DESIGNING FOR SPATIAL ORIENTATION IN ENDOSCOPIC ENVIRONMENTS

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Disorientation or “getting lost” in colonoscopy is common experience even for expert endoscopists. This paper describes a new navigational aid display concept for colonoscopy and presents results of an experiment conducted to evaluate the usefulness of various types of spatial information for supporting navigation and spatial orientation in colonoscopy. Six combinations of 1) direction, 2) location, and 3) shape information were tested. Results show that even though the new navigational aid display concept did not improve navigation performance, spatial orientation error and workload were reduced significantly. This new navigational aid display which provides shape combined with location and direction information in a perspective view and in real time is a useful tool for colonoscopy.

INTRODUCTION

Colorectal cancer is the second leading cause of cancer death in Canada (National Cancer Institute of Canada, 2001). Colonoscopy is now widely used in the investigation of suspected colorectal disease, and as a screening procedure for high-risk individuals (Lieberman et al, 2000). Colonoscopy is a diagnostic and therapeutic procedure performed to examine the inner wall of the colon for lesions and tumours. Inspection of the colon is done using a flexible endoscope, about 180 cm long and 2.5 cm in diameter, inserted into the patient’s rectum and pushed along the length of the colon until it reaches the caecum (Figure 1). The task of navigating the endoscope in the colon is guided by the egocentric view obtained from a camera at the end of the scope. Disorientation or “getting lost” is one of the greatest problems in performing colonoscopy (Cao & Milgram, 2000, Cotton & William, 1990). Disorientation can lead to incomplete examination of the colon and missed detection of lesions, or incorrectly locating a tumour for surgery.

Cao and Milgram (2000) reported several factors that contribute to disorientation in colonoscopy: lack of physical/motoric control and manipulability, a dearth of meaningful perceptual information, and high cognitive demands. Mechanically, the endoscopist has little control over the behaviour of the shaft of the flexible scope within the elastic and floppy colon. The scope can become twisted and entangled in the floppy sections of the colon. Perceptually, there is a lack of cues, both visual and haptic, to provide information about the progress of the procedure. There are few, and often inconsistent as well as variable, landmarks in the colon to support spatial orientation. Also, the physical length of the colon can be stretched or ’accordion-ed’ over the scope such that the length of the scope inserted is not a good indication of location in the colon. Cognitively, the task of integrating the highly unreliable information available is difficult and filled with uncertainty. Navigating through the colon is a difficult skill that involves, in addition to medical knowledge and experience, spatial cognition — being able to maintain a mental representation of the spatial relationships in the colon, and visuomotor co-ordination. Without a direct view of the colon and the endoscope, the endoscopist relies on guesswork to infer the location of the scope, or the location of a lesion. Therefore, a navigational aid designed to provide the necessary information for the endoscopist to localise and orient accurately within the colon is expected to improve the safety and outcome of the procedure. Currently, no navigational aid is available for colonoscopy.

NAVIGATIONAL AID DESIGN

Navigation and Spatial Orientation

Navigation is the process of directing the movements of a craft or ship from one point to another. Spatial orientation refers to the way one determines one’s location in the environment. Successful navigation often implies being able to orient oneself within the environment (i.e., determine where one is relative to objects in the environment, and how one is to move amongst these objects in a particular path without
getting lost). However, it is possible to navigate and travel to the destination without knowing, along the way, where one is within the environment in a global sense. One can merely follow a set of directions using landmarks as signposts and manage to move from A to B without any sense of global orientation along the way. Therefore, spatial orientation can be performed on a local level as well as on a global level. *Local orientation*, in the local immediate surround, is taken here to be distinct from *global orientation*, which involves a global sense of position and direction.

Generally, when people acquire geographical or spatial knowledge, the amount of exposure or experience navigating through the environment determines the level of detail contained in their mental representation, or cognitive map, of the space. With initial exposure, *landmark knowledge* is acquired, which allows ego-referenced way-finding. Further experience travelling through the environment allows for development of ego referenced *route knowledge*, which is more rapid and automatic for navigation. Finally, *survey knowledge* integrates the landmark and route knowledge about an environment and represents the space as a more world referenced cognitive map (Thorndyke, 1980, cited by Wickens and Carswell, 1997). A good cognitive map allows us to determine quickly and efficiently ‘where’ we are, and ‘how’ to get to where we want to go from here.

