Caroline G. L. Cao*
Department of Mechanical
Engineering
Tufts University
Medford, MA 02155

Paul Milgram
Department of Mechanical and
Industrial Engineering
University of Toronto
Toronto, Canada

Direction and Location Are Not Sufficient for Navigating in Nonrigid Environments: An Empirical Study in Augmented Reality

Abstract

Nonrigid environments, such as the human colon, present unique challenges in maintaining spatial orientation during navigation. This paper presents a design concept for presenting spatial information in an augmented reality (AR) display, together with results of an experiment conducted to evaluate the relative usefulness of three types of spatial information for supporting navigation and spatial orientation in a nonrigid environment. Sixteen untrained subjects performed a simulated colonoscopy procedure, using rigid and nonrigid colon models and six different AR displays comprising various combinations of direction, location, and shape information related to the scope inside the colon. Results showed that, unlike navigating in rigid environments, subjects took 44% longer to navigate the nonrigid environment and were less efficient, and suggested that it may be useful to train aspiring endoscopists in an equivalent rigid environment initially. A navigational aid presenting shape information was more beneficial than location or direction information for navigating in the nonrigid environment. Even though the AR navigational aid display did not speed up travel time, navigation efficiency and confidence in direction and location judgment for all subjects were improved. Subjectively, subjects preferred having shape information, in addition to position and direction information, in the navigational aid.

1 Introduction

The purpose of this paper is to report on an investigation of the importance of spatial information in an augmented reality navigational aid display for successful navigation and spatial orientation in a nonrigid environment. In particular, we present the results of our research on teleoperation within the human colon, a special class of remote environment that tends to change its shape not only during, but often as a result of, the act of traveling through it. Little research has been devoted to this topic, presumably because few real-world situations require the average traveler to navigate within an unstable environment.

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*Correspondence to caroline.cao@tufts.edu.

A large amount of research on spatial cognition and geographical orientation for human and nonhuman species can be found in the psychology literature, where much of what is known about how humans navigate without the aid of technology (maps, compasses, etc.) begins with observations of animals and children moving within real worlds. Commensurately, most of our knowledge about the use of navigational aids has been through studies focused on map use. Navigation and orientation have also been studied and described at various levels of abstraction across a wide range of domains, from seafaring to flying a plane to driving to Web browsing (e.g., Downs & Stea, 1973; Hutchins, 1995; Park & Kim, 2000; Wickens & Carswell, 1997). With the advent of technology that allows the controlled manipulation of robotic vehicles and effectors through remote environments, the literature on navigation has expanded to include both remote physical and virtual environments (e.g., Bowman, Davis, Hodges, & Badre, 1999; Chen & Stanney, 1999). Furthermore, the introduction of augmented reality displays has allowed us to exploit technology previously available only in virtual worlds to display complex navigational information through superposition onto otherwise exclusively real-world images.

Much of the research effort in virtual environments has been devoted to the design of realistic interactive techniques to increase one's sense of presence in virtual worlds, and within those studies the majority have attempted to maintain such constant features as the force of gravity or other bounding physical variables such as vertical walls of interior rooms or the presence of the sky above (e.g., Appleyard, 1976; De Jonge, 1962; Downs & Stea, 1973; Golledge, 1999; Hutchins, 1995; Lynch, 1960; Moar & Carleton, 1982; Montello, 1998; Pailhous, Lepecq, & Peruch, 1987; Wickens & Carswell, 1997). Furthermore, the spatial layout of the environment in those studies is typically constant and rigid. What happens when not only gravity or the sky is unavailable to be used as anchors, but also when the spatial structure of the environment changes unpredictably, such that the length of the route, as well as the location and appearance of the landmarks, change continually? In summary, little to no research has yet been carried out in flexible environments, such as the human colon, in which the spatial structure of the physical environment itself changes in response to physical forces exerted upon it by the navigator.

1.1 Navigating Within the Human Colon

Colorectal cancer is the second leading cause of cancer death in Canada and the US (National Cancer Institute of Canada, 2003; National Cancer Institute, 2003). Colonoscopy, a diagnostic and therapeutic procedure performed to examine the inner wall of the colon for lesions and tumors, is now widely used for the investigation of suspected colorectal disease, especially for high-risk individuals, and (in North America) as a general screening procedure for individuals over the age of 50 (Lieberman et al., 2000). Inspection of the colon is done using a flexible endoscope, about 180 cm long and 2 cm in diameter, inserted into the patient's rectum and pushed along the length of the colon until it reaches the caecum (a pouch at the end of the colon, where the large intestine begins). The endoscopic image is processed by a video processor and displayed on a monitor, typically with an adequate resolution and frame rate for successful visualization.

Even though colon cancer can be successfully treated in 90% of cases if detected at an early stage, the compliance rate in the United States for screening is only 30%. Resistance to regular colonoscopies is due, in large part, to the fact that the procedure is reputed in the eyes of many to be extremely uncomfortable, with the uncomfortable nature of the procedure being due, among other things, to the frequent need for trial-and-error poking and probing with the scope while negotiating the colon.

In carrying out the procedure, the endoscopist[1] must manipulate the scope to travel along the entire length of the patient's large colon, with essentially four degrees of

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[1] Note that this procedure can variously be carried out by colorectal surgeons, gastroenterologists, or general surgeons. For convenience, in this paper we shall simply refer to the practitioner as *the endoscopist*.

