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The present research investigated factors that contribute to the compatibility of attitude display formats with actions taken to control an aircraft. In three experiments, participants performed a speeded response task in which they responded by banking an aircraft according to a nonspatial aspect of lateralized stimuli. The format of attitude display was *horizon-moving* or *aircraft-moving*, and each participant used *normal* and *reversed* controls. These manipulations dissociated influences of three response factors (aircraft, display, hand) on the *stimulus-response compatibility*, or *Simon, effect*. The influences of the three factors on the Simon effect were nearly additive, and their contributions depended on the task contexts. In particular, throughout the three experiments, the major factors in representing responses were the movement directions of the aircraft and the operating hands, and the influence of display format became small as participants directed attention onto the display.

One of the most important factors in interface design is compatibility between the way information is presented in the display and operations that are performed using that information (Proctor & Van Zandt, 2008; Wickens & Holland, 2000). A design principle that is most relevant in the present study is *the principle of moving part* (Roscoe, 1968), according to which the movement direction of display indicators should be consistent with the physical movement and/or operators' mental model of what is indicated. In the conventional design of a glass cockpit, the roll and pitch of an aircraft are indicated by moving the artificial horizon. This format was adopted based on the assumption that the correct format of an attitude indicator is an exact analogue of the pilots' view from the cockpit window (Roscoe, Corl, & Jensen, 1981, p. 343). However, the issue of whether or not this conventional format is really representative of pilots' mental models is a classic one (e.g., Conklin & Lindquist, 1958) that is still a topic of debate (e.g., Previc & Ercoline, 1999). The present paper reports three experiments that examined this issue. More specifically, the current research investigated what factors are relevant to represent the task context and to what extent the relevant factors influence performance.

Stimulus-Response Compatibility and Representation of Task Context

The stimulus-response (S-R) compatibility effect refers to the fact that, in a choice-reaction task, responses are faster and more accurate when stimuli and responses share certain properties, or when they correspond, than when they do not (Proctor & Vu, 2006). This effect is known to be so robust that it is observed even if the S-R correspondence is irrelevant to performing the task. For instance, in a task in which participants are instructed to press a left or right key in response to the color of a stimulus, responses are faster and more accurate when the stimulus occurs on the same side as the location of the correct key than when it occurs on the opposite side. The variation of the S-R compatibility effect that occurs on the basis of task-irrelevant S-R correspondence is termed the *Simon effect* (Simon, 1990). The Simon effect implies that task-irrelevant information is still encoded and affects performance. In turn, it is an indication of how the task context is represented.

The study of task representations in the context of the Simon task can be traced back to Simon, Hinrichs, and Craft (1970). In their experiments, participants were asked to respond by pressing a left or right response key to high- or low-pitch tones that were presented to the left or right ear. Therefore, the task-relevant stimulus feature was the tone pitch, and the side of the ear to which the tone was presented was task-irrelevant. In a condition where the left key was pressed by the left hand and the right key by the right hand, responses were faster if the location of the response hand corresponded with the side to which the tone occurred, yielding a regular Simon effect. However, in a condition where the left key was pressed by the right hand and the right key by the left hand (i.e., when the hands were crossed), responses were faster if the location of the response hand was opposite to the side to which the tone occurred. From these results, Simon et al. inferred that responses were encoded in terms of the key locations, not the hands with which the keys were pressed.

More recently, Hommel (1993) conducted experiments in which high- and low-pitch tones were presented from the left or right speakers, and participants pressed the left or right key in response to the tone pitch. In his experiments, two lights were positioned near the speakers, and a keypress turned on a light that was spatially noncorresponding to the key location (i.e., a left keypress turned on a light on the right, and a right keypress turned on a light on the left). When participants were instructed to press a key, responses were faster if the key location corresponded to the speaker location from which a stimulus was presented, yielding a regular Simon effect. However, when they were instructed to turn on a light, responses were faster if the key location did not correspond to the speaker location, that is, if participants turned on the light that was located at the same side as the speaker location. Thus, in the latter condition, responses were coded in terms of the light location, rather than the key location. Note that the illumination of a light is a distal effect of keypress response. The consequence of one's action, like the illumination of a light as a result of hitting a switch, is called an *action effect*, which Hommel's study has shown to be an important component in representing the task context.

