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Effects of Electronic Map Displays and Individual Differences in Ability on Navigation Performance

William Rodes and **Leo Gugerty**, Clemson University, Clemson, South Carolina

Objective: The aim of this study was to determine how strongly the performance of navigation tasks is affected by changing electronic map interfaces and by individual differences in spatial ability.

Background: Electronic map interfaces have two common configurations, north up and track up. Research suggests that north-up maps benefit some navigational tasks and track-up maps benefit others. However, little research has investigated how map configuration affects the important navigation task of judging cardinal direction or how individual differences in spatial ability interact with map configuration in affecting navigation performance.

Method: In an aerial reconnaissance task, 16 participants completed route-following, cardinal direction, and map reconstruction tasks. Participants also completed three spatial ability tests.

Results: The track-up map led to better performance on the cardinal direction and route-following tasks. The north-up map led to better performance on the map reconstruction task. Effects of map configuration showed small to medium effect sizes. Spatial ability correlated positively with performance of each navigation task, showing medium to large effect sizes. For some tasks, a helpful map interface compensated for low ability. For other tasks, ability facilitated the performance of the helpful interface; optimal performance required a helpful interface and high ability.

Conclusion: Achieving high performance at particular navigation subtasks requires two things: using the map configuration that optimizes subtask performance and having high spatial ability.

Application: Some aspects of navigation performance can be improved primarily by using the optimal map configuration; other aspects require using the optimal configuration and having better spatial ability.

Keywords: track-up maps, north-up maps, spatial ability, navigation, cardinal directions

Address correspondence to Leo Gugerty, Clemson University, 418 Brackett Hall, Clemson, SC 29634-1355; e-mail: gugerty@clemson.edu.

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INTRODUCTION

Electronic map displays can be displayed in either a track-up configuration, with the vehicle icon always pointing toward the top of a rotating map, or a north-up configuration, with a translating and rotating vehicle icon on a fixed map. Shepard and Hurwitz (1984) suggested that a key cognitive task in using maps is coordinating the cognitive reference frames applied to the map and the 3-D view. In the egocentric reference frame, headings and distances in the world are expressed with respect to the observer. In the world-centered reference frame, headings and distances are expressed with an unchanging reference frame outside of the viewer. Aretz (1991) argued that a north-up map has the benefit of stability and congruence with a world-centered reference frame but the cost of the mental rotation needed to align headings on the map with the egocentric forward view. In contrast, a track-up map has the benefit of congruence with the egocentric forward view but the cost of an unstable, changing map from which one must build a cognitive map.

Aretz (1991) and Wickens, Liang, Prevett, and Olmos (1996) found evidence that relative bearing judgments (as in following a route by deciding the direction of the next turn) were performed better with a track-up map, whereas learning about a locale by navigating through it (as assessed by drawing a map from memory) was performed better with a north-up map. These findings support the theoretical claims about the relative benefits of track-up versus north-up maps and suggest that the optimal map configuration depends on what type of navigational task is performed.

In the current study, we examined the effect of map configuration on three navigation tasks. Participants performed route-following, map reconstruction, and cardinal direction judgment

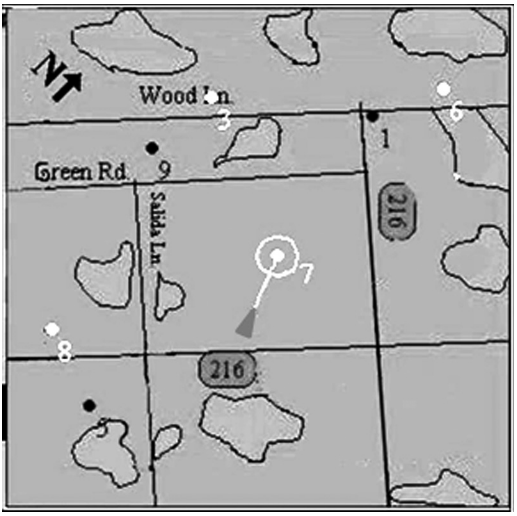

Figure 1. The unmanned aerial vehicle map view. The actual display was in color.

