Compatibility of motion information in two aircraft attitude displays for a tracking task

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In a conventional aircraft attitude indicator, the artificial horizon moves in the direction opposite to the pilot’s hands and the movement of the aircraft. This horizon-moving format is believed to be response–effect (R–E) incompatible. An alternative format, aircraft-moving, presents movement of the aircraft symbol that is compatible with both the pilot’s hand movements and the movement of the aircraft. In the present study, nonpilot participants performed an attitude tracking task with a horizon-moving or aircraft-moving display for 6 training sessions and 1 transfer session in which the display was switched to the other format. The participants performed the task equally well and showed similar rates of improvement with the 2 displays. However, a switch of display format degraded tracking performance, indicating that learned skills did not transfer between formats. The results of a secondary choice reaction task, performed concurrently during tracking, suggested that attention can be divided between visual and auditory modalities better with the horizon-moving display than with the aircraft-moving display. We argue that the horizon-moving format is R–E compatible, as far as the tracking task is concerned, and that the effects of display format on the secondary task may be due to different modes of spatial representation being used to monitor the formats.

Compatibility between display designs and mental models or actions is of great interest in operational environments (Andre & Wickens, 1990; Proctor & Vu, 2006). In the aviation industry, the notion of compatibility is reflected in the design of cockpit instruments. For instance, in the conventional format of an attitude indicator, the aircraft symbol is fixed at the center, and the artificial horizon rotates or moves upward or downward to indicate the current roll and pitch of the aircraft (see Figure 1, top panel). This horizon-moving format was assumed to be optimal because the moving horizon on the display is compatible with the apparent motion of the actual horizon viewed from the cockpit by the pilot (Roscoe, Corl, & Jensen, 1981). However, researchers (e.g., Previc & Ercoline, 1999) have pointed out that, with that format, the physical motion of the artificial horizon is incompatible with both the movement of the pilot’s hands and the actual movement of the aircraft, which may cause interference with control operations. Thus, they proposed that a more intuitive format is that of a moving aircraft and a fixed horizon (see Figure 1, bottom panel), called the aircraft-moving format. The present study compared these two display formats and examined influences of motion information in an attitude display on tracking and choice reaction performance.
Variations of compatibility effects
In a spatial task, responses are faster and more accurate when stimuli are mapped to spatially compatible responses than when they are mapped to spatially incompatible ones. This phenomenon is known as the spatial stimulus–response (S–R) compatibility effect (Proctor & Vu, 2006). A typical explanation of the S–R compatibility effect is that the spatially compatible mapping allows the use of direct associations (e.g., van Duren & Sanders, 1988) that bypass an effortful and time-consuming S–R translation process.

The S–R compatibility effect has been demonstrated in numerous task contexts. For example, it is observed even when the spatial correspondence is irrelevant to performing the task (Simon, 1990). Moreover, actions are more quickly and accurately executed when the direction of a moving stimulus is compatible with the actions (e.g., pressing a left key to a stimulus moving to the left) than when it is not (Proctor, Van Zandt, Lu, & Weeks, 1993). This motion compatibility effect has also been demonstrated with illusory motion, where a moving frame surrounding a stationary stimulus induces a false perception of motion in the stimulus (Kerzel, Hommel, & Bekkering, 2001).

Also, recent studies demonstrated that action effect can be a critical factor for task performance. Action effects are any perceptual events that occur as a consequence of taking actions (e.g., illumination of a light when hitting a light switch). Hommel (1993) showed that a Simon-like effect occurs when the location of a stimulus corresponds to the location of a light that is flashed when participants press a response key, even if the location of the response key (hand location) is spatially incompatible with the stimulus location. Moreover, Kunde (2001) demonstrated a response–effect (R–E) compatibility effect. In his study, four horizontally arrayed response keys were mapped to the four colors of a centered object, and each keypress triggered a visual effect that appeared at one of four horizontal positions on the screen. Responses were faster when the location of the visual effect corresponded to the key location than when it did not.

Thus, compatibility arises in several different levels, and multiple compatibility relations may be involved in a complex operational environment. These relations are not necessarily consistent with each other (as in the attitude indicator for which the display motion is compatible with the actual horizon but incompatible with the hand direction), and the relative degrees of their contributions determine the overall compatibility effect. Therefore, to assess the optimality of display design, it is important to consider the compatibility relations that may be involved in particular operational environments and the extent to which these relations influence human performance.

