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Effects of Field Dependence-Independence and Frame of Reference on Navigation Performance Using Multi-dimensional Electronic Maps

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A B S T R A C T

Most prior studies regarding navigational efficiency of electronic maps mainly investigated map characteristics such as the frame of references of maps (track-up maps vs. north-up maps) and the map dimensionality (2D maps vs. 3D maps). However, relatively little research has been found regarding how user characteristics, especially a user's cognitive style, affect the effectiveness of navigational displays. The present study examined how individuals' field dependence-independence, as an essential dimension of cognitive styles, affects user performance in orienting and navigating tasks with 2D and 3D electronic maps. The results suggested field-independent individuals had higher mental rotation ability than field-dependent individuals. The results also indicated significant interactions between field dependence-independence and frame of reference on both orienting and navigating tasks. Field-independent (FI) individuals responded more quickly and with higher accuracy compared to field-dependent (FD) individuals when using north-up maps, but no such differences was revealed when track-up maps were used. This implication could be further utilized to improve user-centered designs of navigation displays by considering individual differences.

1. Introduction

Recent advances in information technology have led to the wide use of electronic maps in navigation tasks. An important question is how to present information about locations and directions in order to facilitate navigation tasks in various complex systems, such as driving navigation systems, air traffic control systems, and ship navigation planning and control systems (Hsu, Lin, & Chao, 2012). Previous research has provided recommendations on the design of electronic maps to achieve display effectiveness regarding the display characteristics (Aretz, 1991). However, relatively little research has been found regarding how user characteristics, especially a user's cognitive style, affect the effectiveness of navigational displays. A small number of research included cognitive ability rather than cognitive style when studying wayfinding, orienting, and navigation with virtual environments (Satalich, 1995; Waller, 1999; Waller, 2000; Waller, Beall, & Loomis, 2004; Waller, Hunt, & Knapp, 1998).

Cognitive style refers to the consistent and stable individual differences in their ways of organizing and processing information (Messick, 1984). Several cognitive styles have been identified and each of these cognitive styles is stable over time, resistant to training and changes, and is independent from general intellectual ability (Ausburn & Brown, 2006). Among these various dimensions of cognitive styles, the field dependence-independence dimension has been the most extensively and systematically studied (Evans, Richardson, & Waring, 2013; Evans & Waring, 2012). Witkin and his colleagues first proposed the concept of field dependence as one dimension of cognitive styles (Witkin, Moore, Goodenough, & Cox, 1977). The field dependence-independence (FDI) reflected the extent to which a person perceives and processes part of a field as discrete from the surrounding environment as a whole, rather than embedded in the field (Witkin et al., 1977). This construct determined how people look for information in the environment, and how they organize and interpret this information in an individual manner (Hayes & Allinson, 1998). Previous studies have indicated that field-dependent individuals are more likely to be influenced by external cues and are less likely to view information separate from the environment. Field-independent individuals are more likely to be influenced by internal cues and are able to separate essential information from its environment (Riding & Cheema, 1991; Zhang, 2004). Several studies have investigated the effects of cognitive style on navigational behaviors with web-based searching and navigations (Alomyan, 2004; Dong & Lee, 2008; Fiaola & MacDorman, 2008; Kim & Allen, 2002), and hypertext and hypermedia links (Chou & Lin, 1998; Korthauer & Koubek, 1994; Weller, Repman, & Rooze, 1994). Kroutter (2010) studied the effect of field dependence-independence on

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navigation behaviors and crime scene drawings of the virtual environment after their exploration along with the effects of other individual differences, such as gender and experience. They found cognitive style was associated with time spent in virtual environment learning but was not associated with learning outcomes. This work suggested that the dimension of field dependence-independence affected an individual's way of processing environmental information. However, this work focuses on the interactions of field dependence-independence with other individual differences rather than the interactions between field dependence-independence with display characteristics.

Among the display characteristics being studied, frame of reference (ego-centered vs. world-centered) and map dimensional (2D vs. 3D) are two important aspects of research on electronic maps (Wickens & Baker, 1995). In terms of the frame of reference, the orientation of the map in the display may potentially impact the workload of the driver and the time needed to process the presented information (Aretz & Wickens, 1992). Map display designs can be ego-centered, referred to as track-up (TU). The map display design can also be world-centered, referred to as north-up (NU) since north is always at the top of the map display (Aretz & Wickens, 1992). Extensive studies in literature have investigated the effect of frame of reference on navigation performance, finding disparate results, however, with regard to determining the best type of maps to optimize performance. Aretz and Wickens (1992) explains the benefit offered by either display is task-dependent. Studies found that the NU display supports route planning, route learning, communication, and cognitive map development, whereas the TU display benefits users in their decision making, navigation, tracking and relative judgment. Cuevas, Huthman, Knudsen, and Wei (2001) explored the effect of navigation display type (i.e. north-up vs. track-up) on the performance of computer-based navigation tasks. The results suggested that neither display lead to better performance, but there was a significant effect of a user's spatial orientation ability on navigation tasks. In particular, the track-up group had more difficulties in the tasks (higher workload) and rated the map display less helpful.

With advancements in graphic display technology, researchers in the field of navigation have focused on 3D maps. The 3D view is defined as a perspectival view of an object or scene displayed on a 2D image (St. John, Cowen, Smallman, & Oonk, 2001). The naturalistic look of a 3D map has leaded it to be preferable to users (Gould et al., 2009; Smith & Wilson, 1993). However, researchers warned system designers that 3D displays might not always enhance user performance (Andre and Wickens, 1995). St. John et al. (2001) reviewed empirical evidence of map dimensionality on user performance and found mixed results (Hickox & Wickens, 1999; Van Breda & Veltman, 1998; Wickens, Liang, Prevett, & Olmos, 1996; Wickens & Prevett, 1995). The inconsistency of results illustrated that there was an interaction between the task type and the type of display employed for that specific task. Haskell and Wickens (1993) argued that when there was a strong resemblance between a real world task and the display, the 3D display was best suited. Also, when 3D displays were implemented the user forgoes the mentally demanding process of combining two 2D displays to synthesize a mental representation of a 3D space. St. John et al. (2001) found that 3D displays facilitated shape understanding such as mental rotations, and 2D displays led to better performance for tasks that required judgments on positions in terms of both response time and response accuracy.

Although research has been conducted to study the effects of map characteristics and individual differences on navigational behaviors, the interaction between individual's field dependence-independence cognitive style and map characteristics (i.e. Frame of reference and map dimension) has not been studied. The present study investigated how an individual's field dependence-independence and its interaction with a map's frame of reference influenced performance in orienting and navigation tasks with 2D and 3D navigation maps. The first experiment focused on the effect of field dependence-independence on mental rotation task performance with 2D and 3D maps. The second and third experiments studied the interaction between field dependence-independence and frame of reference on orienting tasks with 2D and 3D maps, respectively. The forth experiment studied the same interaction effect on navigation tasks in a simulated virtual environment. Field dependence was used to refer to the dimension of field dependence-independence in the following sections. By studying the effects of map characteristics and individual differences on navigational behaviors, the results from the present study could be applied to improve the design of navigation maps in different systems, such as driving navigation systems, air traffic control systems, and ship navigation planning and control systems.

