Human-Robot Collaborated Exploration and Wayfinding: Orientation Awareness and its Enhancement

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Abstract
Orientation awareness, being aware of heading direction, current location, and an object’s location relative to current location are all critical for wayfinding. Obtaining and maintaining the orientation awareness is a challenging task and even more difficult in remote wayfinding where the wayfinder cannot physically be in the environment. This study designed an interface to enhance the orientation awareness under a remote wayfinding condition by providing a route map showing the previous path taken by the operator and evaluated its effectiveness. Sixteen participants were tested in this study with eight people in each group. The experimental group received the interface enhancement while the control group did not. Participants were required to remotely navigate a robot to explore an unknown environment, learning the layout as well as searching for exists and dangerous objects. They were then asked to draw the layout of the area and mark out exists and dangerous objects on the map they made. It was found that with the previous route map available, participants resulted in better understanding of the layout as reflected by the quality of the maps they made, compared to those that received no external information. It was also found that even with more information to perceive and process for the users of the enhanced interface, efficiency and subtask performance stayed the same as those who had less information to perceive or process. Results of this study proved the effectiveness of the proposed enhancement.

Disciplines
Ergonomics | Industrial Engineering | Operations Research, Systems Engineering and Industrial Engineering

Comments

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Orientation awareness, being aware of heading direction, current location, and an object’s location relative to current location are all critical for wayfinding. Obtaining and maintaining the orientation awareness is a challenging task and even more difficult in remote wayfinding where the wayfinder cannot physically be in the environment. This study designed an interface to enhance the orientation awareness under a remote wayfinding condition by providing a route map showing the previous path taken by the operator and evaluated its effectiveness. Sixteen participants were tested in this study with eight people in each group. The experimental group received the interface enhancement while the control group did not. Participants were required to remotely navigate a robot to explore an unknown environment, learning the layout as well as searching for exists and dangerous objects. They were then asked to draw the layout of the area and mark out exists and dangerous objects on the map they made. It was found that with the previous route map available, participants resulted in better understanding of the layout as reflected by the quality of the maps they made, compared to those that received no external information. It was also found that even with more information to perceive and process for the users of the enhanced interface, efficiency and subtask performance stayed the same as those who had less information to perceive or process. Results of this study proved the effectiveness of the proposed enhancement.

Introduction
Human-robot collaborated wayfinding
In most human-robot collaboration that is focused on exploring, human operators are usually responsible for navigating the robot. At the very least, human operators supervise the robot as it autonomously searches an area. In this case, the operator typically gains an understanding of the layout of that area and the location of objects of interest. The definition for “wayfinding” varies depending on the context. In the above scenario, it can be defined as “goal-directed search in an unfamiliar environment” (Wiener, Buchner, and Holscher 2009). The wayfinding discussed in this study occurs in a human-robot collaboration scenario, in which human operators are separated from the environment where the wayfinding takes place. Therefore, it is referred to as remote wayfinding.

Difficulties in remote wayfinding can be broken down into two types: 1) classic wayfinding, and 2) remote perception. Classic wayfinding refers to the difficulties existing even when someone explores an area with themselves physically being there, while remote perception refers to the perception difficulties that arise when an observer is separated from the environment.

One of the greatest challenges in classic wayfinding is orientation: awareness of heading direction, current location, as well as current location relative to other places. This is fundamental information required in wayfinding Montello and Sas 2006). Disorientation is common among people even in daily life (Hegarty, Richardson, Montello, Lovelace, and Subbiah 2002). Disorientation not only directly affects wayfinding, but also easily leads to anxiety, frustration, and tardiness which increases a person’s mental workload, resulting in deteriorated wayfinding performance.

Remote wayfinding tasks are more cognitively demanding because wayfinders cannot directly go into the environment, but instead observe everything through cameras and/or other sensors. Perception is impaired in both quality and quantity. Limited field of view (FOV), unnatural viewpoints, and degraded image quality all resulted in greater levels of difficulty related to perceiving and understanding the environment (Chen, Hass, and Barnes 2007).

Riley and Endsley (2004) performed an observational study and found that orientation awareness was the most challenging part of human-robot collaborated wayfinding. The preponderance of the evidence indicates that remote wayfinding presents a host of issues that can easily lead to increased cognitive load and increased human error/confusion and disorientation.