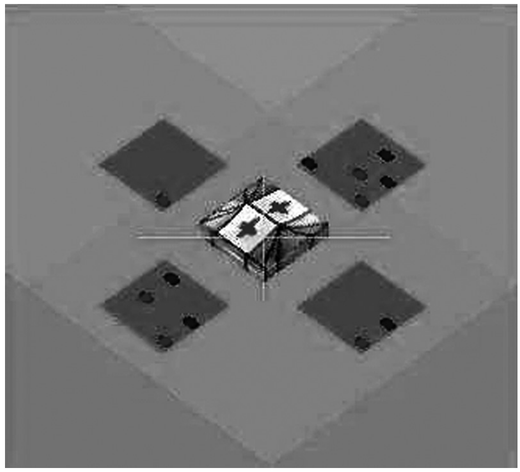

Figure 2. The unmanned aerial vehicle display from the aircraft's camera showing a ground target used in a cardinal direction problem. The actual display was in color.

tasks using track-up and north-up maps while completing aerial reconnaissance missions in an unmanned aerial vehicle (UAV) simulator. This simulator represented a Predator UAV, in which teams of three operators—pilot, sensor operator, and mission planner—perform reconnaissance functions (Gugerty, 2004). In this study, the simulator was used in a single-operator mode. With the help of automation, the participant performed piloting and camera control functions.

Our route-following and map reconstruction tasks were similar to the tasks in Aretz (1991) and Wickens et al. (1996). In our cardinal direction task, participants used a 2-D plan-view map that contained explicit cardinal direction information, for example, an arrow pointing to north (see Figure 1), and the 3-D view of the ground (see Figure 2) to determine the bearings (cardinal directions) between objects visible only in the 3-D view. For example, participants might have to find the parking lot that is west of a building. A task analysis demonstrated that Predator UAV operators regularly perform the three navigation tasks studied in our experiment (Gugerty, 2004).

The effect of track-up versus north-up maps on cardinal direction judgments about objects in the 3-D view has received little study. Thus, providing a better understanding of how map configuration affects cardinal direction judgments is one novel contribution of this research. Prior research exclusively involving north-up maps has demonstrated that cardinal direction judgments are quite difficult for many operators, and this difficulty is caused by the fact that the forward aircraft heading on the map is usually misaligned with the top of the map and with the forward heading in the 3-D view, which is always toward the top (Gugerty & Brooks, 2004). This claim is supported by consistent misalignment effects such that errors and reaction time (RT) increase as the aircraft heading on the map became increasingly misaligned with the top of the map (Gugerty & Rodes, 2007; Gugerty & Brooks, 2001, 2004; Gunzelmann, Anderson, & Douglas, 2004).

These performance degradations attributed to misalignment suggest that the key difficulty in making cardinal direction judgments using a 2-D map and a 3-D ground view is coordinating direction information across the two displays. Our cardinal direction task involved a common situation in aviation in which world-centered directional information is explicitly displayed only in the map, but these world-centered directions must be coordinated with the 3-D view, where information is probably represented egocentrically. Thus, this task is not wholly world centered or egocentric but instead involves coordinating information with the use of both world-centered and egocentric representations. According to cognitive modeling, a key mechanism for performing this coordination involves using mental rotation to align headings in the map and the 3-D view (Gugerty & Rodes, 2007; Gunzelmann et al., 2004). However, mental rotation is necessary only with a north-up map. In a track-up map, the forward heading is always aligned with top on both the map and the 3-D display, so no mental rotation is needed. Thus, track-up maps should lead to better cardinal direction judgments compared with north-up maps.

One goal of the current study is to better understand how to select the electronic map configuration that best facilitates a particular navigational task. However, correctly matching map configuration to task demands may not be sufficient to optimize performance at difficult navigational tasks. Egan (1988) has pointed out that effect sizes attributable to individual differences in cognitive abilities can sometimes be considerably larger than effects attributable to interface manipulations. Therefore, we also investigated how individual differences in relevant cognitive abilities were associated with navigation performance. Doing so allowed us to compare an interface manipulation with individual differences in terms of their strength of association with navigation performance.

We measured three aspects of spatial ability that seemed related to the navigational tasks we assessed: mental rotation, spatial visualization, and spatial memory. We expected that each of these measures would be positively correlated with performance on each of the navigation subtasks. In particular, the cardinal direction and route-following (direction-of-turn) tasks are known to require mental rotation ability (Gugerty & Rodes, 2007; Shepard & Hurwitz, 1984), and the map reconstruction task, as a memory task, was expected to be associated with spatial memory ability.

However, more complex relationships between ability and map configuration are possible. For example, if the track-up map removes the need for mental rotation by physically rotating, then it could compensate for poor mental rotation ability. If so, then this interface would lead to overall better performance and reduced ability differences, relative to the north-up map. The essence of compensation is that one interface is more beneficial than another, and low-ability performers are benefitted most by the better interface. Compensation is one type of aptitude-treatment interaction (ATI; Cronbach & Snow, 1977). Although human factors research on ATIs is scarce, Goska and Ackerman (1996) found an ATI such that segmented part-task training compensated for poor reasoning ability in an air traffic control task. Since the mechanism of compensation in the current study involves physical map rotation in place of mental rotation, we expected compensation only for mental rotation ability.