2. The Classification of Field Dependence Using Embedded Figure Test

An Embedded Figure Test was used to measure the field dependence of the participants (Witkin, Oltman, Raskin, & Karp, 1971). The experimenter presented instructions and an example of the test to participants first. The test included three sessions, a practice session and two formal test sessions. In the practice session, participants had four minutes to answer nine questions. Each of the formal test sessions had ten questions, and participants were given four minutes to complete all questions.

Each correct answer in the test session counted one score. Any misses or mistake answers were not counted in the final score. The full mark of the Embedded Figure Test was twenty.

The Embedded Figure Test was conducted 11 times with each test having 20 to 70 participants. There were 553 valid participants (215 males and 338 females). The valid scores were distributed normally between 0 and 20. Participants with scores ranging from 0 to 11 were classified as field-dependent, and participants with scores ranging from 17 to 20 were classified as field-independent. The classified sample included 126 field-dependent subjects (22.8%) and 106 field-independent subjects (19.2%). The subjects in the second phase of the experiments were randomly selected from this sample.

3. Experiment 1. Effects of Field Dependence on 2D and 3D Map Mental Rotation

Previous studies have indicated that there are significant effects of field dependence on performance in Mental Rotation Tests (Guillot, Champely, Batier, Thiriet, & Collet, 2007). The present study examined this effect on mental rotation with 2D and 3D maps.

3.1. Method

3.1.1. Participants

Thirty-nine undergraduate students (22 females and 17 males) participated in the experiment. All had normal or corrected-to-normal vision with ages ranging from 18-23. Nineteen of them were classified as field-dependent subjects, while twenty of them were classified as field-independent subjects based on their performance on the Embedded Figures Test.

3.1.2. Stimuli and Apparatus

The stimuli were 2D and 3D rotation maps. The spinning images for 2D maps were created with the normal image for 0° 90°, 180° or 270° of clockwise rotation, illustrated in Fig. 1 (a). The mirror-image versions of the 2D maps were produced for each of the orientations as spinning images, illustrated in Fig. 1(b).

The spinning and flipping versions of the 3D maps were produced in the same way as were 2D maps, illustrated in Fig. 2.

The 2D and 3D maps were presented on a 17-inch LCD with 1024×768 pixel resolution. The same-different judgment tasks were completed using E-Prime software 2.0. Standard keyboards were used to record subject responses.

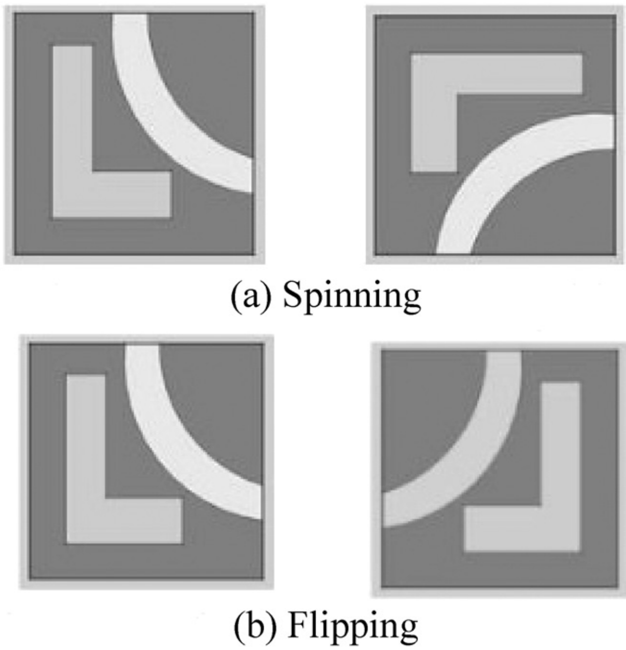

Fig. 1. Example of spinning (90 degree) and flipping versions of 2D maps.

3.1.3. Experiment design and data analysis

This experiment adopted a three-factor mixed design with field dependence (field-dependent vs. field-independent) as the between-subjects independent variable, map dimensionality (2D maps vs. 3D maps) and degree of rotation (0°, 90°, 180° and 270°) as within-subjects independent variables. Each subject experienced all 8 combinations of map dimensionality and rotation degree. The order of map dimensionality was counterbalanced in order to eliminate the ordering effect. The dependent variable was the response accuracy. Environmental factors including temperature, light and noise were controlled.

Factorial repeated-measures ANOVA was used to examine the effects of field dependence, view dimensionality and degree of rotation on mental rotation performance.

3.1.4. Procedure

Upon arrival, all participants were first asked to sign a consent document and were briefed on the operation of the tasks. They then completed a practice block that allowed them to get familiar with the operation. The practice block consisted of 8 trials with varying experimental conditions. After each key pressed by the subject, a blank screen displayed for 1000ms and the next trial started automatically. The experimenter would answer any questions from the subjects after the practice block. Following the practice block, participants completed a test block comprising 80 trials randomly presented with every combination of the experimental condition repeating 10 times. In each trial, there were two maps displayed, one being the original image and the other one produced by spinning or flipping the original image. Subjects were asked to judge whether the original image on the left and the rotation image on the right were the same by pressing '1' for 'same' and '2' for 'different'.

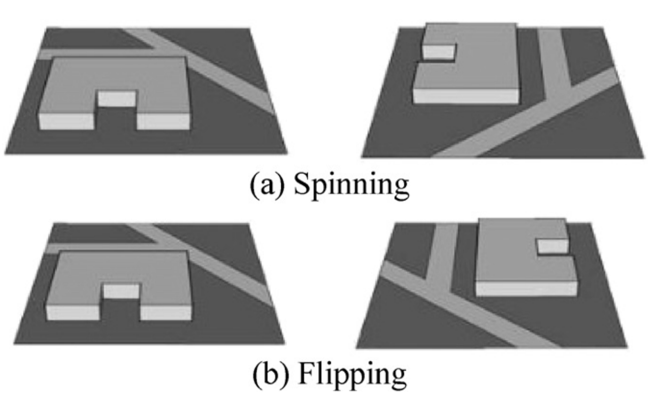

Fig. 2. Example of spinning and flipping versions of 3D maps.

3.2. Results

Data for two subjects were excluded due to their accuracy of judgment using 2D maps below the chance level (50%) under the no-rotation condition (rotation degree of 0). The overall accuracy was 80% for 2D maps and 79% for 3D maps. A repeated measures ANOVA was conducted on response accuracy with map dimensionality and rotation degree as within-subjects variables, and field dependence as a between-subjects variable. The assumptions of sphericity and homogeneity of variance were met.