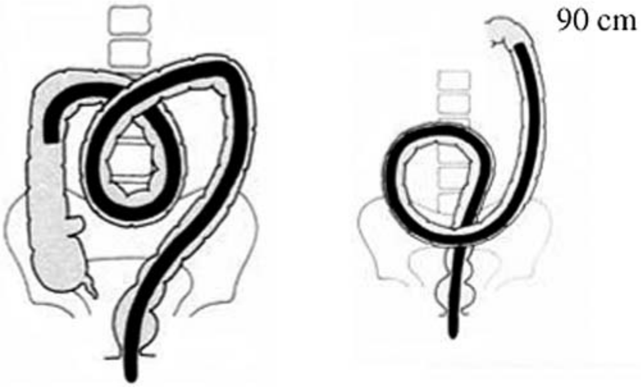


Figure 1. *Common loops in the colon during colonoscopy.*

control freedom available: longitudinal (pushing and pulling), roll (twisting the scope), and pitch and yaw (using independent knobs at the proximal end of the scope). As a consequence of coping with the many twists and turns while traversing what is essentially a landmark-less "tunnel," the endoscopist can become disoriented with respect to his or her location and orientation within the colon. Several factors contribute to this disorientation, including limited manipulability due to insufficient degrees of control freedom, the dynamic nature of the colon, and the lack of meaningful haptic feedback, in addition to a dearth of meaningful perceptual information for spatial orientation, resulting in high cognitive demand (Cao & Milgram, 2000). These combine to increase both the physical and mental workload for the endoscopist, not to mention discomfort for the patient.

Perhaps most seriously, *loops* can potentially form anywhere along the length of the flexible scope. In those cases where the colonoscope gets twisted into a loop (see Figure 1), pushing the scope further into the patient results only in enlarging the loop. Unfortunately, looping in the colon is surprisingly common, reportedly occurring in 91% of cases (Shah, Saunders, Brooker, & Williams, 2000). Even so, it is often difficult to detect looping just from the feel of the scope, due to the stiffness of the scope itself and the high tension developed once it has been twisted inside the colon.

From the endoscopist's point of view, the lack of full visual guidance in this procedure is often the key bottleneck determining the success of colonoscopy procedures. Occasionally the procedure is even abandoned before its completion because of difficulties in blind navigation. Disorientation, or getting lost, is consequently one of the greatest problems encountered in performing colonoscopy (Cao & Milgram, 2000; Cotton & William, 1990), leading to incomplete examination of the colon, potential missed detection of lesions, or incorrect locating of tumors for surgery. Navigating through the colon is therefore a difficult, visually guided motor skill that requires good visuomotor coordination and a high degree of spatial cognition, that is, being able to maintain an adequate mental representation of spatial relationships within the colon. While the lack of meaningful haptic feedback is certainly a deterrent to the task of manipulating the scope inside the colon (Boer et al., 1999; Howe, Peine, Kontarinis, & Son, 1995; Massimino & Sheridan, 1994; Rosen, Hannford, MacFarlane, & Sinanan, 1999; Salcudean, Ku, & Bell, 1997), the lack of adequate spatial information is critical to the endoscopist's ability to guide the manipulations. In fact, most endoscopists are not able to determine the state of the scope in the colon based on feel alone, as the resistance to scope advancement is high throughout the length of the colon (Cao, 2001). Without an outside-in, or exocentric, view of the colon and the scope, the endoscopist on occasion has to rely on guesswork to infer the location of the scope, and thus the location of a lesion.

It stands to reason, therefore, that a navigational aid able to provide the information necessary for the endoscopist to localize and orient accurately within the colon should significantly improve the safety, efficiency, and comfort of the procedure. Moreover, presenting that navigational aid at a location proximal to the primary colonoscope display, in a manner afforded by augmented reality, should be even more effective. To date, however, there has been limited effort invested towards the development of such navigational aids. Cirocco and Rusin (1996) have advocated the use of fluoroscopy to guide colonoscopic examination, as well as for learning scope intubation techniques. However, most hospitals do not have such equipment readily available in their endoscopy suites. Furthermore, some endoscopists find fluoroscopy too time-consuming, as it requires the interruption of the procedure to take the X-ray pictures, which in any case are only static 2D images. Also, the patient is exposed to excessive radiation with fluoroscopy.

More recent developments have steered away from the use of external radiation for tracking. Shah and colleagues have shown that, by using magnetic endoscope imaging, a non-radiographic technique for imaging the colonoscope shaft in real-time, performance of colonoscopy can be improved (Saunders, Bell, Williams, Bladen, & Anderson, 1995; Shah et al., 2000). In particular, they were able to present a computer generated 2D display of the shaft of the scope inside the patient, with anatomical markers to indicate the positions of various organs surrounding the colon, as well as gray shadings to create a 3D effect. The preliminary result, with one expert endoscopist, showed that, even though time to task completion was not reduced, the number of attempts at straightening loops in the scope was reduced.

Other researchers have experimented with mechanical solutions, such as a robotic colonoscope (Carrozza, Arena, Accoto, Menciassi, & Dario, 2003; Ng, Phee, Seow, & Davies, 2000), oblique transparent cylinders (Tsumura, Torii, Fujita, Takeda, Hikita, Nishikawa, Ochi, & Miura, 2003), and using a body with graduated stiffness to gain more control over the behavior of the scope (Brooker, Saunders, Shah, & Williams, 2000). Others have endeavored to circumvent entirely the need to perform colonoscopies by doing virtual colonoscopies (Bond, 1999), or by using wireless ingestible capsules (for small bowel inspection) (Iddan, Meron, Glukhovsky, & Swain, 2000; Meron, 2000; Sidhu, Sanders, & McAlindon, 2006). With the exception of the virtual colonoscopy technique, however, all of these proposed solutions do not address the problem of orientation in the navigation process, with or without loop formation.

1.2 Navigation and Spatial Orientation

Adopting the terminology of Golledge (1999), navigation, or wayfinding, is the process of determining and following a path or route between an origin and a destination. Successful navigation often implies being able to orient oneself within the environment, that is, determining where one is relative to objects in the environment, and how one can move among these objects or along a particular path without getting lost. Nevertheless, it is possible to navigate and travel to a destination without knowing along the way where in a global sense one is located within the environment. For example, one could merely follow a set of directions, using landmarks as signposts, to move from A to B without any real sense of global orientation along the way. In other words, spatial orientation can be performed on a local level as well as on a global level. In the context of the present study, local orientation, with respect to the local immediate surrounding, is taken to be distinct from global orientation, which involves a sense of position and direction with respect to one's larger environment or surrounding world.