The above studies exemplify the effectiveness of using the Simon task to investigate how people represent a task context. That is, if the Simon effect is observed between a task-irrelevant stimulus feature and a response component of interest, it can be taken as evidence that participants represent the response in terms of that component. The present study uses this paradigm to examine factors that contribute to performance in flight operations with two formats of an attitude indicator.

Present Study

The conventional format of an attitude indicator has been that of horizon-moving, in which the artificial horizon rotates to the left if the aircraft banks to the right, while it rotates to the right if the aircraft banks to the left; on the other hand, the aircraft symbol stays stationary at the center of the display. This format is in accordance with the pilot's perspective of the actual horizon as it is viewed from the cockpit window. However, several researchers suspect that the apparent movement of the horizon may be inconsistent with the pilot's mental representation of the relationship between the horizon and the aircraft (e.g., Previc & Ercoline, 1999; Roscoe et al., 1981). For instance, Patterson et al. (1997) argued that the spatial representation constructed for monitoring the cockpit indicators is different from that constructed for viewing the scene outside the cockpit window. When monitoring the indicators, the spatial representation is based on the coordinate system that is centered at the aircraft, which, as the aircraft changes its attitude, moves in relation to the actual horizon but is stable in relation to the pilot. In contrast, when viewing the outside scene, the spatial representation is based on the coordinate system that is centered at the direction of the gravity, which is stable in relation to the horizon but moves in relation to the pilot when the aircraft changes its attitudes (see also Previc, 1998). The researchers proposed that a format more consistent with the spatial representation for monitoring the attitude indicator is that of an aircraft-moving, in which the artificial horizon stays stationary while the aircraft symbol rotates with the roll of the aircraft.

The aircraft- and horizon-moving displays present physically equivalent information, that is, the relationship between the aircraft's attitude (roll and pitch) and the horizon, but in different ways. Their difference is which display object is actually moving to represent the relationship. According to the *principle of moving part*, the compatibility of the two displays with pilots' operations depends on which aspects of display information enter into the mental representation of the operations. Because the mental representation is not directly observable, one has to use an indirect method to investigate the issue. For this purpose, the Simon task is useful.

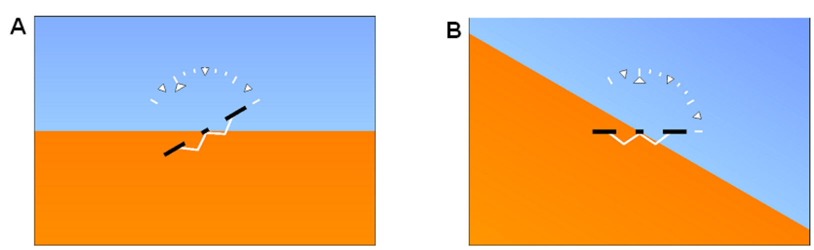

Figure 1. The aircraft-moving (A) and the horizon-moving (B) displays used in Experiments 1-3.

In the present study, participants were asked to bank an aircraft simulated in the computer display with an aircraft-moving format or a horizon-moving format (see Figure 1). Responses were made by turning a flight yoke, and stimuli were auditory tones in Experiment 1 and visual signals in Experiments 2 and 3, both of which contained a spatial feature (left or right). However, the spatial feature of stimuli was irrelevant to performing the task. In the context of these Simon tasks, there are at least three factors that can contribute to task representation. These factors are (a) the movement direction of the operating hands, (b) the movement direction of the display object, and (c) the movement direction of an aircraft simulated on the display. Note that the latter two factors are distal effects of the operating hands, that is, they are action effects. As mentioned, they are known to constitute an action representation.