Results indicated a significant main effect of field dependence on response accuracy, $F(1, 35)=8.07$, $p<.01$, indicating that the accuracy was significantly higher for field-independent subjects ($M=85\%$) than for field-dependent subjects ($M=75\%$). There was not a significant main effect of map dimensionality on response accuracy, $F(1, 35)=.32$, $p=.57$, indicating the accuracy was similar overall for 2D and 3D maps. There was a significant main effect of rotation degrees on response accuracy, $F\ (3, 105)=76.08$, $p<.001$. Contrasts revealed that response accuracy ($M_0=94\%$) for maps with no rotation was significantly higher than that of maps with the other three levels of rotation degrees. The accuracy for maps with rotation ($M_{180}=68\%$) was significantly lower than that of maps with the other three levels of rotation degrees. There was no significant difference between the accuracy for maps with rotation M_{90} (79%) and with rotation M_{270} (78%). As is shown in Fig. 3, response accuracy in the mental rotation test was a function of rotation degree such that the accuracy decreased as the rotation degree of map increased with either clockwise or counter-clockwise rotation.

There was a significant interaction effect of field dependence and rotation degree on response accuracy, $F\ (3, 105)=2.86$, $p<.05$. This indicated that the response accuracy of different map rotation degrees differed in field-dependent and field-independent participants. The contrasts were comparing each level of map rotation to no rotation level across field-dependent and field-independent participants. The results revealed a significant difference in response accuracy for field-dependent participants and field-independent participants when comparing 180°rotation maps to 0° rotation maps, $F(1, 37)=5.82$, $p<.05$. The difference in response accuracy for field-dependent participants and field-independent participants was marginally significant when comparing 270°rotation maps to 0° rotation maps, $F(1, 37)=4.04$, $p=.05$. Although the difference in response accuracy for participants with different dimensions of field dependence was slightly larger for 90° rotation maps than for 0° rotation maps, the difference was not significant.

The ability of mental rotation ability is computed as the difference of response accuracy for 180° rotation maps comparing to 0° rotation maps. A repeated measures ANOVA indicated a significant main effect of field dependence on response accuracy, $F(1, 37)=5.82$, $p<.05$. As is shown in Fig. 4, the mental rotation ability of field-independent subjects ($M=20\%$) was significantly higher than that of field-dependent subjects ($M=30\%$). There was no significant main effect of map dimensionality, $F(1, 37)=0.42$, $p=0.5$. There was no significant interaction effect of field dependence and map dimensionality, $F(1, 37)=0.08$, $p=0.77$, indicating that the effects of field dependence on mental rotation ability were consistent across different map dimensionalities.

The results of experiment 1 suggested that the participants with different spatial transformation mechanisms (field-independent vs. field-dependent) performed differently in various judgment tasks. This result was consistent with previous studies. There is a similar process in

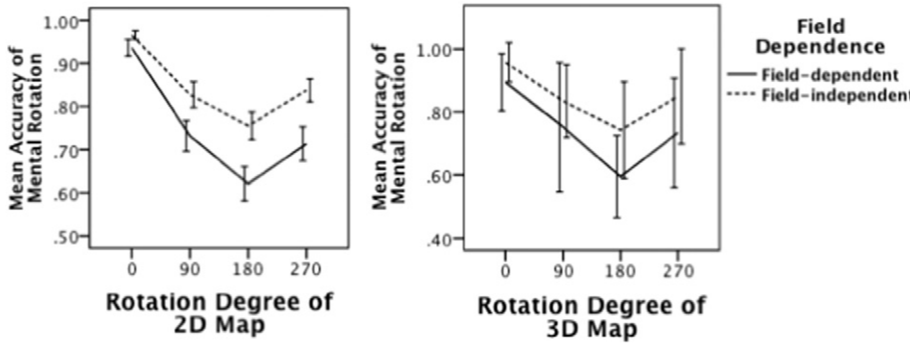

Fig. 3. The effect of field dependence on accuracy in mental rotation for 2D and 3D maps (Error bar: +/- 1SE).

mental map rotation as in physical object rotation. That is to say, the spatial transformation information might be stored in the working memory to be compared with the original map. Therefore, the larger degree of the rotation, the more difficult it is to make judgments. In the information processing of mental rotation, it appears that field-independent participants using object-centric frame of reference rely more on internal perceived information, which enables them to process the spatial information integrally. On the other side, field-dependent participants using egocentric frame of reference rely more on external information in the environment, which forces them to process the spatial information gradually.

Compared with previous studies using classic mental rotation material, the present study indicated that the accuracy in mental rotation tasks is lower using 2D and 3D maps than the accuracy using numbers and letters. This result is natural since map stimuli are more complicated and less meaningful than a single number or letter symbol. Therefore the higher task difficulty resulted in a lower accuracy in responses.

The results in Experiment 1 also indicated that the changes of response accuracy along with different rotation degree were consistent between field-independent and field-dependent subjects. There was a 'V' shape of response accuracy changing with the degree of rotation. The lowest correct rate was reached when the rotation degree increased to 180 degrees. The results indicated that strategy of mental rotation was highly variable rather than fixed, which was consistent with the process in physical object rotation.

4. Experiment 2. Interacting Effects of Field Dependence and Frame of Reference on Mental Rotation with 2D Maps

Orientation is defined as a sense of up and down or north, south, east, and west (Blade & Padgett, 2002). It is relevant to an individual's ability to determine their location relative to other important objects in the environment. Kroutter (2010) argued that field dependence-independence influenced their ways of orienting in virtual environments but not their performance in orienting tasks. However, the study did not investigate whether there was an interaction between field dependence-independence and display characteristics such as frame of reference. Experiments 2 and 3 addressed this interaction effect with 2D and 3D maps with orienting tasks.

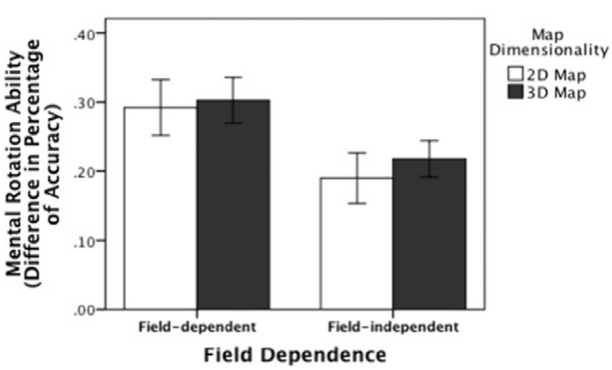

Fig. 4. The effect of field dependence on mental rotation ability for 2D and 3D maps (Error bar: +/- 1SE).

4.1. Method

4.1.1. Participants

Forty-two undergraduate students (24 females and 18 males) participated as subjects. All had normal or corrected-to-normal vision with ages ranging from 18-23. Twenty-two of them were classified as field-dependent subjects, while twenty of them were classified as field-independent subjects based on their performance on the Embedded Figures Test.