We also considered the possibility of another type of ATI, in which high-ability performers are benefitted most by the better interface. In this type of ATI, which we called facilitation, one interface is more beneficial than another, and high-ability performers are benefitted most by the better interface. Shute, Gawlick-Grendell, Young, and Burnham (1996) found an ATI such that an intelligent computer-based statistics tutor facilitated statistics learning more than other training methods but only for high-aptitude students. We expected facilitation in the current study primarily for difficult tasks, because for these tasks, it might take both a beneficial interface and high ability to bring about high performance. Since the cardinal direction task is known to be more difficult than the direction-of-turn task (Gugerty & Brooks, 2001), we expected facilitation on the former and not the latter task.

Hypotheses

Direction-of-turn task. We hypothesized that the direction-of-turn (route-following) task would show a track-up advantage in accuracy and RT because with the track-up configuration, the plane's heading is always aligned with the top of the map. Therefore, costly mental rotation is needed only with the north-up map.

Map reconstruction task. We hypothesized that map reconstruction would be more accurate with a north-up map, because the stationary consistent location of each target in this configuration should allow a more stable and accurate mental model of the spatial configuration to be learned than in the track-up configuration, where targets are in constant motion.

Cardinal direction task. We hypothesized that the track-up map would lead to faster and more accurate cardinal direction judgments than would the north-up map, on the basis of our earlier arguments. In addition to the overall poorer performance with a north-up map, we hypothesized that with a north-up map, we would find the normal misalignment effects such that errors and RT increase as the plane heading is increasingly misaligned with the top of the map. In contrast, with a track-up map, errors and RT should remain constant with increased misalignment.

Spatial ability measures. We hypothesized main effects such that mental rotation, spatial visualization, and spatial memory ability would be positively related to performance at each of the navigational tasks. In addition, we hypothesized an ATI demonstrating compensation such that the track-up map would lead to overall better performance and a *decreased* influence of mental rotation ability relative to the north-up map, whereby low-ability people would benefit most. Finally, for the cardinal direction task, we hypothesized an ATI demonstrating facilitation such that the track-up map would lead to overall better performance and an *increased* influence of spatial ability relative to the north-up map, whereby high-ability people would benefit most.

METHOD

Participants

Participants were 4 males and 12 females with normal or corrected-to-normal vision. Mean age was 23.0 years (range = 20 to 32). No participants were licensed pilots. The mean number correct was 98.9 (SD = 21.0) out of 160 items for the mental rotation test, 10.2 (SD = 4.0) out of 20 items for spatial visualization, and 17.9 (SD = 4.4) for building memory. These statistics for the rotation and visualization tests were similar to those from a similarly aged sample in Miyake, Friedman, Shah, Rettinger, and Hegarty (2001). The mean score on the Waterloo Handedness Questionnaire was 1.06 (SD = 1.03; Bryden, Pryde, & Roy, 2000). This mean corresponds to performing tasks "usually with the right hand."

Design

Each participant completed four missions in the UAV simulator: two with the north-up map (blocked) and two with the track-up map (blocked).

Materials

Participants performed piloting and camera control functions in a UAV simulator that ran on a personal computer with a joystick and keyboard. The monitor displayed the view from the aircraft's camera on the left side of the screen (see Figure 2). On the right side of the screen, the electronic map displayed the locations of the targets, an icon showing the location and heading of the UAV, the direction in which the camera was pointing, and the ground footprint of the camera (see Figure 1). To reduce piloting difficulty, forward and lateral joystick movements controlled forward and yaw aircraft movements, respectively, at a fixed altitude. Participants used function keys to lock the camera onto a particular ground target, after which the camera automatically stayed on that target.

The north-up map remained stationary while the plane icon, indicated by the triangle, rotated and translated about the map as the plane's location and heading changed. Cardinal direction, indicated by an icon with a canonically oriented *N* next to an upward-pointing arrow, was always located in the upper left-hand corner of the map. The track-up map rotated and translated while the plane icon remained pointing toward the top of the screen and fixed in the center of the map frame. The cardinal direction icon was located in the upper left-hand corner of the map. However, the *N* and the arrow rotated so that the arrow always pointed north (see Figure 1).