Generally, when people acquire geographical or spatial knowledge, their accumulated 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 wayfinding. Further experience traveling 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 an essentially world-referenced cognitive map (Thorndyke & Goldin, 1983), which in turn allows one to determine quickly and efficiently where one is, and how to get to where one wants to go from here.

2 Design of a Navigational Aid Prototype

2.1 Design Issues

The goal of the navigational aid presented here is to help endoscopists with orientation and dealing with loops in the colon. It could also be used as a training tool for novice endoscopists. In designing tools to support human interaction with complex systems, one aims to give the human operator advantages that can be otherwise gained only through extended exposure and learning through trial and error. In other words, a well-designed tool will make explicit, to the novice, information that was otherwise vague, that requires a great deal of inference, or that needs to be derived indirectly from other pieces of information. Visualization, "a graphical representation of data or concepts" (Ware, 2000, p. 1), is one such technique that can be used to support decision-making, by lowering cognitive demands on the human operator. (On the other hand, a poorly designed tool can impose higher cognitive demands on the operator, requiring additional cognitive manipulations in order to derive the needed navigational information.) In order to make effective use of this principle in design, it is necessary, in general, to determine the nature of the task, the information requirements, the cognitive demands, and the constraints.

Navigational aids can take on many different forms, from maps (paper, electronic, etc.), to route lists, to signs. Chen and Stanney (1999) have classified navigational aids into five categories, according to their function: 1) tools displaying the navigator's current position (e.g., GPS coordinates); 2) tools displaying the navigator's current orientation (e.g., compass directions); 3) tools for logging the navigator's movements (e.g., seafaring charts); 4) tools demonstrating the surrounding environment (e.g., maps); and 5) guided navigation systems (e.g., arrows, signs, predictive displays, and autopilots). The choice of navigational aid used depends on the nature of the task's goals: traveling, understanding, problem solving, planning, and so on (Thorndyke & Hayes-Roth, 1982). For example, a route list (e.g., "turn left at the intersection, go to the stop sign, turn right") is good for guiding travel along a path while en route, but not for a traveler who has wandered off the path and must find his or her way back. Similarly, a paper map is good for helping the traveler understand the spatial layout of the environment and select routes for travel, but is useful only if the traveler is able to establish his or her own position and orientation on the map (Levine, 1982). Finally, a predictive display that shows the predicted path of travel can help the traveler maintain course by adjusting errors of position, direction, velocity, and/or acceleration (Chapman & Ware, 1992; Lintern, Roscoe, & Sivier, 1990; Morphew & Wickens, 1998; Wickens, Haskell, & Harte, 1989). Such information is especially useful for controlling higher-order and/or slowly responding systems, such as supertankers or submarines (Kelly, 1968). Of note is that all of these aids presume a spatially stable, if not static, physical environment, where the terrain does not alter its form with time or navigator action, which is not the case in a nonrigid environment such as the colon.

Since our primary goal is to provide endoscopists with a tool to aid in establishing and maintaining global orientation, the obvious choice is to provide the navigational aid in the form of a *map*. Furthermore, in order to determine the form of maps, it is necessary to understand the spatial information processing that takes place during navigation. In general, however, mismatched frames of reference have been shown to negatively affect navigation performance (Gugerty & Brooks, 2004; Levine, Marchon, & Hanley, 1984). In particular, the navigator must locate his or her position on the map and match that to the image available from his or her current viewpoint within the environment. This requires cognitive transformations that add time and effort to the navigation task. Consequently, any design that supports the task by simplifying these necessary cognitive transformations has the potential to be an effective aid. For example, Aretz (1991) found that, for pilots in a simulated flying task, a rotating track-up map aided navigation by eliminating the need for mental rotation. He also found that a wedge design, which indicated to the pilots the relationship between the forward field of view and the map, facilitated navigation because it reduced the time and effort spent in performing mental transformations to match the two views.

2.2 Design Requirements

The uniquely distinctive characteristics of nonrigid endoscopic environments, where landmarks are few and variable, and sometimes unavailable altogether, require that a navigational aid address spatial information needs that are not normally addressed by conventional maps. On the basis of a field study of colonoscopists (Cao, 2001; Cao & Milgram, 2000), it was determined that the endoscopist's task of navigation is performed at two different levels. At the level of local wayfinding, knowing one's local orientation is important, that is, "which direction am I heading?" (relative to the visible colon). Independently, the second level concerns global orientation, that is, "where am I within the colon?" It was also found that the flexible endoscope was a major contributing factor to disorientation in colonoscopy, and that this was compounded by the nonrigid and stretchable nature of the colon. This was further exacerbated by the lack of manipulability of the scope inside the colon, due to the incongruent mapping of the four control degrees of freedom to the resultant movements of the scope. That is, although the tip, or last 6 cm, of the scope can be steered in the pitch and yaw dimensions, the visual feedback resulting from these inputs becomes irrelevant once the scope has entered the colon and has been twisted several times.

In summary, spatial congruency between the endoscopic image and the external (body) frame of reference becomes extremely difficult to maintain. As the colon structure stretches and twists with each manipulation of the scope, the endoscopist is essentially dealing with trying to form a spatial cognitive map of an unstructured environment which itself is continuously changing in shape. These field study findings lead us therefore to hypothesize that information about the instantaneous *shape* of the colonoscope should be essential in supporting spatial orientation, in terms of minimizing uncertainty about the status of the scope, as well as reducing the cognitive load required for mentally integrating the observed video images with the endoscopist's internal conceptual representation of the remote workspace.