In the aircraft-moving format, the aircraft symbol rotates to the left or right according to the direction of the yoke input. In the horizon-moving format, the artificial horizon rotates to the left or right but in the opposite direction to the yoke input. Although the roll of the aircraft is simulated differently in the two formats, both displays convey physically equivalent information; the rotational relationship between the aircraft and the horizon. Thus, the aircraft rotates in accordance to the direction of the yoke input in both displays. Therefore, the directions of the operating hands and the aircraft are always consistent. To examine the separate contributions of the three factors to pilots' mental representation, we introduced a manipulation in which the control was either 'normal' or 'reverse'. In the *normal-control* condition, the aircraft banked to the left (right) if the yoke was turned to the left (right). In the *reverse-control* condition, the aircraft banked to the left (right) if the yoke was turned to the right (left). With this manipulation, there were a total of eight trial conditions, which are summarized in Table 1. For the aircraft-moving format with normal-control (the first and second rows), the three response components are all compatible (incompatible) with the stimulus location if one of them is compatible (incompatible). When the control is reversed (the third and forth rows), the compatibility relationship of the operating hand is dissociated from the other two components. Similarly, for the horizon-moving format, the compatibility of the display object is isolated from the other components in the normal-control condition, whereas the compatibility of the aircraft is isolated from other components in the reverse-control condition. Therefore, by comparing the Simon effect for these trial conditions, the extent to which the three factors contribute to mental representation of the task context can be assessed.

Table 1. *Summary of Compatibility Relationships between Stimulus and Three Response Components*.

		Response Component		
Display Format	Control Condition	Aircraft	Display	Hand
Aircraft-Moving	Normal	+	+	+
		–	–	–
	Reverse	+	+	–
		–	–	+
Horizon-moving	Normal	+	–	+
		–	+	–
	Reverse	+	–	–
		–	+	+

Note. Plus (+) and minus (–) signs indicate 'compatible' and 'incompatible', respectively.

General Method

Three experiments are reported. In each experiment, 40 undergraduate students enrolled in Introductory Psychology at Purdue University participated (a total of 120 participants). Participants were randomly assigned to one of the two display formats (aircraft-moving, horizon-moving) and performed two trial blocks between which the control (normal, reverse) varied. The order of the two control conditions was counterbalanced across participants. At the beginning of an experimental session, participants were shown the display that they were about to use during the test trials. They were told that the display represented the roll of an aircraft (the pitch was fixed in the present study) and asked to move the aircraft to familiarize themselves with the display. The attitude indicator was 22 cm in width and 14.6 cm in height (see Figure 1). The viewing distance (unrestricted) was approximately 70 cm. After the familiarization, participants read instructions for the task presented on the computer screen and were told that one block would be the normal-control condition and the other would be the reverse-control condition. Each block began with 12 practice trials, followed by a pause screen. The test trials started when the experimenter pressed a start key. A test block consisted of 156 trials (of which the first 12 trials were considered to be warm-up and thus discarded from the analysis). The experiment was conducted individually in a well-lit cubicle. An experimental session lasted for less than 30 minutes.

Each trial started with the roll angle of 0°. With a 1,000-ms foreperiod, the imperative stimulus was presented. In Experiment 1, the stimuli were high- and low-pitch tones (880-Hz and 440-Hz, 64 dB) presented through headphones to the left or right ear. In Experiments 2 and 3, the stimuli were green and red rectangles (2.2 cm in width and 1.5 cm in height) presented on the left or right above the attitude indicator. Participants wore headphones throughout the session in all experiments.

In Experiments 1 and 2, participants were simply instructed to turn the aircraft to the left or right according to the task-relevant aspect of stimuli. When the aircraft banked 45°, the display was paused until the yoke was returned to the neutral position, after which the roll was automatically set to the initial zero point. In Experiment 3, participants were asked to bank the aircraft to the bank marker at 45° and maintain the roll angle for 1 s (the error window was ±3º from the target position). Therefore, the difference between Experiments 2 and 3 was that the former required participants simply to turn the yoke to the left or right, whereas the latter required more fine control. Note that in both cases, the task instructions were based on the aircraft movement, not the operating hands or the display objects.

Response time (RT) was the interval between stimulus onset and displacement of the yoke from the neutral position approximately 10° to the left or right. A response was considered to be an error when the yoke was turned to a wrong direction beyond this criterion position, but participants were not aware of this response criterion (thus, they could correct before completing a trial, though the response was recorded as an error on that trial). If the eventual response was incorrect, an error message "ERROR" (Experiment 1) or an error tone (440 Hz, 64 dB; Experiments 2 and 3) was presented at the end of a trial.