Each mission in the UAV simulator required the participants to follow a predefined path to eight targets and to make a cardinal direction and direction-of-turn judgment at each target. Each target showed a building surrounded by four parking lots, and each lot contained a different number of cars (see Figure 2). To make a cardinal direction judgment, participants heard a voice message stating the target objective (e.g., "How many cars are in the parking lot to the north of the building?") as they approached the target, then responded using the keyboard and received audio feedback. After the cardinal direction task for one target was completed, the direction-of-turn task began for the next target. A voice message asked the participants in what direction they would turn to reach the next target. Then the next target appeared on the map. Participants responded using keys labeled *left* or *right* and received audio feedback. Each mission took about 15 min.

Each of the mission routes was laid out so that participants approached targets from eight directions (north, northeast, etc.). To ensure that the participant's actual heading when approaching each target was similar to the planned route heading, fences surrounded the building and parking lots in the 3-D view to force the participant to fly close to the target before answering each cardinal direction question. This meant that even though the camera rotated to remain locked on a target, camera heading usually aligned with aircraft heading as participants made cardinal direction judgments (as shown in Figure 1). Routes were constructed so that for the direction-of-turn task, the turn required to reach the next target was always approximately 90° to the right or left. There were four left and four right turns for each mission in a pseudorandom order.

After each mission, participants completed the NASA Task Load Index (Hart & Staveland, 1988) workload measure and then the map reconstruction task by recalling from memory and drawing a map of the targets for that mission on paper 22 cm^2. Participants drew as many target locations as they could recall and labeled each recalled target with its numeric label from the map. Drawing a map took less than 3 min.

The spatial tests used were the Card Rotation, Paper Folding, and Building Memory tests from the Factor-Referenced Cognitive Tests (Ekstrom, French, & Harman, 1976). Carroll (1993) considered the Card Rotation, Paper Folding, and Building Memory tests to be measures of spatial relations (including mental rotation), spatial visualization, and spatial memory, respectively. These three tests were administered on paper, and each took about 5 min to complete. Participants also completed the Waterloo Handedness Questionnaire and the Preferential Reaching Task (Bryden et al., 2000).

Procedure

In the first session, participants first received 40 min of computer-based training and practice using the UAV simulator, focusing on one of the map configurations. During training for the cardinal direction task, participants were taught the same strategy for both map configurations: First, determine the plane's heading on the map; then transfer that direction to the forward view; then determine the direction to the upper two lots; and finally, determine the direction to the two lower lots. Following training, participants completed two UAV missions, each followed by reconstructing the map. In the second session, participants received computer-based training similar to the first session but for the other map configuration. Then they completed two UAV missions with map reconstruction. Finally, participants completed the three spatial tests and the two handedness tests. Each of the sessions took 1.5 hr. The order of map configurations and individual maps were counterbalanced.

RESULTS

The workload for the north-up map (M = 49.2, SE = 4.6) was significantly greater than was the track-up workload (M = 28.2, SE = 4.0), $t(15) = 4.55$, $p < .01$. Because of space limitations, the handedness data are not presented. Analyses focused on the navigation tasks.

For both the cardinal direction task and the direction-of-turn task, performance was measured by the percentage of correct responses and the mean RT for correct responses. Outlier RTs (more than 3 standard deviations above the mean) were excluded, resulting in 1.0% of RTs being excluded for both the cardinal direction and direction-of-turn task. A natural logarithm transformation was applied to the nonnormal RT data; untransformed means are presented in the text.

Performance on the map reconstruction task was measured by the average difference in bearings between targets on each actual map and the participants' reconstructed map. First, each target on a participant map was hand-matched to the target that corresponded closest to it on the actual map. Then the bearing was calculated (from 0° to 360°) for all 56 target-to-target bearings for the eight targets on the participant's map. The same 56 bearings were calculated for the actual map. For each of the 56 bearings, the unsigned difference between the bearing on the participant's and the actual map was calculated. The mean of the 56 difference scores represented the average angular bearing deviation for the participant's map. This deviation score could range from 0°, which represented perfect configuration recall, to a maximum of 180°.

Hierarchical linear modeling (HLM; Snijders & Bosker, 1999) was used to test hypotheses about the effects of map configuration and spatial ability. For the binary accuracy variable, HLM was conducted with generalized estimating equations (GEE) models (Ballinger, 2004). GEE applies a logit transformation to the accuracy variable, which reduced the negative skew resulting from high accuracy in the cardinal direction and direction-of-turn tasks. For each navigation performance variable, HLMs were tested with map configuration, a spatial predictor, and an interaction term as predictors. The interaction term was used to test for ATIs, as in Goska and Ackerman (1996). In these models, an alpha of .05 consistent with one-tailed tests was used when testing directional hypotheses. For each navigation task, performance was not affected by whether the task was completed in the first block of two missions or the second block, so the effect of block was not analyzed further.