4.1.2. Stimuli and Apparatus

The stimuli included north-up maps and track-up maps. The north-up map was a fixed square map presenting a stationary view of an interaction with four regions nearby. Each region consists of different road symbols and building symbols. There was a letter 'T' appearing in one of the four regions with equal probability. The direction of a red arrow on the map indicated the direction of a subject's view. It was located at the center of the bottom on the map, shown in Fig. 5. As it moved towards the center of the interaction, the red arrow would turn left or right with an auditory tone.

As is shown in Fig. 6, the track-up maps used in the experiments are similar to north-up maps, except that the arrow remained pointing towards the top of the screen. As the arrow moved towards the center of the intersection and made turns, the track-up map rotated correspondingly. Subjects perceived the turning direction of the arrow through the direction of map rotations. In other words, the subject would perceive the arrow turning left when the map rotated 90 degrees clockwise, and turning right when the map rotated 90 degrees counter clockwise.

The north-up and track-up maps were created by Google SketchUp 8, transferred by the Windows Live adding the movement of the red arrows, and presented on a 17-inch LCD with 1024 × 768 pixel resolution. The moving direction judgment tasks were completed using E-Prime software 2.0. Standard keyboards were used to record subject responses.

4.1.3. Experiment design and procedure

This experiment adopted a two-factor mixed design with field dependence (field-dependent vs. field-independent) as a between-subjects independent variable, and frame of reference (north-up map vs. track-up map) as a within-subjects independent variable. The dependent variables were the correct response rate and reaction time. The environmental factors including temperature, light and noise were controlled.

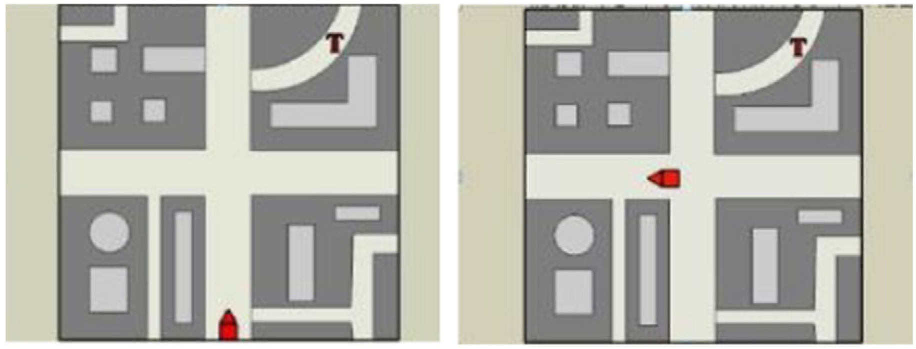

Fig. 5. The north-up maps in navigation task.

Upon arrival, all participants were first asked to sign a consent document and then were briefed on the operation of the tasks. They were then asked to complete a practice block that allowed them to get familiar with the operation. The practice block consisted of 16 trials with each experimental condition repeated 4 times. After each keypress by the subject, a blank screen displayed for 1000ms and the next trial started automatically. The experimenter would answer any questions from the subjects after the practice block. Following the practice block, participants completed a test block comprising 64 trials randomly presented with every combination of the experimental condition repeating 16 times. At the start point of each trial, the red arrow located at the center of the bottom on the map was showing. As it moved towards the center of the interaction, the red arrow would turn left or right with an auditory tone. After the auditory tone, the subjects were asked to make judgments of their corresponding location with target letter 'T' (on their left or right) by pressing either '←' for left or '→' for right.

4.2. Results

A repeated measures ANOVA was conducted on response accuracy with frame of reference as a within-subjects variable and field dependence as a between-subjects variable. The assumptions of sphericity and homogeneity of variance were met. As is shown in Fig. 7, the main effect of frame of reference on the accuracy of direction judgment was significant $F\,(1, 40) = 19.81$, $p < .001$, indicating that accuracy in judging directions using track-up maps ($M = 98\%$) was higher than that of using north-up maps ($M = 94\%$). The main effect of field dependence was not significant, $F\,(1, 40) = 1.75$, $p = .19$.

The results showed a significant interaction effect of frame of reference and field dependence on direction judgment accuracy, $F(1, 40) = 4.30$, $p < .05$, indicating that the effects of frame of reference on response accuracy in direction judgments was influenced by the field dependence. Simple effects analysis showed that field-dependent subjects had a significantly higher accuracy when using the track-up maps than when using the north-up maps ($F(1, 43) = 10.62$, $p < .01$), whereas there was no difference between the judgment accuracy of using two types of maps for field-independent subjects ($F(1, 39) = 1.99$, $p = .17$).

In order to exclude the ceiling effects, t tests were conducted to compare the response accuracy in each of four combined experimental conditions with 100% accuracy. The results indicated that the response accuracy in each condition was significantly smaller than the 100% correct rate, suggesting that the significant interaction effect between field dependence and frame of reference was not a result of any ceiling effects.

5. Experiment 3. Interaction Effects of Field Dependence and Frame of Reference on Mental Rotation with 3D Maps

5.1. Method

5.1.1. Participants

Forty-two undergraduate students (24 females and 18 males) participated as subjects. All had normal or corrected-to-normal vision with ages ranging from 18-23. Twenty-two of them were classified as field-dependent subjects, while twenty of them were classified as field-independent subjects based on their performance on the Embedded Figures Test.

5.1.2. Stimuli and Apparatus

The stimuli included north-up 3D maps and track-up 3D maps with a 45° vertical viewing angle. The north-up map was a fixed square map presenting a stationary view of an interaction of two main roads with four regions nearby. Each region consisted of different road symbols and building symbols. There was a letter 'T' appearing in one of the four regions with equal probability as a target in the tasks. The direction of a red arrow on the map suggested the direction of subject's view. It was located at the center of the bottom on the map as shown in Fig. 8. As it moved towards the center of the interaction, the red arrow would turn left or right with an auditory tone. The speed of the arrow movement was constant.

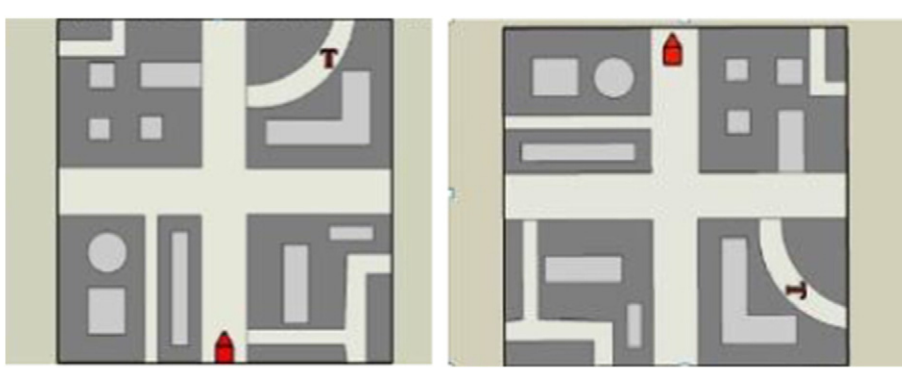

Fig. 6. The track-up maps in navigation task.