Compatibility factors in attitude displays
The adoption of the horizon-moving display was based on the assumption that the correct format is the exact analog of the pilot’s view from the cockpit window. This is plausible if the pilot’s mental representation is an exact copy of the retinal image. However, researchers have expressed their doubts...
about that assumption and proposed alternative formats for the attitude indicator (Roscoe et al., 1981). One of these alternatives is the aircraft-moving format (Previc & Ercoline, 1999), in which the artificial horizon stays stationary and the aircraft symbol moves according to the attitude of the aircraft (see Figure 1, bottom panel). Indeed, most proposed displays are some combination of the horizon-moving and the aircraft-moving formats (Kovalenko, 1991; Roscoe & Williges, 1975). Nevertheless, these alternatives have rarely been used in actual U.S. aircraft.

In the aircraft-moving display, the physical motion of a display object is consistent with the control action of the pilot. Thus, the aircraft-moving format is R–E compatible; that is, if the pilot turns the flight yoke or stick, the display object (i.e., the aircraft symbol) turns in the same direction as the direction of the control movement. In contrast, the horizon-moving format is R–E incompatible; the display object (i.e., the artificial horizon) moves in the opposite direction to the pilot’s operation. For this reason, the aircraft-moving display is believed to be superior to the conventional display.

Yet there is a finding that might disagree with this analysis. In a previous study of ours (Yamaguchi & Proctor, 2006), participants performed a choice reaction task to visual stimuli presented to the left or right side, at the top of either a horizon-moving or aircraft-moving display. Participants’ task was to bank the aircraft to the left or right by turning the flight yoke in response to the visual stimuli. In that experiment, the task involved at least two S–R compatibility relationships: the compatibility between stimulus location and the movement direction of the hands operating the yoke and the compatibility between the stimulus location and the movement direction of the display object (the artificial horizon for the horizon-moving, the aircraft symbol for the aircraft-moving).

Because the aircraft-moving display is R–E compatible, if the hand movement is compatible with stimulus location, the display movement is also compatible with stimulus location. In contrast, because the horizon-moving display is R–E incompatible, if the hand movement is compatible with stimulus location, the display movement is incompatible with stimulus location. Consequently, one would expect that the S–R compatibility effect (as computed in terms of the compatibility between stimulus location and hand direction) would be smaller for the horizon-moving display than for the aircraft-moving display because the two compatibility relationships are conflicting in the former but consistent in the latter. It is equally reasonable to predict that the S–R compatibility effect for the horizon-moving display should be reversed if the display motion is the major determinant of choice reaction performance (Hommel, 1993). However, the results suggested that the S–R compatibility effects were almost equivalent for the two displays. This outcome indicates that, at least in that particular condition, display motion on the attitude indicator was not a major factor in performing the task. This finding is counterintuitive and contrary to the assumed inferiority of the horizon-moving display to the aircraft-moving one.

Nevertheless, the choice reaction task used in our previous study may not represent task conditions that are usually encountered during actual flight. In particular, whereas the choice reaction task is performed in a discrete manner, real flight entails continuous aircraft control. In the present experiment, therefore, we adopted a tracking task that approximated real flight operations more closely than did the choice reaction task and examined whether any differences would be observed between the aircraft- and horizon-moving display formats.

EXPERIMENT

The present study investigated influences of the two types of display format on attitude tracking performance. In the experiment, participants were presented with a simulated aircraft whose attitudes (roll and pitch) were arbitrarily and continuously perturbed over time. Participants were asked to maintain the attitude of the aircraft at the wings-level (the wings of the aircraft parallel to and overlapped with the artificial horizon), and the performance measurement was root mean square error from the wings-level. The display format was a horizon-moving or aircraft-moving format. Tracking performance was examined over six training sessions, which allowed practice effects to be assessed with the respective displays.

If the physical motion of visual objects is a major determinant of task performance, then an aircraft-moving display is R–E compatible (display information is compatible with control action), whereas a
horizon-moving display is R–E incompatible. Consequently, participants should perform the task better with an aircraft-moving display than with a horizon-moving display. However, if the display motion is not a major determinant of tracking performance, as suggested in our previous study (Yamaguchi & Proctor, 2006), little difference in performance between the two displays is expected.