We calculated effect size (R^2) for the main effect of map configuration by comparing the residuals of a full model with map configuration as the predictor with a reduced, intercept-only model. We calculated incremental effect size (R^2) for each spatial ability predictor, after controlling for map configuration, for main effects using the reduction in intercept variance between a model with ability, map configuration, and their interaction as predictors and a map configuration–only model. Incremental R^2 for interaction effects used the reduction in slope variance between these two models. Direction-of-turn accuracy could not be transformed to normality, so effect sizes were not calculated. We discuss effect size qualitatively using Cohen's (1992) levels for multiple correlation coefficients, in which R^2 of 2%, 15%, and 35% corresponds to small, medium, and large effects, respectively.

Cardinal Direction Task

Effects of map configuration and ability on accuracy. The mean percentage correct for the track-up map, 97.6 (SE = 1.3), was greater than that for the north-up map, 86.3 (SE = 3.4), supporting the hypothesis of a track-up advantage. This difference was statistically significant, $\chi^2(1) = 11.02$, $p < .01$, and showed a large effect size, R^2 = 34 (see Table 1). As hypothesized, accuracy was positively and significantly associated with mental rotation ability, $\chi^2(1) = 4.10$, $p < .05$, R^2 = 25, and spatial memory, $\chi^2(1) = 6.06$, $p < .05$, R^2 = 40. However, accuracy was not significantly associated with spatial visualization, $\chi^2(1) = 0.01$.

To test for ATIs, for each spatial ability, we ran a separate HLM model with accuracy on each trial as the dependent variable and map configuration, spatial ability, and their interaction as predictor variables. The interaction term for the mental rotation model was not significant. For the spatial visualization model, the interaction was significant, $\chi^2(1) = 5.60$, $p < .01$, $R^2 < 1$. We show this interaction in Figure 3 by plotting the predicted percentage correct values on the basis of simple effects regressions of visualization on accuracy for the track-up and north-up maps. (To estimate variability around the predicted values, we could not plot the binary [correct or incorrect] raw data; instead, we plotted the percentage correct across the eight direction judgments in each of the two missions participants flew for each map type.) This interaction provides evidence for facilitation because the better-performing track-up interface accentuated individual differences in performance and benefitted high-ability more than low-ability participants. Evidence for facilitation is that the positive slope of the predicted regression line is steeper for the track-up (r = .40,

TABLE 1: Effect Size (via *r* and R^2) for the Relationship of Map Configuration and Spatial Ability With Performance of Navigation Tasks

		Map Type		Rotation		Visualization		Memory	
Task	Performance Variable	*r*	R^2	*r*	R^2	*r*	R^2	*r*	R^2
CDIR	% correct	.30*	34	.49*	25	.18		.62*	40
	RT	.59*	12	–.51*	18	–.19		–.24	
LR	% correct	.09*		.37*		.05		.34*	
	RT	.73*	15	–.70*	42	–.32		–.54*	24
Map	Draw error	.64*	9	–.24		–.47*	18	–.16	

Note. R^2 values shown only for significant effects. CDIR = cardinal direction; LR = left-right (route following); RT = reaction time.
*p < .05 for *r* with one-tailed test given the directional hypothesis.

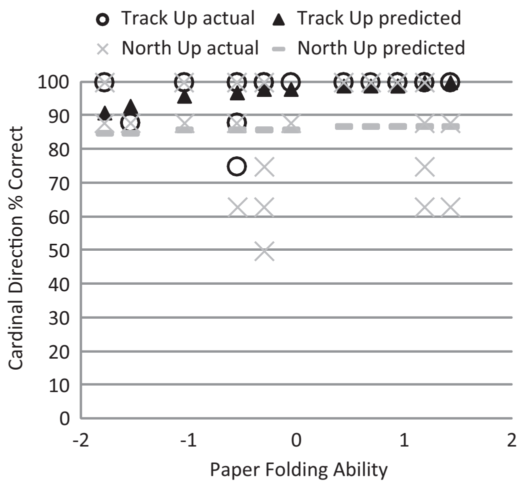

Figure 3. The interaction between spatial visualization ability and map configuration in affecting cardinal direction accuracy is shown by the predicted percentage correct values for each map configuration. Estimated actual percentage correct data points are also shown for each map type.

p < .05) than for the north-up map (r = .05, *ns*), and only the track-up slope is significantly greater than 0. However, although statistically significant, this ATI had a very small effect size, possibly because overall accuracy at the cardinal direction task was high.