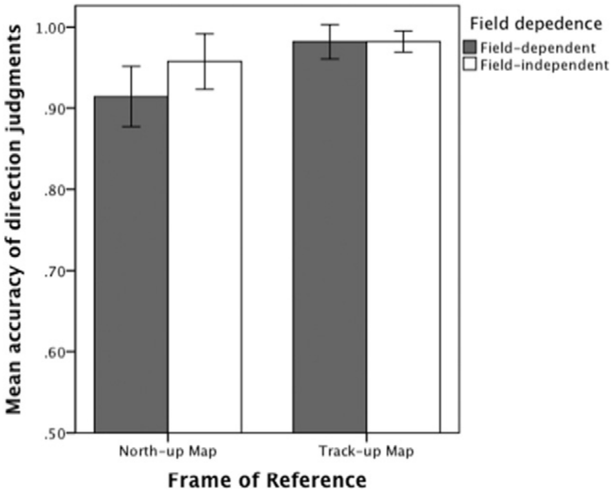

Fig. 7. The effect of frame of reference and field dependence on accuracy of the direction judgment tasks using 2D maps.

As is shown in Fig. 9, the track-up maps used in the experiments are similar to north-up maps, except that the arrow remained pointing towards the top of the screen. As the arrow moved towards the center of the intersection and made turns, the track-up map rotated correspondingly. Subjects perceived the turning direction of the arrow through the direction of map rotations. In other words, the subject would perceive the arrow turning left when the map rotated 90 degrees clockwise, and turning right when the map rotated 90 degrees counter clockwise.

The north-up and track-up maps were created by Google SketchUp 8, transferred by the Windows Live adding the movement of the red arrows, and presented on a 17-inch LCD with 1024×768 pixel resolution. The moving direction judgment tasks were completed using E-Prime software 2.0. Standard keyboards were used to record subject responses.

5.1.3. Experiment design and procedure

This experiment adopted a two-factor mixed design with field dependence (field-dependent vs. field-independent) as a between-subjects independent variable, and frame of reference (north-up map vs. track-up map) as a within-subjects independent variables. The dependent variables were the correct response rate and reaction time. The environmental factors including temperature, light and noise were controlled.

Upon arrival, all participants were first asked to sign a consent document and then were briefed on the operation of the tasks. They were then asked to complete a practice block that allowed them to get familiar with the operation. The practice block consisted of 16 trials with each experimental condition repeated 4 times. After each key press by the subject, a blank screen displayed for 1000ms and the next trial started automatically. The experimenter would answer any questions from the subjects after the practice block. Following the practice block, participants completed a test block comprising 64 trials randomly presented with every combination of the experimental condition repeating 16 times. At the start point of each trial, the red arrow located at the center of the bottom on the map was showing. As it moved towards the center of the interaction, the red arrow would turn left or right with an auditory tone. After the auditory tone, the subjects were asked to make judgments of their corresponding location with target letter 'T' (on their left or right) by pressing either '←' for left or '→' for right.

5.2. Results

A repeated measures ANOVA was conducted on response accuracy with frame of reference as a within-subjects variable and field dependence as a between-subjects variable. As is shown in Fig. 10, the main effect of frame of reference on direction judgment accuracy was significant $F(1, 40) = 20.61$, $p < .001$, indicating that accuracy in judging directions using track-up maps ($M = 98\%$) was higher than that of north-up maps ($M = 94\%$). In the meantime, the main effect of field dependence was not significant $F(1, 40) = 2.77$, $p = .10$.

The significant interaction effects of frame of reference and field dependence, $F(1, 40) = 4.97$, $p < .05$, suggested that the effects of frame of reference on accuracy of direction judgment was influenced by the field dependency. Simple effects analysis showed that field-dependent subjects had a significantly higher accuracy when using the track-up maps than when using the north-up maps ($F(1, 43) = 6.82$, $p < .05$), whereas there was no difference between the judgment accuracy of using two types of maps for field-independent subjects ($F(1, 39) = 2.17$, $p = .15$).

In order to exclude the ceiling effects in the interaction effects, t tests were conducted to compare the reaction correct rates in each of four combined experimental conditions with the 100% correct rates. The results indicated that the correct rate in each condition was significantly smaller than the 100% correct rate ($p < .05$), suggesting that the significant interaction effect between field dependence and frame of reference was not the result of any ceiling effects.

To test the hypothesis that the effect of field dependence on direction judgment using north-up maps was mediated by the ability of mental rotation, a correlation analysis was conducted to test the relationship between mental rotation performance and direction judgment performance with north-up maps by controlling the field dependence. Results indicated a significant positive correlation between mental rotation ability and direction judgment performance with north-up maps ($r = .39$, $p = .019$). In other words, subjects with higher mental rotation abilities might have higher correct rates in direction judgments tasks with north-up maps no matter which field dependence category they were classified as.

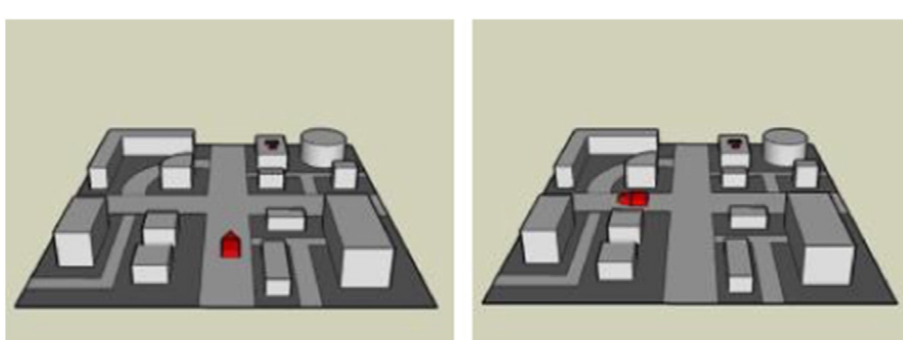

Fig. 8. The view and an example of a left turn in north-up maps.

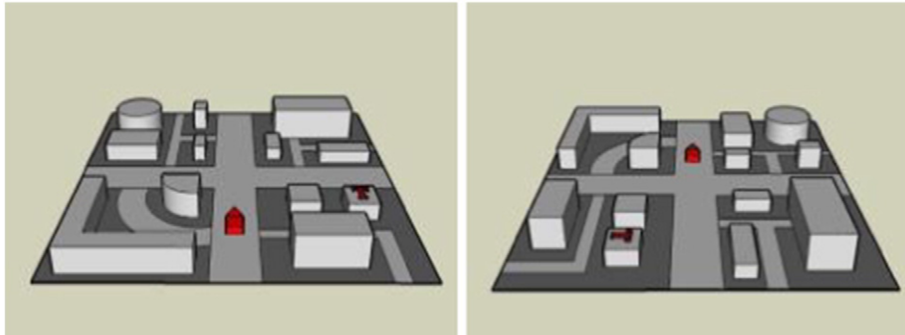

Fig. 9. The view and an example of a left turn in track-up maps.