In designing tools to support navigation, one aims to give the traveller the advantage of experience which can be gained only through extended exposure and learning through trial and error. Navigational aids can take on many different forms, from maps (paper, electronic, You-Are-Here, etc) to route lists, to signs, compass, GPS, etc. The choice of navigational aid used depends on the nature of the task goals: travel, understanding, problem solving, planning, etc. (Thorndyke & Hayes-Roth, 1982). The best tool is the one that supports the task by simplifying the cognitive transformations required (Aretz, 1991, Wickens, 1998). For example, a route list (e.g., “turn left at the stop sign, go for 2 miles, then turn right”) is good for guiding travel along a path while en route, but not for a traveller who has wandered off the path and must find his way back. Similarly, a paper map of the city is good for helping the traveller understand the spatial layout of the environment and select routes for travel. However, this is only useful if the traveller can establish his own position and orientation on the map.

The requirements for the design of a navigational aid were determined based on a field study of colonoscopy (Cao & Milgram, 2000). The field study determined that, among other factors, the flexible endoscope, compounded by the non-rigid and stretchable nature of the colon, was a major contributing factor to disorientation in colonoscopy. The endoscopist’s task of navigation was performed on two different levels. On the level of *local* way-finding, knowing the local orientation is important (“which direction am I heading?”). Independently, the second level concerns *global orientation* (“where am I in the colon?”).

The key, therefore, to successful navigation in colonoscopy is to provide endoscopists with the missing information necessary to support global and local orientation, such as the location and direction of the end of the scope in the colon. Furthermore, as the configuration of the colon changes with each manipulation of the scope, the endoscopist is essentially dealing with an unstructured spatial layout. Therefore, information about the shape of the colon/endoscope should be helpful in supporting spatial orientation. This can serve to minimise uncertainty in deducing the situation, and in reducing the cognitive load required for mentally integrating the observed video images with the internal representation of the remote workspace.

**Design Concept**

Ideally, a 3-D global map of the colon, with a see-through view of the endoscope inside the colon would solve all the problems of localisation, orientation, untangling loops formed, and stretching the colon past its limits. Such a tool would be equivalent to continuous fluoroscopy. In the real world, a good solution would provide the critical information for maintaining spatial orientation without imposing additional processing demands on the endoscopist, and without utilising too much additional computing power. At the same time, it could be implemented without affecting patient outcome.

The optimal solution has the following characteristics. First, a fixed global “map” of position and direction in the colon would be provided to complement the egocentric view of the endoscopic image. Second, as the endoscopists all use 2D front or view of the colon as the common frame of reference when referring to the colon, this orientation with the head of the patient at the top of the display, the feet at the bottom, and the left side of the patient on the right side of the display, would be the most meaningful and least confusing. Third, instead of a planar view of the colon as it lies in the patient’s abdominal cavity, a perspective view, as if viewed from the endoscopist’s stance at the feet of a supine patient, would enhance the depth dimension of the colon within a 3D abdominal cavity. (See Figure 2a).

To obtain the position, heading, and shape information of the endoscope, a shape sensor is used. This shape sensor, the SHAPETAPE (model S1280CS), is made of a series of fibre optic sensor pairs, encased in a narrow strip of flexible plastic and elastomers. The optical fibres are configured to measure twist and bend. There are a total of 16 pairs of sensors placed 6 cm apart along the length of the tape. Analogue sensor signals are digitised and used to calculate the position of each sensor pair relative to the first proximal pair of sensors. Thus, by coupling the SHAPETAPE to the endoscope, the position, direction, and shape of the endoscope were tracked by the SHAPETAPE in real-time. An SGI O2 workstation was used to generate a graphical model using imaging software written in C++ and OpenGL. The shape of the tape was rendered in real time as a cylindrical object with a tapered end, on a perspective grid plane (see Figure 2a). The graphics depicting the scope was rendered in cyan, while the background of the display was in grey. The display space above the grid represented the abdominal cavity (size of space and graphics were scaled to the scope and task space). Information displayed showed the beginning of scope starting at the insertion point and the length of the scope inside the colon in real-time in the display space.
EXPERIMENT

The objectives of this experiment were two-fold. The primary objective was to evaluate the effectiveness of the display concepts for navigation and spatial orientation in colonoscopy. The secondary objective was to validate the hypothesis that shape information is critical for accurate spatial orientation in non-rigid endoscopic environments. In particular, this experiment was designed to demonstrate the relative importance of three types of spatial information for the design of a useful navigational aid: direction, location, and shape. It was hypothesised that navigation was more difficult and spatial orientation was more cognitively demanding in the non-rigid colon than the rigid colon, and that shape information was more useful than direction and location information alone in a navigational aid display for colonoscopy.