Ideally, an exocentric 3D global image of the colon, with a see-through view of the endoscope inside of it, somewhat akin to the illustrative sketch shown in Figure 1, would solve all the problems of localization, orientation, looping, and stretching of the colon, were such an image to be achievable. (In fact, such a tool would be equivalent to continuous fluoroscopy, a solution which, as discussed above, is unfortunately not feasible.) In the real world, a good solution would provide all critical information needed for maintaining spatial orientation without imposing additional processing demands on the endoscopist, in addition to not requiring too much additional computing power; while at the same time, the solution above all else, could be implemented without affecting patient outcome.

Given that a continuously refreshed fluoroscopy-like exocentric display is not feasible, the optimal solution, in light of our continued need to rely on the primary endoscopic image, should therefore have the following characteristics. First, a fixed global "map" of position and direction within the colon should be provided, to augment the egocentric view available from the existing endoscope image. Second, given that endoscopists conventionally all use the frontal view of the colon as the common frame of reference when referring to the colon, as illustrated in Figure 1, 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 2D planar view of the colon within the patient's abdominal cavity, a perspective view, as if viewed from the endoscopist's position at the feet of a supine patient, would enhance the depth dimension of the colon within a 3D abdominal cavity.

In accordance with these design requirements, it would therefore clearly be desirable to provide information to the endoscopist about the position and heading of the endoscope end point, as well as information about the shape of the entire endoscope. Technologically, in other words, some kind of a position-plus-shape sensor is required, that is, a device that would be analogous to a snake, that knows not only where its head is located and in which direction it is pointed relative to the world around it, but also what the shape is of its body trailing along behind it. Furthermore, in accordance with the endoscopist's need to maintain visual momentum while shifting gaze between the traditional colonoscope (real) image and the additional position-plus-shape (virtual) information, it is highly desirable that the two images be in close proximity, in a manner which approximates as much as is feasible an augmented reality display.

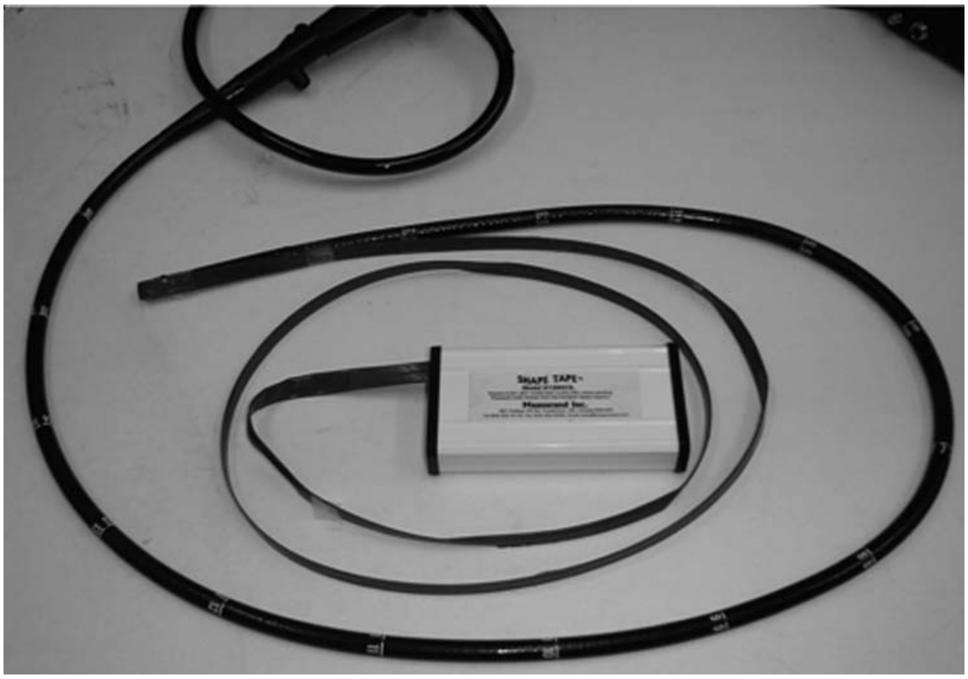


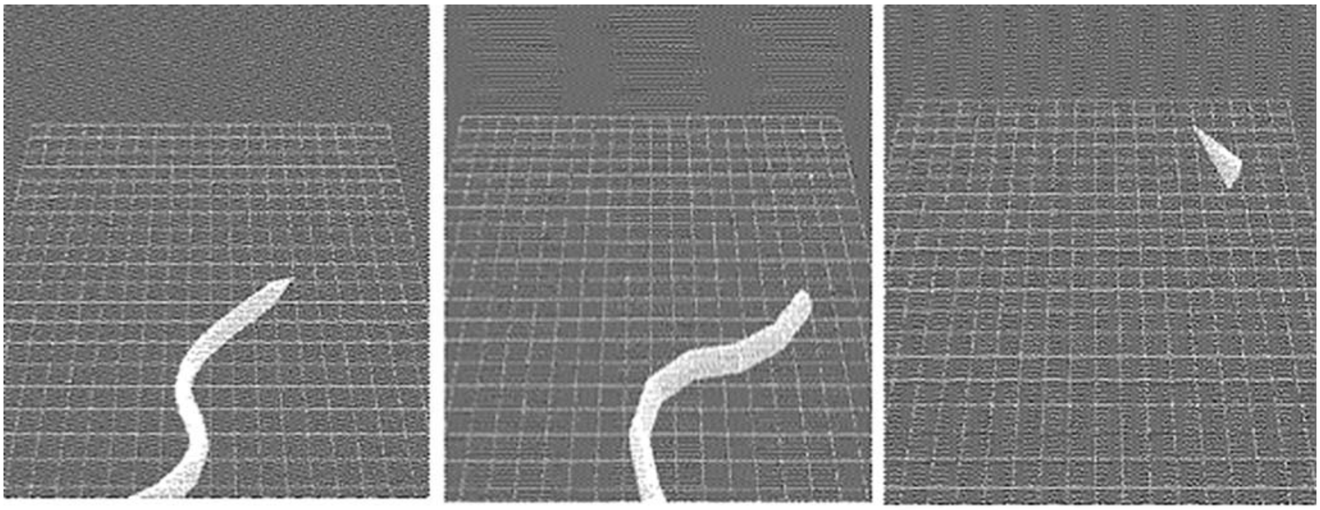
Figure 2. *Coupling of ShapeTape to colonoscope for tracking.*