5.2.1. Field dependence, frame of reference and map dimensionality

To test the interactions between field dependence, frame of reference and map dimensionality, a repeated measures ANOVA was also conducted on data from both experiments 2 and 3 with frame of reference and map dimensionality as within-subjects variables and field dependence as a between-subjects variable. The main effect of map dimensionality on direction judgment accuracy was significant $F(1, 37) = 25.13$, $p < .001$, indicating that accuracy in judging directions using 3D maps ($M = 98\%$) was higher than when using 2D maps ($M = 94\%$). The main effect of field dependence was not significant $F(1, 37) = 2.88$, $p = .10$. The significant interaction effects of map dimensionality and field dependence, $F(1, 37) = 5.73$, $p < .05$, suggested that the effects of map dimensionality on accuracy of direction judgment was influenced by the field dependency. Simple effects analysis showed that field-dependent subjects had a significant higher accuracy when using the 3D maps than 2D maps ($F(1, 18) = 27.32$, $p < .001$), whereas there was no difference between the judgment accuracy of using two types of maps for field-independent subjects ($F(1, 19) = 3.45$, $p = .08$).

Another repeated measures ANOVA was conducted on response time from both experiments 2 and 3. The main effect of frame of reference on direction judgment accuracy was significant $F(1, 37) = 7.33$, $p < .05$, indicating that response time in judging directions using north-up maps ($M = 0.68$s) was quicker than that of track-up maps ($M = 0.70$s). The significant interaction effects of frame of reference and map dimension, $F(1, 37) = 7.31$, $p < .05$, suggested that the effects of frame of reference on response time was influenced by the map dimensionality. Simple effects analysis showed that subjects responded faster to 2D maps than to 3D maps when using track-up maps ($F(1, 38) = 12.10$, $p < .01$), whereas there was no difference between the response time to 2D and 3D north-up maps ($F(1, 38) = 1.78$, $p = .19$).

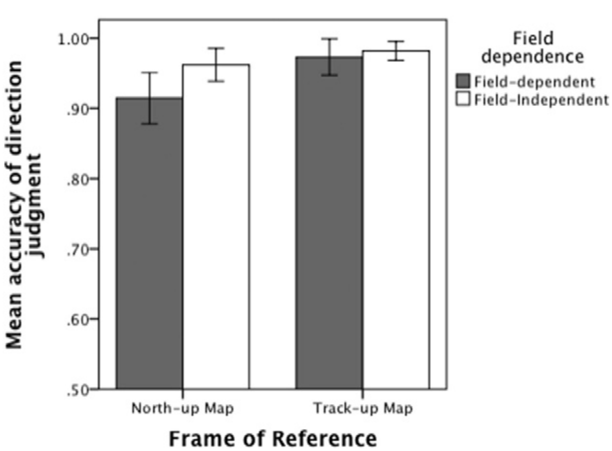

Fig. 10. The effects of frame of reference and field dependence on the accuracy of direction judgments using 3D maps.

6. Experiment 4. Interaction Effects of Field Dependence and Frame of Reference on Navigation Efficiency with 2D Maps in the Virtual Environment

The last two sections have investigated how an individual's field dependence- independence interacted with map frame of reference on orienting tasks. Besides orienting ability, navigation tasks also required the ability to follow a path from one location to a target destination with the process of using spatial and environmental information. Experiments 2 and 3 have studied the interaction between field dependence-independence and frame of reference on the performance in orienting tasks. The following experiment studied this interactive effect on the performance of navigation tasks in a virtual environment.

6.1. Method

6.1.1. Participants

Twenty-two undergraduate students (14 females and 8 males) participated as subjects. All had normal or corrected-to-normal vision with ages ranging from 18-23. Half of the subjects were classified as field-dependent subjects, whereas the other half were classified as field-independent subjects based on their performance on the Embedded Figures Test.

6.1.2. Stimuli and Apparatus

The virtual environment was developed with Abstract Windows Toolkit in Java and presented on a 17-inch LCD with 1024×768 pixel resolution. Two types of maps, including north-up maps and track-up maps, were created for the virtual environment on a scale of 1:10. Standard keyboards were used to record subject responses.

As is shown in the following Fig. 11, the virtual environment was presented with a first-person perspective consistent with the direction of the arrow showing on the 2D map. The virtual environment had only one exit. Subjects could move in the virtual environment by pressing the following four keys '↑', '↓', '←', '→'. There was a button on the right top corner to show/hide the 2D map. The keys for movement only worked when the subjects exited the map view.

As is shown in Fig. 12, the north-up map was a fixed square map presenting a stationary view of the map of the virtual environment. The direction of a red arrow on the map suggested the moving direction of the subject in the virtual environment.

As is shown in Fig. 13, the track-up map used in the experiments was similar to the north-up map, except that the arrow remained pointing towards the top of the screen. The pointing direction of the arrow was consistent with the perspective of the virtual environment. Therefore, the track-up map rotated as subjects changed directions in the virtual environment. In other words, the map rotated clockwise when the subject turned left, and counter clockwise when the subject turned right.

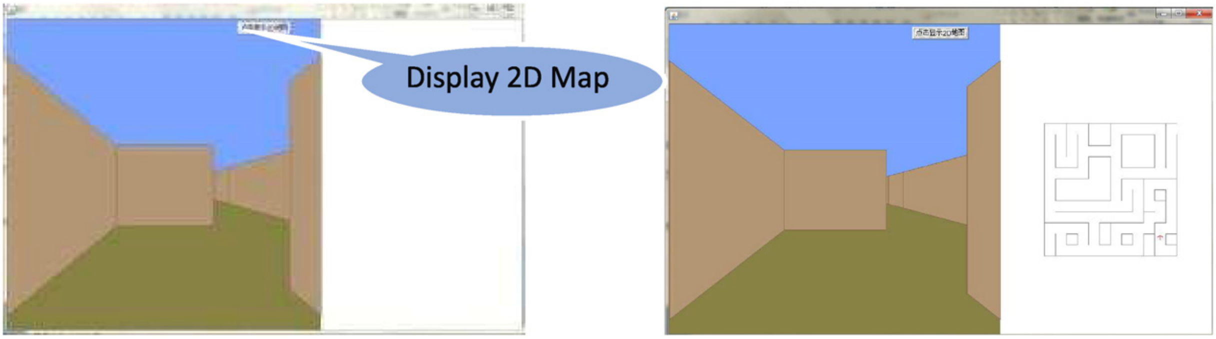

Fig. 11. The operation mode and map mode in the virtual environment.