Results

Trials for which RT was less than 100 ms or greater than 1,500 ms were discarded (< 1% of all trials). Mean RT for correct responses and percentage errors were computed for each participant (we report only the analysis of the RT data due to the space limitation) and submitted to analysis of variances as a function of Correspondence (corresponding vs. noncorresponding; within-subject), Control (normal vs. reverse; within-subject), and Display Format (aircraft-moving vs. horizon-moving; between-subject). Note that the Correspondence variable was coded based on the spatial relationship between stimulus and the correct direction of the aircraft. The Simon effect was computed by subtracting mean RT for the corresponding trials from mean RT for the noncorresponding trials, which is summarized in Figure 2.

Experiment 1: Auditory Stimuli

There was significant interaction between Display Format and Correspondence, $F(1, 38) = 5.11$, $MSE = 331$, $p < .030$, and between Correspondence and Control, $F(1, 38) = 42.08$, $MSE = 360$, $p < .001$. The Simon effect was larger for the aircraft-moving format ($M = 28$ ms) than the horizon-moving format ($M = 15$ ms), and for the normal-control condition ($M = 41$ ms) than for the reverse-control condition ($M = 2$ ms). However, the three-way interaction of the Display Format, Correspondence, and Control was not significant, $F(1, 38) = 2.68$, $MSE = 360$, which indicates little evidence for a violation of additive effects of Display Format and Control on the Simon effect.

From Table 1, the larger Simon effect for the aircraft-moving format than the horizon-moving format implies a contribution of the display motion to the response representation. Similarly, the larger Simon effect for the normal-control than the reversed-control implies a contribution of the operating hands to the response representation. Also, there was still a significant main effect of Correspondence, $F(1, 38) = 57.76$, $MSE = 331$, $p < .001$, which yielded a 21 ms of the Simon effect. This observation implies a contribution of the aircraft to the response representation (because the null effect is expected if there is no contribution of that factor). Therefore, Experiment 1 suggests that all three components contribute additively to the response representation.

Experiment 2: Visual Stimuli

As in Experiment 1, there was a significant interaction between Correspondence and Control, $F(1, 38) = 5.25$, $MSE = 682$, $p < .028$. The Simon effect was larger for the reverse-control condition ($M = 38$ ms) compared to the normal-control condition ($M = 19$ ms), implying a contribution of the operating hands to the response representation. In contrast to Experiment 1, however, the interaction between Correspondence and Display Format was not significant, $F(1, 38) < 1$. That is, the contribution of the display motion to the response representation was very small when visual stimuli were used. However, a main effect of Correspondence was still significant, $F(1, 38) = 32.63$, $MSE = 1{,}007$, $p < .001$, which implies the contribution of the aircraft movement to response representation. The 3-way interaction of Correspondence, Display Format, and Control, $F(1, 38) < 1$, was not significant, as in Experiment 1.

Experiment 3: Fine Control

There was a significant effect of Correspondence, $F(1, 38) = 118.06$, $MSE = 781$, $p < .001$. Thus, the contribution of the aircraft movement to response representation appears to be an important factor when fine control of the aircraft attitude is required. However, the interaction between Correspondence and Control or between Correspondence and Display Format was not significant, *F*s(1, 38) < 1. Thus, in contrast to the preceding experiments, neither the contributions of the operating hands nor the display motion were apparent in Experiment 3. There was a trend of a main effect of Display Format, $F(1, 38) = 4.02$, $MSE = 26{,}574$, $p < .052$, reflecting faster responses for the horizon-move display ($M = 566$ ms) than for the symbol-move display ($M = 617$ ms). This outcome is, however, probably a between-subject error because the effect was not consistent throughout the three experiments (responses were faster for the horizon-moving in Experiment 1 but slower in Experiment 2).