Method

Subjects. Ten subjects (3 female and 7 male graduate and undergraduate students at the University of Toronto) participated in this study. Subjects were paid $20 for their participation.

Apparatus. A mock-up of an endoscopy unit was set-up with endoscopy equipment and a simulated colon. To address the rigidity issue, a rigid and a non-rigid colon models were built and used as the task environment. Details of model construction are reported elsewhere (see Cao, 2001). The non-rigid colon model was representative of the real colon environment in visual appearance and mechanical compliance as experienced through an endoscope. The rigid colon was identical in visual appearance, but was not compliant. Their high degree of realism was validated by two expert endoscopists.

Equipment. A 180-cm diameter video colonoscope (Pentax EC-3830L), a Pentax EPM-3300 video processor and light source were used. A 27-in Sony PVM monitor was used to display the endoscopic image and the navigational aid display in a split screen. The navigational aid display was placed as an inset in the upper right hand corner of the screen.

Navigational aid displays. The original display, “Rearview + Compass” display, shown in Figure 2a, was modified to remove direction and location information to yield the following: “Rearview” display (Figure 2b), “Radar + Compass” display (Figure 2c), “Compass” display (Figure 2d), “Radar” display (2e), and “No Aid” display (2f). Each display provided varying amounts of spatial information with respect to the direction, location, and/or shape of the endoscope in real-time.

Task. The task was a modified colonoscopy procedure in the simulated colon using the endoscopic image plus one of the six navigational aid displays. Subjects were asked to guide the scope from the ‘rectum’ to the ‘caecum’ as quickly and as safely as possible, as in a real colonoscopy. Unbeknownst to the subjects, the trials always stopped when the splenic flexure was reached, even though subjects were told that the trials ended at random points during the procedure, and that no trials would reach the end of the colon.

There were two subtasks: navigation, and spatial orientation. The navigation subtask was essentially a wayfinding and travel task. The spatial orientation subtask was primarily a global orientation task. Subjects were told that in addition to good performance with the scope (i.e., reach the end quickly and safely), they were required to keep track of how far they have gone in the colon. At the end of the trial, the displays were turned off and subjects were asked to indicate the location of the end of the scope inside the colon.

Experimental Design. A 2X2X6 (colon rigidity X order X display) within-subjects design was used in this experiment. Each of the 10 subjects was exposed to all 6 displays in both the rigid and non-rigid colons. The order of colon was counterbalanced. The order of display presentation for each subject in each colon condition was randomised, with no repeats of the order. Subjects were given one practice trial with the “Rearview + Compass” display. For each subject, data were collected for one trial per condition, for a total of 12 trials.

Dependent Measures. Performance measures were time to task completion, accuracy of localisation. Accuracy in localisation was measured at the end of each trial. The responses were made by marking an arrow on a pen-and-paper drawing of the colon to indicate position inside the colon. Subjective measure of confidence rating was collected at the same time. Subjects were asked to provide confidence rating for their responses on a 5-point Likert scale. A rating of 1 indicated low confidence that the location was correct, whereas a rating of 5 indicated high confidence of a correct location.

Localisation error was measured manually. The markings made by subjects on the paper drawing of a colon were converted into digital form. The individual drawings plus markings were scanned into the computer using MS Photo Editor, and digitised manually to calculate the error in absolute distance.
As for the measure of cognitive effort involved in spatial orientation, the variable used was mental workload, assessed using the standardised NASA TLX questionnaire (Hart & Staveland, 1988). At the end of each trial, subjects were asked to fill out a NASA TLX questionnaire, using all six dimensions of mental demand, physical demand, temporal demand, performance effort and frustration.

Other subjective measures included preference rankings and usefulness ratings of the navigational aid displays. At the end of the experiment, subjects ranked order their preference of the 6 navigational aid displays (from 1 to 6: most preferred to least preferred), and rated the usefulness of the displays on a scale from 0, very useless, to 10, very useful. This was followed by a debriefing session.

RESULTS AND DISCUSSION

An analysis of variance was performed on the variables of time, localisation error, workload and confidence rating.