There was also a significant ATI involving spatial memory, as spatial memory interacted with map configuration in predicting accuracy, $\chi^2(1) = 5.60$, $p < .01$. However, although the interaction was significant, spatial memory had a positive correlation with accuracy that was similar in size for the track-up (r = .55, p < .05) and north-up maps (r = .51, p < .05). Also, this interaction had a small effect size (R^2 < 2%). Thus, this ATI does not clearly support compensation or facilitation.

Effects of map configuration and ability on RT. The RT data supported the hypothesized track-up advantage for cardinal direction RT. Mean RT was 7.04 s (*SE* = 0.76) for track-up and 9.83 s (*SE* = 0.76) for north-up maps. This difference was significant, $t(448) = 7.84$, p < .01, and showed a small effect size, R^2 = 12 (see Table 1). As hypothesized, RT was positively and significantly associated with mental rotation ability, $t(14) = 2.03$, $p < .05$, R^2 = 18. However, RT was not significantly associated with spatial visualization or memory.

An ATI involving mental rotation ability supported the compensation hypothesis, as the interaction between rotation ability and map configuration was significant, $t(448) = 4.58$, p < .01, R^2 = 18, and the correlation between rotation ability and accuracy was weaker for track-up (r = –.29, *ns*) than for north-up maps (r = –.57, p < .05). As shown in Figure 4, the track-up map led to overall better performance and improved the performance of lower ability more than it did that of higher ability participants. The main effect and interaction effect of rotation ability account for a combined 36% of variance in cardinal direction RT, a large effect size. Map configuration did not interact with either

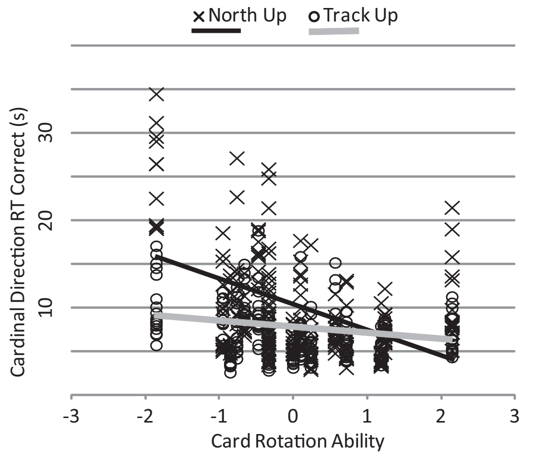

Figure 4. Interaction between mental rotation ability and map configuration in affecting cardinal direction reaction time (RT). The lines show the predicted RT values for each map configuration. The actual data points are also shown.

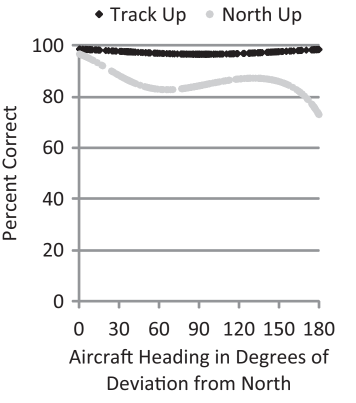

Figure 5. Effect of angular deviation of unmanned aerial vehicle heading from the top of the map on cardinal direction task accuracy for track-up and north-up maps. The graph shows the predicted percentage correct values based on the best-fitting regression analysis.

spatial visualization ability or spatial memory in predicting RT.

Effects of aircraft heading on accuracy and RT. We also hypothesized that increasing misalignment of the aircraft heading from the top of the map would degrade cardinal direction performance but only for the north-up map. The UAV simulator recorded the aircraft heading whenever participants made cardinal direction judgments. Camera direction could not be recorded, but the scenarios were designed so that participants usually made cardinal direction judgments with the camera direction closely aligned with aircraft heading. To test the effects of heading on accuracy, we calculated the angular deviation (in degrees) between the top of the map and the heading of the aircraft at the time each cardinal direction question was answered.