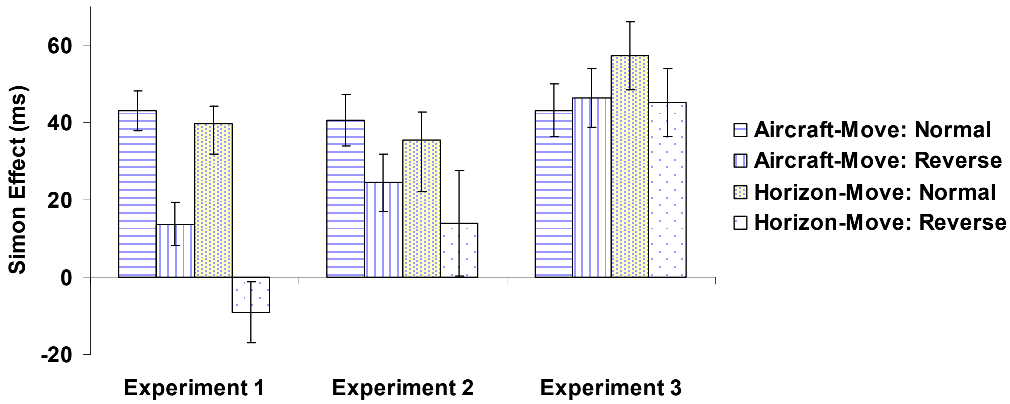

Figure 2. Compatibility effects as a function of display format and control conditions for Experiments 1-3.

Discussion

The study of the display format in attitude indicator has been centered at the compatibility of display information with pilots' mental representations of flight operations. To address this issue, we used the Simon task that has been shown to be effective to investigate the influences of task features on stimulus and response representations. A particular focus was placed on how action (response) is represented in controlling the roll of an aircraft while monitoring an attitude indicator.

The three factors of interest were the movement direction of (a) the aircraft simulated on the display, (b) the display object, and (c) the operating hands. The former two factors are action effects that result from the physical action taken by the operator, which have been shown to be important factors in representing one's actions. To examine the contributions of the two action effects and the physical action to the mental representation of the task context, we dissociated their influences by introducing the normal- and reverse-control conditions. The three experiments also differ in whether the imperative stimuli were auditory or visual and whether a ballistic or fine control of the aircraft was required.

In Experiment 1, where the stimuli were auditory, all three factors influenced the Simon effect, implying that participants represented their responses in terms of the three response components. Because the only difference between the aircraft- and horizon-moving was the movement of the display objects, the most important observation in this experiment is the influence of the display object. That is, the result implies that if the motion of display object is incompatible with the direction that the pilot intends to move, it can interfere with flight operations. Hence, the present experiment supports the advantage of an aircraft-moving format for an attitude indicator, as several researchers have argued (e.g., Patterson et al., 1997; Previc & Ercoline, 1999). However, this conclusion is attenuated by the results of Experiments 2 and 3.

In Experiment 2, where the stimuli were visual, only the aircraft movement and the operating hands were significant factors, and little influence of the display motion was obtained. The use of visual stimuli was likely to have forced participants to pay more attention to the screen, compared to when the stimuli were auditory. At surface, such a manipulation would have increased the influence of the display motion. The results indicate the contrary; the influence of the actual display motion is weakened if participants pay more attention to the display. A likely reason for this outcome is that the display information is interpreted more accurately if participants attend to that information, which is the relationship between the aircraft's attitude and the horizon. If so, Experiments 1 and 2 collectively imply that the advantage of an aircraft-moving format can occur when a sudden change in the flight condition forces the pilot to quickly read the attitude indicator or when the pilot has to quickly shift between multiple displays, but when the pilot continuously monitors the attitude display, the difference between the aircraft- and horizon-moving formats is not influential.

In Experiment 3, participants were asked to roll the aircraft to the bank marker at 45° and maintain the angle for a period of time. Thus, the task required continuous monitoring of the indicator, in contrast to the preceding two experiments. Consistent with the above interpretation, participants represented their actions in terms of the aircraft's movement, and the other two factors were virtually ignored. Thus, when participants had to pay attention to the screen, the display information was correctly interpreted throughout the session.

In conclusion, the three experiments suggest that the two display formats provide equivalent task performance as long as the pilot pays attention continuously to the attitude indicator. However, the advantage of an aircraft-moving format may emerge when the pilot has to read the aircraft's attitude quickly, for example, to recover from an abnormal attitude. It should also be acknowledged that the conclusions are restricted to the type of display used in the present experiments. Whereas the current results are likely to be applicable to a head-down glass cockpit display, which embeds an attitude indicator similar to the one used in the present study, the generalization of the results to different types of displays, such as head-mounted displays and analogue attitude indicators, requires caution. Finally, while the present research relied on a nonpilot population, the validity of the results for the trained pilot population is an important issue for future investigations.

Acknowledgements

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