Also, we consider the issue from the aspect of possible mechanisms that process motion information in the two displays. If display motion is not a major determinant of tracking performance, to what do participants pay attention during the task? A possible candidate is their hands that operate the aircraft. In this case, participants should perform the tracking task using one display in the same way as using the other display. However, this possibility is unlikely in the present task because the attitude information can be acquired only by monitoring display motion. Another possibility is the movement of the “aircraft” simulated by the display motion. Remember that both the horizon-moving and aircraft-moving displays present the same attitude information of the aircraft, even though they present that information in different manners. Thus, participants presumably construct a mental model of the actual aircraft that they operate while monitoring an attitude display, and this movement of the mental model could be what participants focus on as they perform the task. If this is the case, participants may be able to perform the tracking task with the horizon-moving display at the same level as performing it with the aircraft-moving display.

At the same time, however, there should be differences between the two displays in the cognitive processes of translating display motion into the movement of the mental model. There is a large body of literature showing that some alternations of task contexts degrade performance of a previously practiced perceptual–motor task (e.g., Franks & Romanow, 1993; Healy, Wohldmann, Sutton, & Bourne, 2006; Proteau & Carnahan, 2001). If processes involved in performing the task with the horizon- and aircraft-moving displays are the same (e.g., focusing on their hands), the trained skills for the tracking task should be transferred freely between the two display conditions. Therefore, there should be no degrading of performance levels when participants are required to perform the same task but with a different format. However, if participants’ performance relies on the mental model constructed via the display information, the translation process from the display information to the mental model should differ between the two formats, and thus performance should degrade when participants switch between the formats.

In addition, the present experiment included sessions in which participants were asked to perform a secondary choice reaction task while performing the primary tracking task. In our previous study (Yamaguchi & Proctor, 2006), influences of display formats were not observed when participants performed a choice reaction task in isolation. The inclusion of the secondary task allowed us to assess whether the same conclusion holds when choice reaction is a secondary task. Stimulus modality for the secondary task was either visual or auditory. In our recent study (Yamaguchi & Proctor, 2009), we observed that the influences of display motion on choice reactions were absent when participants responded to visual stimuli, consistent with the earlier study (Yamaguchi & Proctor, 2006), but they appeared when participants responded to auditory stimuli. Thus, the interaction between stimulus modality and display format was also examined in the present experiment.

Participants pressed a button located on the same side of a visual or auditory stimulus in one condition (compatible mapping) and a button located on the side opposite to the stimulus in another condition (incompatible mapping). The compatibility manipulation was included because some accounts of S–R compatibility state that response selection processes operate differently for compatible and incompatible mappings (e.g., Kornblum, Hashbroucq, & Osman, 1990; van Duren & Sanders, 1988). Thus, the results that hold for one S–R mapping may not hold for the other mapping, and the use of two mappings is necessary to examine generality of the modality effects.

METHOD

Participants
Forty undergraduate students enrolled in introductory psychology courses at Purdue University participated for credits toward a course requirement. All were nonpilots and reported having no prior experience of flight training or education. All participants had normal or corrected-to-normal visual acuity.
normal color vision, and normal hearing assessed by self-report. Participants were randomly assigned to one of two display conditions, horizon-moving or aircraft-moving (N = 20 for each group).

Stimuli and apparatus

The apparatus consisted of a personal computer equipped with a 17-in. monitor. A custom computer application was constructed to present an attitude display (see Figure 1). The attitude display (19 cm in width and 9 cm in height) was composed of the artificial horizon and the aircraft symbol. The upper portion of the display was colored in light blue, representing the sky, whereas the lower portion was colored in brown, representing the ground. The aircraft symbol was a composite of white and black rectangles. For a horizon-moving format display, the aircraft symbol was stationary at the center of the screen, and the artificial horizon rotated and shifted upward or downward according to the roll and pitch of the aircraft, respectively. For the aircraft-moving format display, the artificial horizon was stationary on the screen, and the aircraft symbol rotated and shifted upward or downward according to the roll and pitch of the aircraft. Pitch and roll of the aircraft were sampled every 20 ms (i.e., a sampling rate of 50 per second).