Enhancing Orientation Awareness
Wayfinding tasks require the development of spatial knowledge related to a region. This knowledge includes the layout and location of objects in that region. A wayfinder needs to constantly maintain and update a cognitive map which is the mental representation of a region’s spatial information (Tolman 1948) in his/her memory system. Human working memory capacity is limited and requires special processing to convert information in working memory to long-term memory. This is a highly cognitively demanding task. In remote wayfinding, apart from the cognitive load for processing and maintaining spatial knowledge, additional cognitive resources are required due to the remote nature. It leads to less information being available due to narrower FOV caused by the limitations of the camera; and it leads to inaccurate information gained from things like scale ambiguity where the wayfinder’s perception of objects’ width relative to self-dimension is inaccurate (Tittle, Roesler, and Woods 2002). Therefore, it becomes even harder to maintain and update the cognitive map as a result of both insufficient information and divided cognitive resources.

A map is an external aid for forming, maintaining, and updating the cognitive map in one’s head as it provides a
global view of a region, helping with route planning before wayfinding activity. Even with a map, a human still needs to form a cognitive map, which is their own understanding of a region in their head. This process, however, can be less cognitively demanding with the presence of a map because the physical map serves as a reference with which a cognitive map can be built upon. With this aid, knowledge in the head is transferred to knowledge in the world (Norman 1998), thus relieving one’s cognitive workload.

However, one difficulty of the human-robot collaborated wayfinding lies in the area to be explored being completely unknown. This means that the human has no a priori knowledge, specifically, no understanding of the layout and they have no physical external map to reference. As a substitute for the map, a real-time route map which shows the previous route taken during exploration is proposed by this study. Darken and Peterson (2001) suggested that trails/footprints were helpful, especially for wayfinders, to recognize if they had been to a place and the travelled direction in exploration. But, they also pointed out that simply leaving a trail is marginally useful. It was also suggested by their study that directional information, such as a compass, should be used in combination with positional information. Taking these two suggestions into consideration, it can be projected that the real-time route map would be a helpful tool for gaining and maintaining orientation awareness during remote wayfinding. Moreover, if the route taken follows every wall in a region, the route map is also able to reflect the region’s construction.

This allows us to pose the following question: how much information is needed for that route map? Meilinger, Holscher, Buchner, and Brosamle (2007) compared a standard floor plan with schematized route maps at different levels of abstraction. It was found that providing less than standard information lead to better performance and that the most crucial information needed was turning information. This finding agreed with Butler, Acquino, Hissong, and Scott’s study in 1993 that found users who were provided with directional signs resulted in better performance when compared with “you-are-here” maps. They argue one of the possible reasons lied in the amount of information a person had to process when using a detailed floor plan. This study will focus on providing precise turning history along with exploration with an approximated travelled distance.

Research question and hypothesis

This study focuses on the orientation awareness of wayfinding in human-robot collaborated exploration. Specifically, it is hypothesized that orientation awareness is significantly enhanced with the presence of a real-time route map during wayfinding, in terms of a more accurate sense of current heading/direction as well as a more accurate understanding of the area layout.

Method

Participants

Fifteen college students participated in this study. They were randomly assigned to one of the following groups: unaided-wayfinding group or aided-wayfinding group. The unaided group consisted of three males and five females while the aided group consisted of three males and four females.

Independent variable

The independent variable in this experiment was the presence of a route tracking map: the unaided-wayfinding group only had an interface showing the video sent back from a camera mounted on the robot while the aided-wayfinding group was presented with both video and a route map showing the path which the robot traveled.

Dependent variables

The dependent variables in this experiment were: 1) Efficiency, measured by the time to completion, 2) Number of objects/exists identified during exploration, and 3) orientation awareness, measured by the quality of the map drawn by each participant after the exploration.

The orientation awareness was further decomposed into three factors: 1) logic accuracy: this is the primary indicator for the accuracy of a participant’s perception of the layout. The researcher first compared each wall drawn by a participant with the existence of a wall at the same location on the actual floor plan. If they match, it counted as 1 point, otherwise, 0 points. Upon analyzing every wall drawn by participants, the research calculated the percentage of total points earned over the actual total number of walls (24).

2) Orientation score, indicating a participant’s ability to recognize the overall layout relative to the starting direction. On the empty map give to participants, the entrance and the starting heading direction was indicated. If the layout drawn by a participant was in accordance with them, then orientation score was 1 point; otherwise 0 points as it showed the participant failed to recognize objects’ location relative to the starting position and direction.