2.3 Design Concept

To test our hypothesis, we made use of the ShapeTape sensor (model S1280CS, Measurand Inc., Fredericton, NB) for our display designs. The ShapeTape consists of a series of fiberoptic sensor pairs, encased in a narrow strip of flexible spring steel and elastomers, and configured to measure twists and bends. In the model we used, there were a total of 16 pairs of sensors placed 6 cm apart along the 96 cm length of the tape. Analog sensor signals were digitized and used to calculate the position of each sensor pair relative to the first proximal pair of sensors. For the prototype employed in the investigation reported here, an SGI O2 workstation was used to generate a graphical model, using imaging software written in C++ and OpenGL. The ShapeTape was coupled to an endoscope, allowing its position, direction, and shape to be tracked, in real-time, relative to an origin at the proximal end of the scope (see Figure 2).

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 3a). The graphic image depicting the scope was rendered in cyan, while the background of the display was in gray. The display space above the grid represented the abdominal cavity, with dimensions scaled to the scope and task space. By inserting the adapted scope into a simulated colon (see Section 3.1), information thus displayed showed the location of the beginning of scope, starting at the insertion point, as well as the length and shape of the scope inside the colon, all in real time.

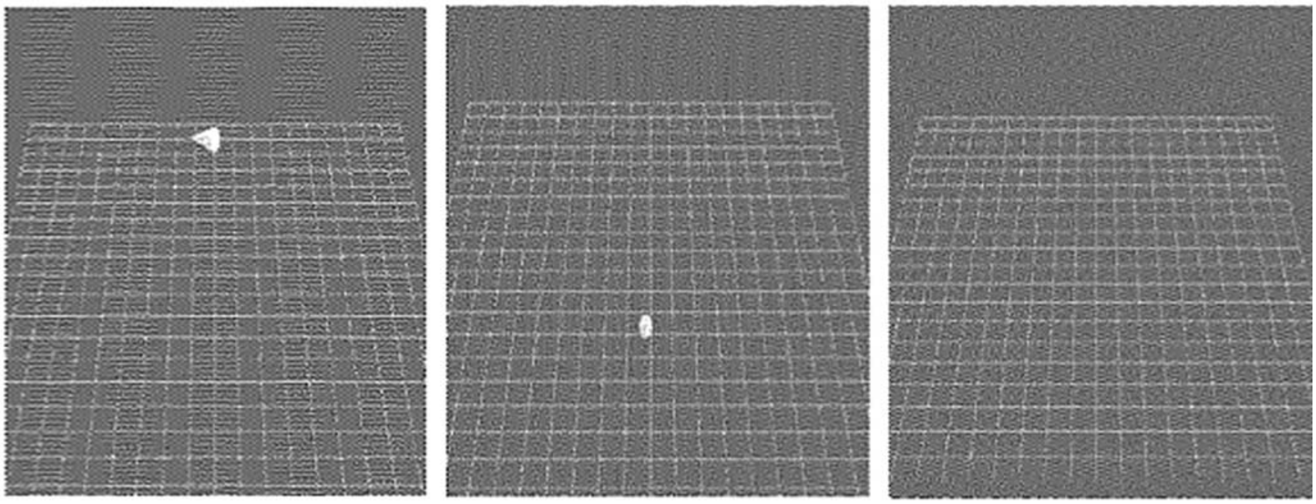
The display concept described above is illustrated in Figure 3a, and was dubbed Rearview + Radar + Compass (RRC), since, recalling our earlier analogy of the snake, it presented information about not only the location (radar) of the “head” of the snake, but also the direction (compass) it was facing, in addition to shape information (rearview) looking backwards along the snake’s body. This new display therefore contains *three* different types of real-time spatial information that have not conventionally been available to endoscopists: with respect to the location, direction and shape of the



a. Rearview + Radar + Compass (RRC)

b. Rearview (RE)

c. Radar + Compass (RC)



d. Compass (CO)

e. Radar (RO)

f. No Aid (NA)

Figure 3. *Proposed conceptual navigational aid displays for colonoscopy.*

colonoscope. In order to carry out a meaningful evaluation of this concept, however, it was deemed necessary to assess the relative value, if any, which is likely to be imparted by each of these three elements, as well as by combinations of these elements. With that in mind, the RRC display was modified, by selectively removing different combinations of these elements.

For the first comparative case, illustrated in Figure 3b, information about the head of the snake's location and direction was removed, thus creating a Rearview (RE) display. To obtain this display, the snake's head plus 6 cm of its "neck" were eliminated from the RRC display, thereby leaving only information about the shape of the snake's body, with no indication about the location or direction of the tip of the scope.

The converse modification is illustrated in Figure 3c, where the snake's entire body has been removed and only its head is shown. Dubbed the Radar + Compass (RC) display, this image was designed to impart location and orientation of the tip of the scope, without any shape information about the body behind.

Further breaking down the display elements, the Radar + Compass (RC) display in Figure 3c was separated into its component parts. The Compass Only (CO) display is illustrated in Figure 3d, showing only the direction faced by the snake's head, where it is important to note that, to eliminate location while retaining direction information, the compass arrow always appears at the same location, in the middle of the screen. The Radar Only (RO) display is illustrated in Figure 3e, showing only the location of the head, as a simple point, with no orientation (compass) information.