Perturbations in pitch and roll were simulated by perturbation functions that consisted of 12 sinusoidal components (sinusoidal perturbation functions have been used in previous tracking studies; e.g., Cohen, Otakeno, Previc, & Ercoline, 2001). The amplitude and phase of a sinusoidal function were randomly generated at the beginning of each trial. The frequency was derived as the inverse of the amplitude; thus, amplitude was generated so that the mean of errors from the initial position of the aircraft reached zero at each half second (if no control input was given), which eliminated a systematic error in any direction due to the simulated perturbations. At the beginning of each trial, the initial values of roll and pitch were also randomly generated.

According to a preliminary study, because the aircraft symbol occupied a smaller portion of the display than did the artificial horizon, it was more difficult to detect changes in pitch and roll with the aircraft-moving than with the horizon-moving display. To lessen differences in detecting deviations from the wings-level, two horizontal lines were added to the displays (see Figure 1). The lines extended from the left and right wings of the aircraft symbol. As a result, the two displays presented the pitch and roll fluctuations in the same way as the relative position of the horizontal lines to the artificial horizon. Consequently, any difference in performance observed for the two display conditions results from their formats, not their configurations or perceptual detectability of relevant information.

For the secondary choice task, visual or auditory stimuli were presented during a trial session. Visual stimuli were rectangles (2.5 × 1.5 cm) colored in green that appeared above the attitude display, adjacent to the top left or right corner of the display (see Figure 1). The distance from the center of a rectangle and the midline of the display was approximately 8.25 cm. Auditory stimuli were tones presented through headphones in the left or right ear. The tone frequency was 880 Hz, and the intensity was approximately 62 dB measured at headphones.

The flight yoke was located in front of the computer screen at a distance of 15 cm. The distance between the left and right grips was 28 cm. Buttons were located on the back of each grip, facing the computer screen, and participants pressed the left and right buttons with their left and right index fingers, respectively. The simulated aircraft was controlled by operating the flight yoke with both hands. The first-order control was used: The experimental program translated the amount of displacement of the yoke from the neutral position into the speed of changes in pitch and roll. Thus, the aircraft moved faster as the amount of displacement of the yoke increased.

Task and procedure

The experiment was conducted individually in an isolated cubicle. Participants sat in front of the computer with an unrestricted viewing distance of approximately 60 cm. They were told that they were about to perform a flight task and went through a tutorial that explained the meanings of relevant display objects (artificial horizon, aircraft symbol), the aircraft’s dynamics (pitch and roll) with pictures depicting the dynamics, the yoke operations needed to control the aircraft and the relationship between the operations and the resulting aircraft’s motions, and the task they were about to perform. However, no mention was made in the tutorial about the display format. Participants held the yoke with both hands and were instructed to place their index fingers on the left and right buttons and their thumbs on the thumb rests on the yoke grips. They wore headphones throughout the experiment.
There were six training sessions and one transfer session for each participant. The primary task in all sessions was to maintain the aircraft attitude at the wings-level (attitude tracking task). In the first training session, participants performed the attitude tracking task alone for 5 min. In the second to fifth training sessions, participants responded to visual or auditory stimuli by pressing a left or right button on the yoke (choice task) while performing the attitude tracking task. In one condition, participants pressed a button spatially compatible with the side of the visual or auditory stimuli (compatible mapping), whereas in another they pressed a button incompatible with the side of stimuli (incompatible mapping). Hence, there were four combinations of stimulus modality and S–R mappings, and all participants performed the four conditions. The order of the conditions was counterbalanced across participants, so that half the participants had two blocks of the visual task with the compatible and incompatible mappings, which were followed by two blocks of the auditory task also with the compatible and incompatible mappings, whereas the other half had two blocks of the auditory task that were followed by two blocks of the visual task. Similarly, half the participants performed the compatible mapping block first for both the visual and auditory tasks, whereas the other half performed the incompatible mapping block first.