6.1.3. Experiment design and procedure

This experiment adopted a two-factor mixed design with field dependence (field-dependent vs. field-independent) as between-subjects independent variable, and frame of reference (north-up map vs. track-up map) as within-subjects independent variables. The dependent variables included task completion time, total steps to complete task, and number and time of referring maps. The environmental factors including temperature, light and noise were controlled.

Upon arrival, all participants were first asked to sign a consent document and then were briefed on the operation of the tasks. They were then asked to complete a practice block that allowed them to get familiar with the operation. The practice block consisted of one north-up map session and one track-up map session. Subjects were asked to move from the original position to the exit of the map as rapidly and as accurately as possible. They could refer to the map as many times and use as much time as they wanted. The experimenter would answer any questions from the subjects after the practice block. Following the practice block, participants completed a test block with one north-up map session and one track-up map session. The order of using the two types of maps was counterbalanced in order to eliminate any ordering effect. Before the start of each session, the subject sat in front of the screen with their right hand on the keyboard.

After completing the test block, participants were given an introduction to the 7-point Likert type rating scale for subjective satisfaction using two frames of reference, and an open-ended question asking which frame of reference they preferred.

6.2. Results

6.2.1. Task completion time

A repeated measures ANOVA was conducted on task completion time with frame of reference as a within-subjects variable and field dependence as a between-subjects variable. Data points exceeding 3.0 SD from the mean were classified as outliers and data for one of the subjects was excluded from the analysis. As is shown in Fig. 14, the main effect of field dependence on the task completion time was significant F (1, 18) = 4.72, p<.05, indicating field-dependent subjects (M = 137.70s) took longer to finish the task than field-independent subjects did (M = 101.95s). There was a significant interaction effect of frame of reference and field dependence, F (1, 18) = 5.05, p =<.05. The main effect of frame of reference on task completion time was not significant, F (1, 18) = 0.88, p = .36. Simple effects analysis showed that field-independent subjects had a significantly quicker response than field-dependent subjects when using north-up maps (F(1, 18) = 6.69, p < .05), whereas there was no difference in their response times when using track-up maps (F(1, 18) = .60, p = .45).

6.2.2. Number of map references during the navigation task

A repeated measure ANOVA was conducted on the number of map references with frame of reference as a within-subjects variable and field dependence as a between-subjects variable. The results showed a significant main effect of field dependence on the number of map references, F (1, 18) = 5.15, p<.05, indicating field-dependent subjects (M = 29) referred to the map more times in order to finish the task than field-independent subjects did (M = 22). There was no significant effect of frame of reference, F (1, 18) = 0.01, p = .92. No significant interaction effect was found on the number of map references, F (1, 18) = 1.15, p = .30.

As is shown in Fig. 15, results indicated that field-dependent subjects referred to the north-up maps more times compared to using track-up maps, whereas field-independent subjects had no such difference when using either type of map. These results were consistent with the correct rates in direction judgment tasks such that it was more difficult to use north-up maps than to use track-up maps for field-dependent subjects.

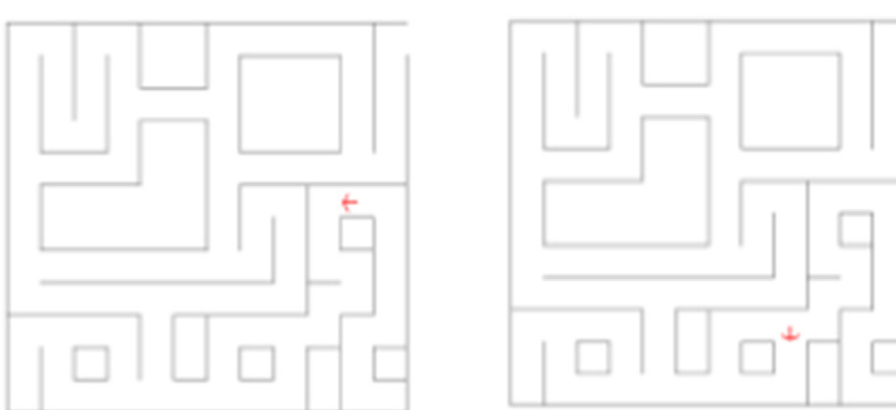

Fig. 12. The north-up map of the virtual environment.

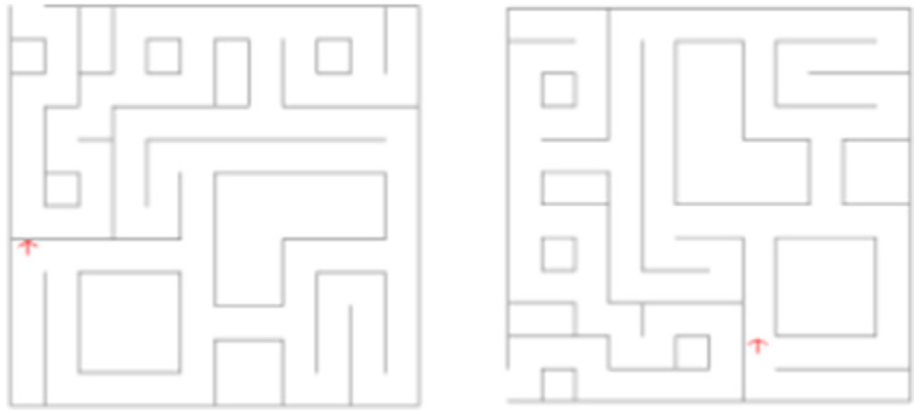

Fig. 13. The track-up map of the virtual environment.

6.2.3. Subjective rating

The main effect of frame of reference on the subjective rating was significant $F(1, 20) = 13.49$, $p < .01$. North-up maps ($M = 5.88$) were rated significantly higher than track-up maps ($M = 4.71$). Neither the main effect of field dependence nor its interaction with frame of reference on subjective ratings was significant. In further analysis of the selection of map in reality, 18 of 24 participants preferred north-up maps, 5 participants preferred track-up maps, and 1 participant did not indicate any preference. In the evaluations of north-up maps, most participants were more familiar with north-up maps from their daily experience such that they would plan the route and complete the task based on the map. However, participants did report they needed further thinking when encountering situations where the direction of the arrow on the map and the direction of the virtual environment were different. In terms of track-up maps, participants reported that map rotation would interfere with their route plan when they had to adjust their routes, which increased mental workloads. However, track-up maps made it easier for direction judgment when subjects made turns in the virtual environment.