Finally, for the sake of completeness, a No Aid (NA) display, containing no spatial information, and thus corresponding to the status quo, was also investigated, as illustrated in Figure 3f. Note that only the combinations discussed here were relevant, due to the contiguous nature of the scope. That is, it is not possible to render shape and location of the tip without also implying the direction of the tip, nor is it possible to render the shape of the scope plus the direction of the tip without also showing the location of the tip.

3 Experiment

To evaluate the navigational aid display prototype, an experiment was designed, with two objectives. The primary objective was to evaluate the effectiveness of providing *any* extra navigation and spatial orientation information relative to the standard egocentric video images used in conventional colonoscopy. The secondary objective, as discussed above, was to evaluate the relative value of each of the three different components of spatial information potentially available during colonoscopy: location, direction, and shape. In addressing both objectives, it is important to keep in mind that our research pertains primarily to the problem of obtaining and maintaining an accurate mental model of spatial location and orientation in nonrigid endoscopic environments. In particular, it was hypothesized that navigation would be more difficult and spatial orientation cognitively more demanding in a nonrigid compared to a rigid colon-like environment. Secondly, it was hypothesized that, for navigating within such nonrigid colon-like environments, the provision of extra shape information would be more advantageous than either location or direction information.

3.1 Method

3.1.1 Subjects. Sixteen subjects (6 female and 10 male graduate and undergraduate students at the University of Toronto and Tufts University) participated in this study. Subjects were paid $20 for their participation. All subjects signed an IRB-approved informed consent form.

3.1.2 Equipment. A mock-up of a colonoscopy unit was set up, using regular clinical equipment, but a simulated colon. To address the rigidity issue, separate models were built to simulate both a rigid and a nonrigid colon. These models, shown in Figure 4, were used as the two independent task environments. As separately evaluated by two experienced colorectal surgeons, the nonrigid colon model was, to a first approximation, representative of the experience of manipulating a real colonoscope within a real colon environment, in terms of both visual appearance and mechanical compliance. The rigid colon was identical in visual appearance to the nonrigid one, but was not compliant.

A regular clinical colonoscope system was used, consisting of a 180 cm video colonoscope (Pentax EC-3830L), a Pentax EPM-3300 video processor, and a light source. A 27″ Sony PVM monitor was used to display the endoscopic image, together with the navigational aid display in a split screen, as an inset in the upper right hand corner of the screen, as shown in Figure 5.

3.1.3 Training. Subjects were given a short explanation of the anatomy of the colon using textbook illustrations, as well as a demonstration of how to use the colonoscope, and how to interpret the various images on the navigational aid display. Since field studies

Figure 4. *Models of nonrigid (left) and rigid (right) colon constructed for the experiment.*

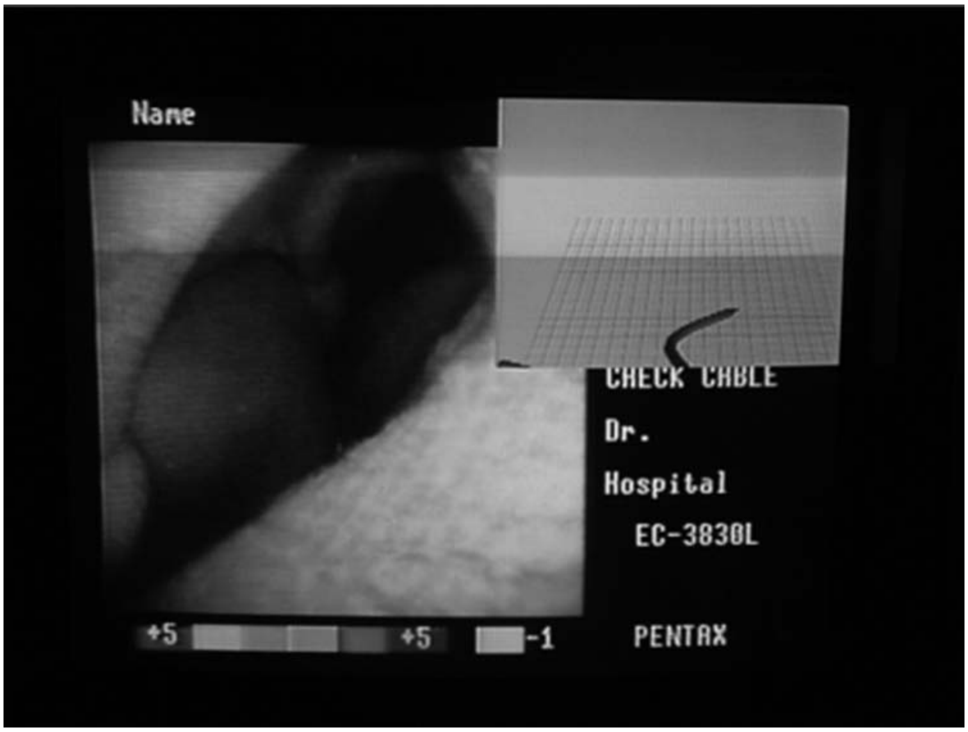


Figure 5. *Endoscopic view augmented with navigational aid.*

in local teaching hospitals had indicated that many colonoscopy procedures were routinely performed by Gastroenterology Fellows, who have not had extensive prior experience with manipulating the colonoscope[2] (Cao & Milgram, 2000), we allowed subjects only a nominal amount of practice, consisting of one practice trial with the RRC display. All subjects were comfortable with the control after the practice.

3.1.4 Task. The task was a modified colonoscopy procedure within the simulated colon using the endoscopic image plus one of the six navigational aid displays illustrated in Figure 3. Subjects were asked to guide the colonoscope[3], as in a real colonoscopy, from the rectum through the colon to the caecum, "as quickly and as safely as possible." The safety constraint was included as recognition of the caution needed, as in actual colonoscopy, to prevent perforation of the colon, which could result in the experiment from continued pushing with the tip of the scope against the wall of the colon. As a consequence of our cautioning, no subject perforated the colon during the experiment.