The imperative stimuli for the choice task occurred 132 times during each session. The interval between successive stimuli was randomly chosen to be between 1,000 ms and 2,800 ms, with 200-ms intervals. A stimulus was displayed until a response was made. The perturbation function was constructed so that the overall mean fluctuation would be zero every 30 s (zero-mean point). A session ended at the first zero-mean point after response to the last imperative stimulus. Response time (RT) was the interval between stimulus onset and depression of a button. A response was considered an error if the wrong button was pressed. Participants were instructed to respond to stimuli as quickly and as accurately as possible while considering the attitude tracking task as their priority.

The sixth training session was identical to the first trial session in which participants performed the attitude tracking task alone. The experiment ended with the transfer session, in which participants performed the attitude tracking task with the other display format without the secondary choice task. Before the transfer session, participants were told that something would be different from the sixth session, without any further specification of the difference, but the task was identical to that of the sixth session.

RESULTS

Attitude tracking task

Performance on the attitude tracking task was measured as root mean square error from the wings-level for both roll and pitch (Figure 2). Mixed-design analyses of variance (ANOVAs) were conducted for roll and pitch separately, with session (1–7) as a within-participant variable and display format (horizon-moving vs. aircraft-moving) as a between-participant variable. For analyses that involved a factor with more than two levels, degrees of freedom were corrected with the Greenhouse–Geisser procedure.

For roll, the only significant effect was that of session, $F(3.93, 149.38) = 3.06, \text{MSE} = 6.454, \ p < .019$; the main effect of display format and the interaction
of the two variables were not significant, $F_s < 1.0$. As seen in Figure 2a, the main effect of session reflects practice effects; there was a decreasing trend of root mean square errors from Session 1 to Session 6. However, the result of the seventh session departed from this general trend. In fact, there was a significant difference between the sixth and seventh session, two-tailed $t(39) = 2.07, SE = 0.62, p < .045$, indicating that participants performed more poorly in the seventh than in the sixth session. Note that in the seventh session, the display was switched to the other format. As shown in the ANOVA results where the main effect of display was absent, the departure of the seventh session from the general trend is not attributable to the difference between the horizon- and aircraft-moving displays. Instead, it is due to the fact that the display format in the seventh session was different from the one with which participants had practiced the task in the preceding sessions. Thus, the lack of practice effect in the seventh session reflects the fact that participants failed to transfer practiced skills to a novel display format.

An ANOVA for pitch showed that the main effects of display format and session, and their interaction, were not significant (see Figure 2b), $F_s < 1.78$, $p_s ≥ .139$. Previous studies using a similar task that found a significant effect in rollover also reported no reliable effect in pitch (e.g., Cohen et al., 2001). This outcome was probably due to the fact that rotational movements were more salient than vertical displacements on the display.

**Secondary choice task**

Trials for which RT was shorter than 100 ms or longer than 1,500 ms were discarded, and mean RT for correct responses and percentage error were computed for each participant. They were submitted to an ANOVA as a function of stimulus modality (visual vs. auditory; within participants), S–R mapping (compatible vs. incompatible; within participants), and display format (horizon-moving vs. aircraft-moving; between participants).

**Response times**

Mean RTs for the respective conditions are summarized in Figure 3. Main effects of stimulus modality and mapping were significant, $F(1, 38) = 10.30, MSE = 7,790, p < .003$, and $F(1, 38) = 72.23, MSE = 4,167, p < .001$, respectively, but that of display format was not, $F < 1$. However, display format interacted with stimulus modality, $F(1, 38) = 6.98, MSE = 7,790, p < .012$. For the visual modality, responses were faster with the aircraft-moving display ($M = 517$ ms) than the horizon-moving display ($M = 542$ ms), but for the auditory modality, they were faster with the horizon-moving ($M = 550$ ms) than the aircraft-moving display ($M = 598$ ms). The observed pattern differs from the expected effect of stimulus modality. We will discuss a possible reason for these observations in the Discussion section.

The interaction between display format and mapping was not significant, $F(1, 38) < 1.0$, but that between stimulus modality and mapping was, $F(1, 38) = 14.03, MSE = 1,370, p < .001$. The outcome reflects the observation that the S–R compatibility effect was larger for the auditory modality ($M = 109$ ms) than the visual modality ($M = 65$ ms); this is commonly observed in choice reaction tasks (e.g., Roswarski & Proctor, 2003).