3) Location score, demonstrating the accuracy of a participant’s memory of objects and exit locations. This factor was calculated by summing up all the correctly located objects and exists marked on the map.

Interface design and experiment setting

The robot used in this study was the boe bot from parallax equipped with XBee 1mW Wire Antenna RF module and Honeywell HMC5883L compass module. A joystick was used to control the robot. An interface was designed and implemented using C# and PBASIC languages. For the unaided group, only joystick status and camera view were provided on the interface. For the aided group, current heading angle and previous route were provided in addition to those displayed for the unaided group (Figure 1).

Users could also save the current route map and clear the screen for generating a new route map by clicking two buttons (save map and clear map) provided on the interface. The route map was drawn according to the real-time reading of a compass and the duration of participants holding the joystick in forward/backward position. Therefore, the directional information was accurate while the distance traveled in each direction was an approximation.

An area for wayfinding was designed and constructed by the research (Figure 2 and Figure 3). It had two exists and one
entrance where the wayfinding started. Five red objects were placed in different corners within the area which served as dangerous objects within the area with one green object serving as a distraction object.

Procedure

Participants were asked about their gaming experience and frequency of use before they participated in the experiment. Each participant’s spatial ability, specifically spatial visualization ability and visual memory ability were tested using punch-hole paper folding test and building memory test, respectively. In the paper folding test, participants were shown a series of pictures demonstrating how a squared paper was folded and punched by a pencil. They were then asked to imagine how the paper would look after unfolding it. In the building memory test, participants were first given a map with 12 buildings on it and required to memorize locations of each building. Four minutes later, participants were given a list of buildings and an empty map which were the same as the map they just saw. Their task was to mark all the buildings on that map. These two tests were selected because, in this experiment, participants’ ability of transferring three-dimensional information into a two-dimensional representation, as well as their memory of object location, were important.

Prior to the experiment, participants were first told about the tasks they were to perform: 1) learning the layout of that area and draw a map after the exploration, 2) looking for exists and dangerous objects represents by any red-colored object. Then they were given two sections of practice: in section 1, participants are allowed to watch the robot directly while they were driving it, so that they could understand how the robot would respond to their control; in section 2, participants had to drive the robot remotely, only being able to observe the environment through camera mounted on the robot. For participants in the aided group, they were educated with the features provided on the interface during practice section 2.

Upon completion of practice, participants were asked to explore the area with unlimited time. Whenever they felt they had gained enough information for drawing the map, they could terminate the exploration. A piece of engineering paper in which the frame of area drawn and starting position and direction had already been marked on was given to participant for them to draw the layout on it.

Result

Orientation awareness

Orientation awareness was decomposed into three factors: logic accuracy, orientation score, and location score, all of which were obtained from the map drawn. A series of two sample t-tests were performed to compare group means for each variable. The results are presented in the table below.

<table>
<thead>
<tr>
<th>Variable</th>
<th>t-Value</th>
<th>p-Value</th>
<th>Lower 95% CI</th>
<th>Upper 95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Logic accuracy</td>
<td>t(1,13)=</td>
<td>0.05*</td>
<td>-48.58%</td>
<td>0.00%</td>
</tr>
<tr>
<td>Orientation Score</td>
<td>t(1,13)=</td>
<td>0.02*</td>
<td>-1.08</td>
<td>-0.13</td>
</tr>
<tr>
<td>Location Score</td>
<td>t(1,13)=</td>
<td>0.13</td>
<td>-3.88</td>
<td>0.56</td>
</tr>
</tbody>
</table>

Logic accuracy. Significant difference between the unaided and aided group was found. Group mean for the aided group was 51.21% while that for the unaided group was 27.08%. It showed that with the previous route information, accuracy of map was increased by 4.13% with a 95% confidence interval being 0% to 48.58%.

Orientation score. The sense of orientation was also significantly improved with the route map. While only 2 out of 8 participants in the unaided group correctly recognized the layouts orientation relative to the given starting direction, only 1 out of 7 in the aided group failed to figure this out.
Location score. Since there were 5 dangerous objects and 2 exists in the region, the full score for location score was 7. Participants’ memory about objects and exists location was not significantly affected by the presence of route map.