Subjects were told that no trials would reach the caecum, but instead would terminate at random points along the colon. Unbeknownst to them, however, the trials were always stopped when the simulated splenic flexure was reached. Subjects were told that, in addition to "good performance" with the scope, that is, traversing the colon quickly and safely, they were required to keep track of how far they had traveled inside the colon. At the end of each trial, the displays were turned off and subjects were asked to indicate the location and orientation of the end of the scope inside the colon. As illustrated in Figure 6, this was done by marking an arrow on a paper drawing of the colon, with major segments clearly labeled, to indicate the estimated position of the scope end with respect to the colon, as well as the direction in which subjects believed the scope was pointing. (Such paper-marking procedures are in fact common practice among colonoscopists, to record the locations of polyps, and/or to indicate the point furthest traveled within the colon whenever a colonoscopy procedure must be aborted.)

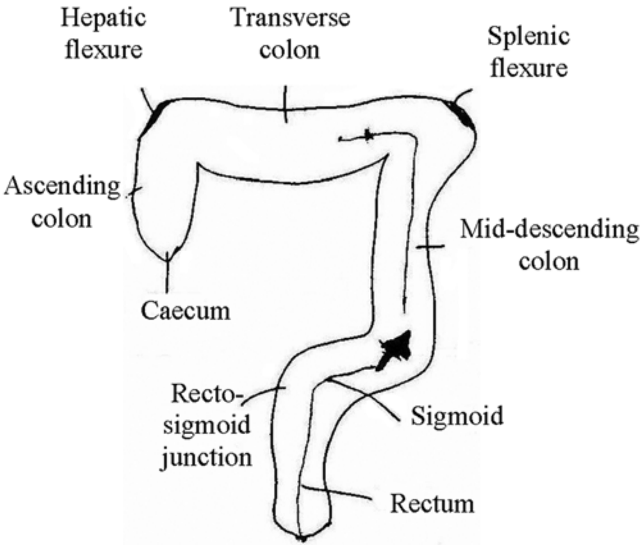


Figure 6. *Drawing of the colon, with each major segment labeled, used for position and direction estimation.*

The experimental task could thus be considered as comprising two subtasks: navigation and spatial orientation. The navigation subtask depended on efficient manipulation of the colonoscope. The spatial orientation subtask, which was a function of one's ability to combine the available information with one's mental map of the simulated colon, was primarily a global orientation task.

3.1.5 Experimental Design. Each of the 16 subjects was exposed to all six displays (Figure 3) in both the rigid and nonrigid colons. Subjects were randomly assigned to one of two groups: Group 1 started the experiment with the rigid colon and then switched to the nonrigid colon, whereas Group 2 started with the nonrigid colon and then switched to the rigid colon. (Due to a scheduling conflict, 7 subjects were assigned

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[2] In reality, endoscopists typically learn on the job, and do not become experts until after about 500 cases.

[3] It is relevant to note that, although from a display point of view the task was primarily 2D in nature, there was nevertheless a significant 3D component, in the sense that the simulated colon consisted of a three dimensional channel, and subjects could quite readily jam the end of the scope against the walls of the channel in both the horizontal and vertical planes.

to Group 1, while 9 subjects were assigned to Group 2.) The order of display presentation for each subject in each colon condition was randomized, with no repeats of the order. The design used was therefore a 2 × 2 × 6 (2 colon rigidities × 2 group orders × 6 display options) mixed design. For each subject, data were collected for one trial per condition, for a total of 12 trials.

3.1.6 Dependent Measures. Performance measures were *time to task completion, total distance traveled* (or efficiency of motion), and *accuracy of localization and direction* of the colonoscope end point. The total distance traveled measure deserves some explanation, since one might expect this to be a constant quantity, given that subjects always ended up at the same point within the same simulated colon. However, the meandering of the tip of the scope inside the colon can trace out an effectively longer trajectory, especially when local disorientation occurs, or when the scope pushes against the nonrigid colon thereby stretching it, serving as an indication of the efficiency of travel. In the present experiment, the lowest possible distance that could have been traveled, that is, the best possible score for this measure, was 400 mm.

As described above, the accuracy in localization and direction data were collected via paper drawings at the end of each trial, as shown in Figure 6. These were scored by first digitally scanning the individual drawings plus markings and then manually calculating the error in absolute distance and absolute angle relative to the global frame of reference.

For each location and direction estimate, subjective ratings of confidence were also collected, using a five-point scale. A rating of 1 indicated low confidence that the location or direction was correct, whereas a rating of 5 indicated high confidence of a correct answer.

Another dependent measure was the standard NASA TLX mental workload questionnaire (Hart & Staveland, 1988), presented to subjects at the end of each trial. In incorporating separate ratings of the mental demand, physical demand, temporal demand, performance effort, and frustration associated with the task, this measure was intended to reflect the cognitive effort involved in spatial orientation.

Finally, at the end of the experiment, all subjects rank-ordered their preferences for the six navigational aid displays and also rated the usefulness of the six displays, on a scale from "very useless" (0) to "very useful" (10).

4 Results and Discussion

An analysis of variance was performed on each of the performance variables (time to task completion, distance traveled, localization error, direction error), as well as confidence ratings (direction and localization error), and workload. Due to the unequal number of subjects in Group 1 (7) and Group 2 (9), this resulted in an unbalanced design for the statistical analyses. Only statistically significant results are discussed here (see Table 1). All error bars shown in Figures 7, 8, 9 are standard errors.