There was also a three-way interaction between stimulus modality, mapping, and display format, $F(1, 38) = 4.75, MSE = 1,370, p < .036$. For the horizon-moving format, the S–R compatibility effect was 57 ms for visual stimuli and 126 ms for auditory stimuli. For the aircraft-moving format, the S–R compatibility effect was 73 ms for visual stimuli and 92 ms for auditory stimuli. As can be seen in Figure 3, however, this interaction seems to rely only on one data point, the condition with the horizon-moving display, auditory modality, and compatible mapping. Although the reason for this observation is unclear, the three-way interaction preserved the general observation that RT was shorter with the aircraft-moving than the horizon-moving for visual stimuli, whereas the pattern was reversed for auditory stimuli.

**Percentage errors**

Percentage errors for the respective conditions are summarized in Table 1. Main effects of stimulus modality, $F(1, 38) = 45.66, MSE = 6.10, p < .001$, and mapping, $F(1, 38) = 41.66, MSE = 3.21, p < .001$, and their interaction, $F(1, 38) = 13.59, MSE = 2.27, p < .001$, were significant. The S–R compatibility effects for visual and auditory stimuli were, respectively, 1.0% and 2.7%.

The main effect of display approached significance, $F(1, 38) = 3.59, MSE = 7.94, p < .066$, as did its interaction with stimulus modality, $F(1, 38) = 3.10, MSE = 7.84, p < .086$, and mapping, $F(1, 38) = 3.95, MSE = 7.34, p < .066$. However, the interaction of display format and stimulus modality was not significant, $F(1, 38) < 1.0$. The percentage error was larger for the visual modality ($M = 6.5$%) than for the auditory modality ($M = 3.3$%).
interaction with mapping, $F(1, 38) = 3.89, MSE = 3.21$, $p < .056$. The S–R compatibility effect was 2.4% for the horizon-moving display and 1.3% for the aircraft-moving display. The interaction between stimulus modality and display format and the three-way interaction of these factors were not significant, $F_s < 1.0$.

**DISCUSSION**

Despite the long history of investigating the optimal format of aircraft attitude indicators (e.g., Conklin & Lindquist, 1958), the issue remains of interest among contemporary researchers (e.g., Cohen et al., 2001; Patterson, Cacioppo, Gallimore, Hinman, & Nalepka, 1997; Previc & Ercoline, 1999). The main purpose of the present study was to examine influences of the two display formats, horizon- and aircraft-moving, on tracking performance. The two formats differ with respect to which display object moves in representing the attitude of an aircraft. Thus, if there is any effect of display format, it can be attributed to the motion involved in the display. Researchers have argued that the motion incompatibility of the horizon-moving format would result in poorer tracking performance.

**TABLE 1.** Percentage error (mean standard error) in the secondary choice task as a function of stimulus modality and stimulus–response mapping for the horizon-moving and aircraft-moving groups

<table>
<thead>
<tr>
<th>Stimulus modality</th>
<th>Stimulus–response mapping</th>
<th>Horizon moving</th>
<th>Aircraft moving</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visual</td>
<td>Compatible</td>
<td>1.65 (0.29)</td>
<td>1.43 (0.23)</td>
</tr>
<tr>
<td></td>
<td>Incompatible</td>
<td>3.00 (0.56)</td>
<td>1.97 (0.25)</td>
</tr>
<tr>
<td>Auditory</td>
<td>Compatible</td>
<td>3.47 (0.48)</td>
<td>3.12 (0.56)</td>
</tr>
<tr>
<td></td>
<td>Incompatible</td>
<td>6.89 (0.73)</td>
<td>5.12 (0.61)</td>
</tr>
</tbody>
</table>

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(e.g., Cohen et al., 2001), but the present results are not consistent with this suggestion. Participants’ performance improved in the course of six training sessions with both displays, and little difference was observed between the two display conditions. In other words, participants could perform the attitude tracking task with the two display formats at similar levels.