As expected, results showed that navigation in the simulated colonoscopy task was faster when performed in the rigid colon (F=8.908, p=0.017). There was a significant order effect (F=23.149, p=0.001) and a significant order x rigidity interaction (F=9.09, p=0.017). Figure 3 shows the average task completion time for the two groups of subjects in the two colons. Subjects who started with the non-rigid colon improved upon switching to the rigid colon, suggesting that the non-rigid colon was more difficult to navigate. On the other hand, the group that started with the rigid colon showed no changes in its performance after switching to the non-rigid colon. The fact that performance did not worsen upon switching to the non-rigid colon suggests a learning effect. However, this training effect may be due to the fact that the subjects were not trained endoscopists. Nevertheless, there would appear to be a benefit in training with the rigid colon before attempting the non-rigid colon.

Contrary to expectations, the accuracy of spatial orientation performance did not differ in the two colon conditions. However, there was a display main effect (F=3.608, p=0.009). A post-hoc Tukey multiple pair-wise comparison showed that performance using the “Rearview + Compass” display was significantly different from the “No Aid” display. Thus, localisation was most accurate using the “Rearview + Compass” display, which provided shape, direction and location information, and least-accurate using the “No-aid” display (Figure 4). The other displays that provided a subset of the 3 spatial information were not different from one another. This suggests that for localisation in the colon, location, direction or shape alone is not enough.

Subjects’ confidence in the accuracy of their localisation was also significantly different as a function of display (F=6.973, p=0.000). A post-hoc Tukey multiple pair-wise comparison showed that confidence using the “No Aid” display was lower than all other displays except the “Radar” display and the “Compass” display. There was also an interaction between colon rigidity and display (F=3.406, p=0.012). Figure 4 shows an approximate mirror image in the correspondence between accuracy and confidence as a function of display. It suggests that as more spatial information was provided, accuracy in localisation was higher, and subjects were more confident about their spatial orientation.

Similarly, workload assessment showed no significant difference between the rigid and non-rigid colons. However, averaged over order and colon conditions, the workload measures as a function of display were significantly different (F=3.284, p=0.014). A post-hoc Tukey multiple pair-wise comparison showed that the difference was between the pair “Rearview + Compass” display and “Radar” display. This would imply that subjects found the Radar display the most difficult to use, even though it contained more information than the “No Aid” display. Most unexpected was the fact that the average workload assessed for the “No Aid” display was lower than the “Rearview”; the “Compass”; and the “Radar” displays (Figure 5). It is possible that while the “Rearview + Compass” display contained the most amount of information and imposed the least amount of workload, the other displays were considered more demanding to use because they lacked a ‘complete’ set of information when compared to the “Rearview + Compass”. When information is not explicit, such as direction or location information (in the “Radar” or “Compass” displays, respectively), workload was higher than...
if the information was made explicit ("Rear-view + Compass"). Therefore, the higher workload may have resulted from trying to fill in context. Probably, the No Aid display was ignored, as it did not offer any information. Thus, the overall workload was lower as subjects did not have to devote any attentional resources to the display. Based on this analysis, it would seem that providing incomplete information is more harmful than no information at all.

![Workload assessment as a function of display.](image)

**Figure 5.** Workload assessment as a function of display.

This explanation is supported by the subjects' rating of usefulness for the displays (Figure 6). The "No Aid" display was rated 1 (very useless) on an 11-point scale (0 to 10), while the "Rearview + Compass" display was rated an 8. The degree of usefulness decreased as the amount of information provided decreased. It also corresponded to the order of preference for the displays (Figure 7). All subjects preferred the "Rearview + Compass" display the most, while 80% of the subjects preferred the "No Aid" display the least. One subject preferred the "No Aid" to the "Compass", while another subject preferred it to the "Radar" display.

![Rating of usefulness for displays.](image)

**Figure 6.** Rating of usefulness for displays.

![Histogram of preference ranking.](image)

**Figure 7.** Histogram of preference ranking.

**CONCLUSION**

The results of this experiment have practical applications for the design of colonoscopy systems. The navigational aid display concept proved to be a useful one for spatial orientation in colonoscopy. Localisation errors in the colon were significantly reduced when the navigational aid provided shape information combined with location and direction information. Confidence in the localisation task was also higher with the navigational aid displays which contained shape information, and highest with all 3 (direction, location, and shape). Subjective ranking of preference and rating of usefulness indicated that more information was preferred. More significantly for future display design work is the result from workload assessment. Workload results showed that partial spatial information imposed higher workload than no information. Therefore, the minimum requirement for a useful navigational aid display in colonoscopy is to provide information of location, direction, and shape of the endoscope inside the colon. Even though the display may not help endoscopists perform colonoscopies faster, it may reduce the error and uncertainty in localising tumours.

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