Separate regression analyses for north-up and track-up maps tested the linear effect of this heading deviation variable (as well as quadratic and cubic deviation variables) on percentage correct judgments. Figure 5 shows the best-fitting regression analyses by presenting the predicted percentage correct value at each heading. For the track-up map, there was a significant effect only of the quadratic heading variable, $\chi^2(1) = 10.84$, $p < .01$, but the graph shows that accuracy remained high and relatively flat across all headings, as predicted. For the north-up map, the predicted decrease in accuracy with increasing heading misalignment was found. As Figure 5 shows, the strongest decrease in accuracy occurred for headings near north and south. There were significant effects on accuracy both for the linear, $\chi^2(1) = 4.25$, $p < .05$, and the cubic, $\chi^2(1) = 4.00$, $p < .05$, heading variables. These findings support the hypothesis and suggest that track-up maps remove difficulties in cardinal direction judgments caused by misalignment of the aircraft heading in the map and the 3-D view.

We also hypothesized that increasing heading misalignment would lead to increased RT but only for the north-up map. With the north-up map, RT increased as aircraft heading went from north (0°) to east or west (90°) and then decreased slightly for headings near south, as shown in Figure 6. This description fits with a positive linear effect of heading on RT, $t(199) = 1.94$, $p < .05$, and a significant quadratic effect, $t(199) = 2.15$, $p < .05$. The increase in RT between headings of 0° and 90° fits the hypothesis and may be attributable to the time needed for mental rotation to compensate for increasing misalignment. The fact that RT decreased slightly as heading went from 120° to 180° was probably attributable to a reversal strategy in which participants determined the cardinal

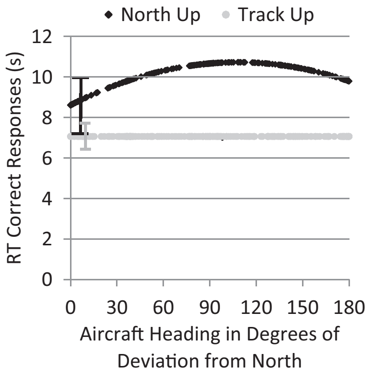

Figure 6. Effect of angular deviation of unmanned aerial vehicle heading from the top of the map on cardinal direction task reaction time (RT) to correct responses for track-up and north-up maps. The graph shows the predicted RT values based on the best-fitting regression analysis. Error bars are for standard error of the intercept.

direction they would give if the aircraft were headed near north and then mentally reversed this direction (Gugerty & Brooks, 2004).

For the track-up map, there was no linear change in RT with heading, $t(233) = 0.15$, $p > .80$, which also fit the hypothesis. There was also no quadratic effect. Overall, these findings are consistent with the claim that track-up maps remove most of the detrimental effects of heading misalignment on RT.

Direction-of-Turn Task

Accuracy. Although accuracy on the direction-of-turn task was high, there was a small accuracy advantage for the track-up map, 99.6% correct (*SE* = 0.4) compared with the north-up map, 96.1% (*SE* = 1.6), as hypothesized. This difference was significant, $\chi^2(1) = 5.20$, $p < .05$, and showed a small correlation of .09 (see Table 1). Mental rotation and spatial memory ability showed significant positive associations with accuracy. For mental rotation, $r = .37$ and $\chi^2(1) = 3.41$, $p < .05$. For spatial memory, $r = .34$ and $\chi^2(1) = 3.81$, $p < .05$.

RT. The RT for the track-up map, 2.00 s (*SE* = 0.22), was faster than that for the north-up map, 2.84 s (*SE* = 0.22), which fit the hypothesized track-up advantage. This difference was statistically significant, $t(470) = 9.33$, $p < .01$, and showed a medium effect size, $R^2 = 15$. Mental rotation ability and spatial memory showed positive and significant associations with RT, with medium and large effect sizes. For mental rotation, $R^2 = 42$ and $t(17) = 3.58$, $p < .01$. For spatial memory, $R^2 = 24$ and $t(16) = 2.42$, $p < .05$. The compensation and facilitation hypotheses were not supported, as no interactions of spatial ability and map configuration were significant.

Map Reconstruction Task

The mean angular deviation for the north-up map, 25.4° (*SE* = 3.1), was less than that for the track-up map, 31.5° (*SE* = 3.1), supporting the hypothesis. This difference was statistically significant, $t(46) = 2.45$, $p < .01$, and showed a small effect size, $R^2 = 9$ (see Table 1). Spatial visualization ability showed a significant and positive association with the accuracy of map reconstruction, $t(21) = 1.99$, $p < .05$, with a medium effect size, $R^2 = 18$. Mental rotation and spatial memory were not significantly associated with map reconstruction performance. The compensation and facilitation hypotheses were not supported, as no interactions of spatial ability and map configuration were significant.