Moreover, the tracking data showed that although performance improved over six training sessions, performance in the seventh session returned to a nearly initial level, suggesting that trained tracking skills were not transferred between different displays. Specificity of training results from the fact that the underlying processes in the task differ between the two display formats (Healy et al., 2006). This finding is interesting because the results of the six training sessions suggest that performance was equivalent between the two display conditions, and the lack of transfer of learning suggests that these two displays are processed differently. A difference can arise because the translation process of display information to participants’ mental model of the aircraft’s movement differs between the two formats. Thus, the observation implies that the equivalent performance level between the two display formats is not due to participants’ ignoring the display motion; instead, the tracking task is performed based on similar mental models, and the process of constructing these mental models based on the display information differs between the two formats.

In our recent study (Yamaguchi & Proctor, 2009), where participants performed only a choice reaction task with the horizon- or aircraft-moving display, we observed that the influences of display motion appeared when participants responded to auditory stimuli but not when they responded to visual stimuli. Thus, for the secondary choice task, one would have expected that when stimuli are visual, responses are as fast with the horizon-moving display as with the aircraft-moving display, but when stimuli are auditory, responses are slower with the horizon-moving display than with the aircraft-moving display. This expectation is because the incompatible motion on the horizon-moving display would interfere with performance in the latter stimulus condition but not in the former condition. However, the present results did not follow this pattern.

For the secondary choice task, responses were faster for the aircraft-moving display than for the horizon-moving display when the imperative stimuli were visual. In contrast, the pattern was reversed when the imperative stimuli were auditory. Note that the results were true regardless of the S–R mapping used, suggesting that the results are generally applicable to both mappings. The pattern of the results suggests that auditory stimuli for the secondary task were handled better when the primary task used the horizon-moving display, whereas visual stimuli were processed more efficiently when the primary task used the aircraft-moving display. One way to interpret these results is to consider that visual and auditory information is processed in separate processors or analyzers (e.g., Treisman, 1969). Because the primary task relied heavily on visual information, participants had to divide their attention between visual and auditory modalities to perform the secondary task with auditory stimuli. That is, the current results suggest that attention is divided between the two modalities better with the horizon-moving than with the aircraft-moving displays.

A speculative explanation of this result is as follows. Previc (1998) suggested that different modes of spatial representations are evoked in interactions with different aspects of visual environments. According to the theory, a holistic, ambient mode is used to represent a wider range of spatial environment that extends 360° around the observer, whereas an analytic, focal mode is used to represent a narrow range of spatial environment surrounding the focal area. It may be that the horizon-moving display evokes the ambient mode of representation, whereas the aircraft-moving display evokes the focal mode. Thus, auditory information is processed more efficiently with the horizon-moving display because the spatial representation is holistic. In contrast, visual information is processed more efficiently with the aircraft-moving display because the analytic mode allows a focus on visual modality. This explanation is consistent with the fact that the horizon-moving format mimics the motion of the actual horizon, which is represented in the ambient mode (Previc, 1998). However, more direct evidence of the associations between the ambient mode and auditory modality and between the focal mode and visual modality must be provided in future investigations to support this hypothesis.
Is the horizon-moving display R–E compatible or R–E incompatible?

It has been argued that the horizon-moving format involves incompatibility between display motion and control action, which interferes with task performance (Cohen et al., 2001; Patterson et al., 1997; Previc & Ercoline, 1999). However, our previous study (Yamaguchi & Proctor, 2006) did not show any difference in choice reaction performance between the two formats, when participants performed only a choice reaction task with visual stimuli. This observation contradicts the assumed inferiority of the horizon-moving display. In that particular task, the equivalence between the two formats could be due to the fact that participants ignored the display motion while focusing on their hand movement.

However, this interpretation is inconsistent with the results of Kunde, Müßeler, and Heuer’s (2007) study. Those researchers showed that when participants pointed to a stimulus location by moving the terminus of a computer-generated lever on the screen, responses were faster if the movement direction of the lever terminus was compatible with the stimulus location, even when the direction of the operating hand was incompatible with the stimulus location. Thus, one would expect that participants would ignore the hand movement rather than the display motion, contradicting the aforementioned interpretation of Yamaguchi and Proctor’s (2006) study. Because several experimental factors differ between the two studies, one cannot point out an immediate cause of the discrepancy. Nevertheless, a reinterpretation of our previous results based on the present results would suggest that the two studies are perfectly consistent.