Wayfinding efficiency
Next, we tested how our enhanced interface affected wayfinding efficiency. A two-sample t-test was conducted to compare the group mean of time to completion. There was no significant difference between the two groups in the time spent on exploration, indicating that with more information to perceive and process, the wayfinding was equally efficient as compared with wayfinding without any aid. This result indicated the route map information did not significantly affect the cognitive workload during wayfinding.

Objects identified
A two-sample t-test was employed to examine the impact of the enhanced interface on the number of objects/exits identified during wayfinding. No significant effect of the presence of heading angle and route map on objects and exits identified during exploration was found. This was not surprising as the interface was not designed for enhancing performance in this aspect. Similar to what can be inferred from the result of time to completion, this result also indicated that the extra information displayed for the aided group did not require significantly more cognitive processing from users.

Spatial ability
Two two-sample t-tests were used to examine the participants’ spatial ability difference on the result of each test separately.

Paper folding test: No significant difference was found between the two groups, indicating participants in both groups had equal spatial visualization ability.

Building memory test: Participants in the two groups had significantly different visual memory test (p=0.02). The result of the 95% confidence interval showed that participants in the unaided group scored 10.61 to 1.18 lower than those in the aided group.

Correlation between spatial ability and performance:
A series of correlation tests were then performed to investigate if any correlation existed between each factor in the spatial ability and each factor of orientation awareness. No significant correlation was found between any pair.

Discussion
This study proved that orientation awareness, including awareness of a region’s layout and sense of orientation could be significantly enhanced by providing a real-time route map during wayfinding. When drawing the map, participants in the aided group had their previous route available for reference. This enabled them to compare what’s in their head to an external objective recording, which also helped them to recall what had happened during the wayfinding. The participants in the unaided group, however, had to memorize everything by themselves. Therefore, they tended to miss more information or had inaccurate information stored.

While it has been pointed out by several studies that maps usage requires users spatial ability and mental effort to transfer from a two-dimensional representation to a three-dimensional structure from an egocentric (first-person perspective) view of objects and their locations (McGee 1079; Thorndyke and Stasz 1980; Butler et al. 1993), tasks in this study requires the converse: converting a three-dimensional representation to a two-dimensional drawing. Few studies have looked into this problem but it can be inferred that their level of difficulty are similar. The route map, not only helps store information, but also makes that transformation for users.

This study provided a general conclusion on the effectiveness of providing route maps, yet there are still questions regarding this enhancement. Referring to the route map while drawing the layout is a task similar to observing remote environments when presented with both egocentric and exocentric (third-person perspective) views. Studies have shown that difficulty in integrating information from both views arose, especially when the exocentric view is presented in an angle that is different from that of the egocentric view (for example, in the egocentric view, the robot is heading east but the exocentric view is north-up (Chadwick and Pazuhancies 2007)). In the current study, participants needed to integrate both route map and their cognitive map which might not necessarily be in the same angle or even of the same dimension. Moreover, the route map is different from an actual map. In fact, they are opposite in that lines in route maps actually indicated hallways in a layout map. One participant in the aided group came up with a wired layout map. From the conversation after experiment it was found out that this participant was confused by the difference between a route map and a layout map.

Another important observation is that the usefulness of the route map is affected by users’ wayfinding strategy. As mentioned in the introduction, if the route taken follows each wall in that region, then the route map will be a precise reflection of the region’s construction. During the experiment, participants employed various strategies. In general, they can be generalized in two categories: top-down and bottom-up. Some participants travelled along the frame walls of the area first, noticing the number and location of each room, and then explore those rooms one by one. This strategy is called top-down. Other participants travelled from room to room and then put each piece of the puzzle together, which is referred to as bottom-up. Constrained by the approximated travel distance on the route map, the bottom-up strategy resulted in intricate maps which were less helpful. However, this limitation can be overcome by improving the precision of the route map.

Conclusions and future work
This study proposed an enhancement for orientation awareness in human-robot collaborated wayfinding, evaluated, and proved its effectiveness. It was proven that with a real-time route map, users were able to gain better orientation awareness in terms of overall layout and direction. Results of this study can be applied to a variety of human-robot collaboration tasks, including urban search and rescue, military reconnaissance, and other tasks requiring exploration.
As augmented reality technology advances, this idea can also be utilized in traditional wayfinding aided by augmented reality.

References


