mappings in a task increases both RT and PE for both mappings. Because the likelihood of creating mixed mapping conditions increases as complexity of a task environment increases (e.g., one alert requires corresponding responses whereas another requires noncorresponding responses), it is desirable to design a cockpit deck in a way that the instruments provide uniform S–R relationships.

Furthermore, the results of the present study suggest that different manual responses influence the SRC effect differently, when responding to the identical stimuli. Critically, the results provided evidence that the processes underlying these different S–R pairings may be distinct. Specific combinations of different stimulus and response sets has been known to be an important factor in SRC since the work of Fitts and Seeger (1953; see also Wickens, Sandry, & Vidulich, 1983, for applied research on this issue). However, the present findings of differential effects resulting from specific combinations of spatial stimuli and manual responses are important for application of SRC principles, considering the fact that various modes of manual responses and stimulus presentations have to be used in operational environments.

In the present experiments, the overall benefit for the congruent mapping was still apparent in mixed mapping conditions when responses were made by turning the yoke, whereas the benefit disappeared with mixed mappings for buttonpresses. Consequently, one needs to keep in mind that expected advantages of SRC may turn out to be disadvantages if such findings as in the present study are ignored. Similarly, we also showed that the differential effect of particular S–R sets is strongly manifested in certain task situations (i.e., with mixed mappings) but not in others (i.e., with pure mappings). It is thus recommended, especially for those concerned with interface design, to consider compatibility between the information presented by operational aids and the actions to be taken in response to that information, as well as the task situations in which the actions will be taken. To support such considerations, further research is needed to clarify the exact conditions in which the benefits of SRC can and cannot be expected and conditions in which they even turn out to be disruptive.

Conclusions

A limitation of the present study in the practical application of SRC is that it is still unclear to what extent the robustness of the SRC effect that has been established in basic research persists in a complex task environment. Though maintaining compatibility can potentially provide great benefits for performance in operational environments, one might argue that the cost of incompatibility may be overcome through extended practice. Schmidt (1987), for example, expressed his concern that the basis of SRC may be extensive practice with particular S–R arrangements in everyday life (e.g., driving a car, playing a musical instrument), though they are initially unnatural or incompatible. However, though performance with incompatible S–R arrangements improves with practice, evidence indicates that the advantage of compatible arrangements is not easily overcome.

The original study of SRC by Fitts and Seeger (1953) reported that slower responses and higher error rates for incompatible S–R pairs than for compatible ones were still apparent after 32 days of training sessions. The tasks used in their study were simple (i.e., moving a stylus to one of eight positions). Consequently, performance had reached an asymptotic level after about 10 to 12 days, well before the study was terminated, suggesting little chance for further improvement. Subsequent studies of two-choice tasks that investigated the influence of practice on SRC also showed persistence of the effect, with an asymptotic level of performance reached after a few hundred trials and the SRC effect remaining evident well after the asymptote was attained (e.g., Brebner, 1973; Dutta & Proctor, 1992; Shulman & McConkie, 1973).

Nevertheless, considering amounts of practice that a person may receive by performing routine tasks in everyday life, one can still question the extent to which the persistent effect demonstrated in previous laboratory studies can be generalized to operational tasks outside laboratories. Yet, it should also be noted that even if it may be possible to overcome disadvantages of S–R incompatibility, the persistence of SRC effects for days of practice suggests that designing human interfaces consistent with the SRC principles can increase the efficiency of training as well. Thus, the effect of SRC on the efficiency of training is a significant factor to be investigated in future research.

Finally, a general contribution of the present study is to demonstrate a dialectic relationship between basic and applied research. The study was structured in such a way that it started with testing a basic research finding in an applied task and identifying differences in the results. In the remaining experiments, possible causes of the differences were evaluated by using tasks that more closely approximated the original basic research setting. Despite the fact that SRC has long been recognized as one of the most important factors influencing the usability of an interface, efforts at relating the vast body of knowledge on SRC to application have been few (e.g., Wickens et al., 1983). The present study provides an attempt to bridge the gap between the basic and applied studies. We think that the approach to the dialectic taken in this study will be fruitful more generally. Steps such as these should be attempted to strengthen the connection between basic and applied studies of SRC.

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