In the present tracking task, equivalent performance for the two display formats was also suggested. In contrast to the choice reaction task used in Yamaguchi and Proctor’s (2006) study, however, it is difficult to imagine that participants in the present experiment were also able to ignore the display information because the tracking task entailed monitoring the attitude of an aircraft that was acquired only through monitoring of the display information. In fact, the lack of transfer of learning in the seventh session where the display format was switched to the other one suggests that the way information is displayed on the screen significantly influenced performance of the tracking task. Thus, it is suggested that although display information was closely monitored, the task was performed based on mental models of the aircraft that were equivalent between the two formats. The equivalence of the mental models is possible because participants encoded and interpreted the display information as the motion of the simulated aircraft they operated.

We noted earlier that the motion compatibility effect can occur based on illusory motion induced in a stationary stimulus when its surroundings move (Kerzel et al., 2001). Induced motion has been shown to result from horizontal and vertical displacements (Duncker, 1929/1938), depth streams, and rotational movements of a background (Reinhardt-Rutland, 1988), and the extent to which motion is induced in a stationary object has been shown to depend on the size and shape of a background frame (e.g., Michael & Sherrick, 1986). These findings suggest that a similar effect may play a role in the pilot’s reading motion information of the horizon-moving display. Because the horizon-moving display simulates the attitude of an aircraft by moving the background (i.e., the artificial horizon), the pilot may perceive the motion of the actual aircraft rather than that of a moving background visible on the display. If that is the case, the compatibility effect in our previous study may be interpreted in terms of compatibility between stimulus and the mental model of the aircraft, not between stimulus and the physical movement of the artificial horizon on the display.

Given that it is the mental model of aircraft, rather than the actual display motion, that influences performance, the results of Kunde et al. (2007) and Yamaguchi and Proctor (2006) may, in fact, be in agreement. When participants monitor the attitude indicator, the movement of the mental model (aircraft) is consistent with the hand movement. Hence, participants in our earlier study may have focused only on their mental model to produce the observed results, while ignoring the display motion and hands altogether. This interpretation implies, then, that the horizon-moving display is R–E compatible because $E$ in this case refers to the actual movement of an aircraft, not that of the display object. Therefore, the assumed inferiority of the horizon-moving display to the aircraft-moving one is contradicted.
Display compatibility
As mentioned earlier, our follow-up experiment (Yamaguchi & Proctor, 2009) also examined choice reaction performance of novice pilots with the aircraft- and horizon-moving displays. That study dissociated the compatibility relationships between stimulus location and mental model (aircraft), display objects, and hands by manipulating display format and control relations (i.e., the aircraft moved in the direction same as or opposite to the hand direction) and found that the influence of mental model was largest, that of hand intermediate, and that of display objects smallest. The results were thus consistent with the aforementioned interpretation of Yamaguchi and Proctor’s (2006) study. Moreover, the influence of display objects was present only when participants responded to auditory stimuli but was absent when participants responded to visual stimuli, which is also consistent with the results of Yamaguchi and Proctor (2006) and those of the present tracking task. Thus, the R–E compatibility of the horizon-moving display depends on the task context.

Previous studies used research conditions that approximated the real flight environment, but the results of these studies are not entirely consistent. Some studies demonstrated advantages of the horizon-moving format (e.g., Beringer, Williges, & Roscoe, 1975; Ince, Williges, & Roscoe, 1975), whereas others suggested advantages of the aircraft-moving format (e.g., Cohen et al., 2001). These mixed results may be due to the fact that compatibility of display format depends on task contexts. Most often, researchers have used compensatory or pursuit tracking and recovery from abnormal attitude to assess the design of attitude indicators. The nature of a recovery-from-abnormal-attitude task may be somewhat different from the tracking task. The former task is typically administered by blanking the screen or by having participants close their eyes for a period of time during the maneuver task so that the attitude of the aircraft is altered; then, the trial starts with the display showing an abnormal attitude. That is, in contrast to the tracking task in which participants continuously read the display information, interpretation of the display information in the recovery-from-abnormal-attitude task is abrupt and discrete. Furthermore, whereas the attitude of an aircraft in the tracking task can be considered to be a component of response (action effect), in the recover-from-abnormal-attitude task it serves as a stimulus. The influence of physical motion on the display may appear in such a task where participants pay less attention to the display information. The issue is of interest in future investigations.

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