DISCUSSION

Effects of Map Configuration

The effects of map configuration in the current study showed primarily small to medium effect sizes. This study replicated Aretz (1991) and Wickens et al. (1996) in that performance on the direction-of-turn task was better with the track-up map, whereas map reconstruction was more accurate with the north-up map. We reported new findings regarding the effect of map configuration on cardinal direction judgments; that is, the track-up map led to more accurate and faster overall performance than did the north-up map; and the track-up map greatly reduced misalignment effects on accuracy and speed. These findings suggest that (a) a key difficulty with the cardinal direction judgments we studied is the requirement to realign and coordinate world-centered direction information across a 2-D map and a 3-D egocentric ground display and (b) the mechanism by which track-up maps improve performance is by automatically aligning directional information across the two displays.

Another factor that may have contributed to the track-up advantage for cardinal direction judgments was that our participants were trained to solve these problems by transferring world-centered headings from the map to the 3-D view, and this transfer strategy is probably easier with a track-up map. Further research should test whether these map configuration effects occur when participants choose their own strategies. Also, this training may have improved overall performance at the cardinal direction task, even for the north-up map, whereby accuracy for our trained student participants averaged 86% (*SE* = 2.2) compared with about 70% in an untrained student sample from the same university in Gugerty and Brooks (2004). This hypothesized training effect needs to be tested in further research. We found little research on how to train navigation knowledge, especially about cardinal direction judgments, other than Hutchins's (1999) study of military naval navigation, which characterized navigation training as on-the-job, highly procedural, and de-emphasizing explicit teaching of conceptual knowledge, such as the relationship between egocentric and world-centered directions.

Our finding that with a north-up map, misalignment of the aircraft heading away from the top of the map degraded cardinal direction performance replicated findings with the same UAV task in Gugerty and Brooks (2001). The findings reported here regarding the reduction of misalignment effects with track-up maps go beyond these prior findings.

Effects of Spatial Ability

The other focus of this study was measuring correlations between individual differences in spatial ability and navigation task performance. We generally found, after controlling for map interface effects, that spatial ability accounted for significant incremental variance in performance for all five performance variables across three navigation tasks, with medium to large effect sizes.

In addition to these main effects of spatial ability, we tested for ATIs such that the track-up map would either compensate for low mental rotation ability or facilitate performance for high spatial performers on difficult navigation tasks (e.g., cardinal directions). We found evidence that the track-up map compensated for low rotation ability with respect to cardinal direction RTs. This ATI, which showed a medium effect size, is similar to a compensation effect found by Goska and Ackerman (1996). The predicted compensation effect was not found for cardinal direction accuracy or for direction-of-turn accuracy and RT, possibly because the overall high performance on these variables limited the influence of ability differences.

We found evidence that track-up maps facilitated accurate performance of high-ability performers on the cardinal direction task, but only for spatial visualization. Our evidence for facilitation of cardinal direction performance was not strong, as the effect showed a small effect size and was not supported for the response time variable.

These individual differences findings are limited because of the small sample size and the unequal gender ratio. In particular, with the small number of males, the generalizability to males is limited.

Application

We focus here on our novel findings involving the cardinal direction task. Our finding of an ATI whereby the track-up map compensated for low mental rotation ability with respect to RT suggests that if an important performance goal is fast cardinal direction judgments, then switching to a track-up map is sufficient to achieve this goal, and considering differences in mental rotation ability will not improve performance much. In contrast, for the goal of accurate cardinal direction judgments, when participants used the better performing track-up map, participants with high mental rotation, visualization, and spatial memory still outperformed those with low ability. In these cases, considering spatial ability differences can add performance benefits beyond switching to a track-up map. In general, there are two ways to optimize performance by considering individual differences: selecting only high-ability personnel or training low-ability personnel to near the level of high-ability personnel, if possible.

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KEY POINTS

- Compared with north-up electronic maps, use of track-up maps led to improved cardinal direction and route-following judgments during aerial navigation.
- Use of north-up maps led to improved long-term learning of the mapped region.
- Mental rotation, spatial visualization, and spatial memory ability are positively correlated with performance at cardinal direction, route-following and spatial learning tasks.
- In some cases, high spatial ability facilitated the effect of a beneficial map type; in other cases, a beneficial map type compensated for low spatial ability.
- Individual differences in spatial ability account for a large amount of variability in navigation performance, even after controlling for effects of map type.

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William Rodes is Video Producer at NewSpring Church in Anderson, South Carolina. He obtained an MS degree in human factors psychology from Clemson University in 2006.

Leo Gugerty is a professor of psychology at Clemson University. He obtained a PhD in experimental psychology from the University of Michigan in 1989.

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