7. Discussion

The present study examined the effect of field dependence-independence and frame of reference on performance in orienting and navigating tasks with 2D and 3D electronic maps. Results indicated significant interactions between field dependence-independence and frame of reference on both orienting and navigating tasks. In particular, field-independent (FI) individuals responded more quickly and with higher accuracy compared to field-dependent (FD) individuals when using north-up maps. In the mental rotation tasks from experiment 1, results showed response accuracy decreased linearly as the angular disparity between images increased regardless of individuals being field-dependent or field-independent. This result supported the analogous physical rotation of an actual object in mental rotation (Shepard and Cooper, 1986). In mental rotation tasks, field-independent individuals showed a higher accuracy than field-dependent individuals regardless of map dimensionality and the difference of their performance increased as the image rotation degrees increased. This results indicated that field-independent individuals were more likely to utilize the internal cues and to be selective in the information input so that their performance was less likely to be influenced by image rotations; field-dependent individuals relied more on external cues and had difficulty in separating input information from contextual surroundings resulting in more difficulties with mental rotation tasks.

Experiments 2 and 3 examined the effects of field dependence and frame of reference on direction judgment accuracy with 2D and 3D maps. Results were consistent for 2D and 3D maps, that field-dependent individuals showed significantly higher accuracy in orienting tasks when using the track-up maps than when using the north-up maps, whereas field-independent individuals had no difference when using either type of maps. Previous research has proposed that a mental rotation has to be performed to align the world frame of reference (north-up maps) with the ego frame of reference (track-up maps) (Aretz, 1991). Along with the results in experiment 1, the current study may imply that field-dependent

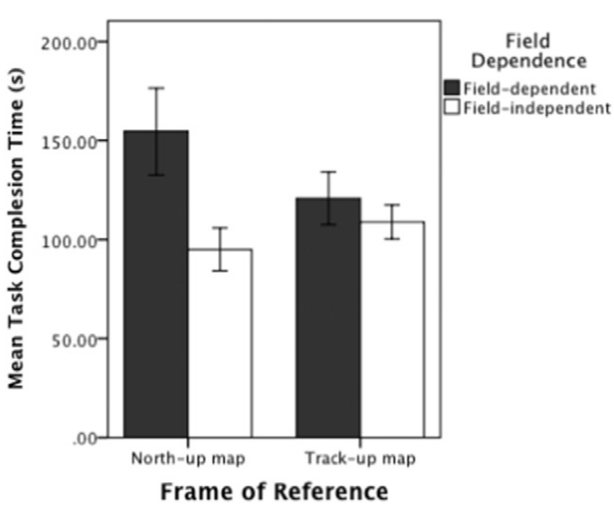

Fig. 14. The effects of frame of reference and field dependence on navigation task completion time in the virtual environment.

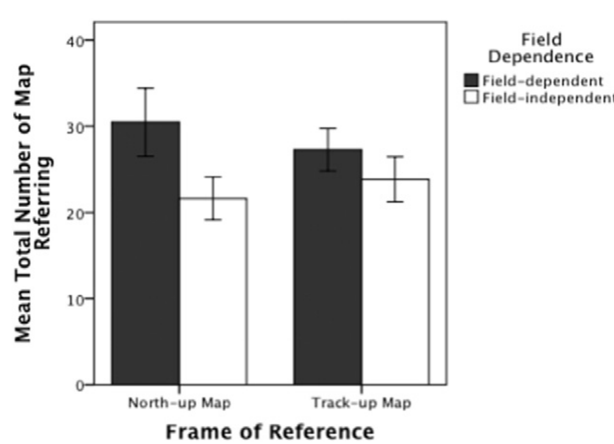

Fig. 15. The effect of frame of reference and field dependence on number of map references in the virtual environment using 2D maps.

individuals showed worse performance than field-independent individuals when using north-up maps because an additional step of mental rotation was included when making direction judgments with north-up maps and FD individuals were more likely influenced by the external cues in mental rotations. Since track-up maps matched with the direction of travel, the mental rotation was not necessary, so that FD and FI individuals showed no significant difference in such direction judgment tasks.

Experiment 4 examined the effects of field dependence and frame of reference on navigation task performance in the virtual environment. Results showed that field-independent individuals had better performance than field-dependent individuals with respect to the number of map references. The results also showed an interaction effect of field dependence and frame of reference on task completion time. In particular, FI individuals showed a significantly quicker time to complete the navigation task than FD individuals when using north-up maps, whereas they showed no difference in task completion time when using track-up maps. Although track-up maps led to superior performance for FD individuals, the subjective rating of track-up maps was lower than that of north-up maps. This was consistent with the previous argument from Andre and Wickens (1995) that there could be inconsistency between users' subjective opinions and objective performance.

When the concept of field dependence-independence was proposed, Witkin et al. (1977) found that field-dependent individuals tended to maintain the structure of the field as it is presented, whereas field-independent individuals tended to impose their own structure of the field. The present study indicated that individuals with different cognitive styles on the dimension of field dependence-independence showed different performance when using different frames of reference in orienting and navigating tasks. This difference may due to their different bearing on the perception, acquisition and processing of environmental information, which in turn caused different ways of orienting themselves in the environment. Field-dependent individuals may utilize the ego-centered frame of reference. Therefore, they had to align their own frame of reference with the world-centered frame of reference when using north-up maps, a process where more errors could be introduced and more time is needed to respond. In contrast, field-dependent individuals may utilize the world-centered frame of reference when they reconstruct the field. Therefore, they could easily adjust their frame of reference with higher accuracy and less time when using north-up maps.

In addition, comparing the results of experiments 2 and 3, map dimensionality was found to interact with both the field dependence of users (FD vs. FI) and frame of reference (north-up vs. Track-up) of navigation displays. In terms of the interaction between individual field dependence and map dimensionality, FD individuals showed higher accuracy when using 3D maps than that of 2D maps, whereas performance accuracy for FI individuals was not significantly different between 3D maps and 2D maps. 3D maps provided users with additional information regarding the external world. This result may imply that FI individuals have better abilities in selecting information from the external world to perform a navigation task. In terms of the interaction between frame of reference and map dimensionality, track-up displays led to faster responses using 2D maps than when using 3D maps, whereas response time for north-up displays was not significantly different between 2D maps and 3D maps. Several studies have investigated the effect of map dimensionality on user performance in navigation tasks and come to similar conclusions. It was found that 3D displays hampered position-judging tasks, whereas the normal viewing angles in a 2D view minimized distortion (St. John et al., 2001). However, further research is needed to study whether these interaction effects still exist in shape understanding tasks.

A limitation of the present study is that only orienting and navigating tasks were investigated for interaction effects with field dependence and frame of reference. Future work should determine whether this interaction effect still exists in more complex navigation tasks, such as air traffic control tasks and ship navigation and planning tasks. In addition, the mental workload of using different frames of reference and different dimensional displays has to be measured systematically in order to select proper navigation displays.

To sum up, previous empirical studies have failed to find clear evidence to support either north-up or track-up designs. The current study proposed one possible implication for such inconsistent findings: that a user's field dependence/ independence dimension in spatial cognition influences their performance when using different frames of reference. The mental rotation cost using a north-up display can be reduced for field-independent individuals since such users showed better performance in extracting and integrating information in order to maintain their mental representation of the system. This implication could be further utilized in the user-centered designs of navigation displays by considering individual differences.

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