4.1 Time to Task Completion

The results showed no difference in time to task completion as a function of display. (This is similar to the result reported by Saunders and colleagues with the non-radiographic magnetic imager in Saunders et al., 1995.) On the other hand, the data did indicate that navigation in the simulated colonoscopy task in general took significantly less time when performed in the rigid colon (87.0 ± 46.9 s) as compared to the nonrigid colon (144.4 ± 74.5 s) ($F(1, 14) = 20.0$, $p = .001$). Although this relative result was anticipated, due to the absence of any need to struggle with stretching in the rigid colon, there was, however, a significant order effect, with Group 1 taking a mean of 90.0 s (± 56.7 s) to perform the task, and Group 2, 148.7 s (± 68.3 s) ($F(1, 14) = 21.7$, $p < .001$). See Table 2 for a summary of the performance measures.

As shown in Figure 7, subjects who started with the nonrigid colon (Group 2) improved upon switching to the rigid colon, suggesting that the nonrigid colon was more difficult to navigate and thus provided more of a learning opportunity. Conversely, the group that started with the rigid colon (Group 1) took slightly longer to complete the task after switch-

Table 1. *Summary of Significant Results from Statistical Analyses**

Factors	Performance and subjective measures Time	Distance	Location error	Location confidence	Direction error	Direction confidence	Workload
Group (g)	√	√					
Rigidity (r)	√	√					
Display (d)		√		√		√	√
g × r					√		
g × d		√					
r × d							
g × r × d							

*Check marks indicate statistical significance at $p < .05$.

Table 2. *Summary Statistics (Means and Standard Deviations) for Time, Distance, Localization Confidence, Direction Confidence, and Workload Ratings*

	Time (s)	Distance (mm)	Localization confidence	Direction confidence	Workload
Group1	90.0 ± 56.7	1,390 ± 923	3.3 ± 0.9	2.9 ± 1.0	64 ± 11
Group2	148.7 ± 68.3	2,402 ± 1452	3.4 ± 0.9	3.1 ± 1.2	64 ± 11
Rigid colon	87.0 ± 46.9	1,392 ± 821	3.3 ± 0.9	3.0 ± 1.1	63 ± 11
Nonrigid colon	144.4 ± 74.5	2,274 ± 1497	3.4 ± 0.9	3.0 ± 1.1	65 ± 11
RRC*	103.9 ± 56.3	1,548 ± 825	3.6 ± 1.0	3.5 ± 1.0	62 ± 12
RE*	104.8 ± 56.9	1,603 ± 1007	3.6 ± 0.8	2.9 ± 1.0	64 ± 11
RC*	122.7 ± 75.4	1,995 ± 1597	3.6 ± 0.8	3.3 ± 1.0	64 ± 12
CO*	124.0 ± 78.2	1,993 ± 1434	3.1 ± 0.8	3.1 ± 1.3	67 ± 10
RO*	122.2 ± 76.6	2,070 ± 1542	3.3 ± 0.9	2.7 ± 0.9	67 ± 11
NA*	116.6 ± 65.9	1,790 ± 1103	2.9 ± 0.9	2.4 ± 0.9	63 ± 12

*RRC = Rearview + Radar + Compass; RE = Rearview; RC = Radar + Compass; CO = Compass only; RO = Radar only; NA = No aid.

ing to the nonrigid colon, but still took less time than Group 2 in the nonrigid colon. Although this strongly suggests a learning effect, the performance of Group 2 subjects in the rigid colon was not as fast as that of Group 1, implying the possibility of asymmetrical training interference from the nonrigid condition. Therefore, there would appear to be a dual benefit in training with the rigid colon before attempting the nonrigid colon. Specifically, training with the rigid colon beforehand reduced the task completion time by 44% when working with the nonrigid colon, compared to not having prior training.

4.2 Distance Traveled

The total distance traveled was intended to reflect how efficiently the colon was navigated, as a function of colon rigidity and display condition. The results for this

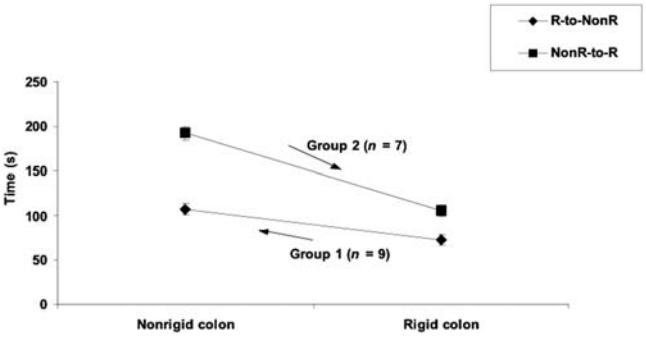

Figure 7. *Total task completion time. Group 1 subjects started in the rigid colon; Goup 2 subjects started in the nonrigid colon. The arrows indicate the order of encountering the simulated models. Error bars are standard errors.*

measure mirrored those of time to task completion, which in general corresponded directly with the longer distance traveled. An analysis of variance showed that there was a significant order effect, with Group 1 traveling a shorter distance than Group 2 ($F(1,14) = 8.07$, $p = .013$); a significant rigidity effect, with a shorter distance traveled in the rigid colon than the nonrigid one ($F(1,14) = 15.3$, $p = .002$); and a significant display effect, with a general increase in distance traveled when shape information is not provided ($F(5, 70) = 3.49$, $p = .007$). There was also a significant display by order interaction ($F(5, 70) = 2.85$, $p = .021$). See Table 2 for a summary of the performance measures.

As shown in Figure 8a, Group 2 (nonrigid to rigid ordering) was less efficient (i.e., traveled longer distances) than Group 1 (rigid to nonrigid ordering). As indicated in Figure 8b, this difference was less pronounced for the two conditions where shape information was available in the navigational aid display (RRC and RE), suggesting that shape information was more effective in guiding the navigation task, regardless of whether the colon was rigid or nonrigid. Pair-wise comparisons by group showed that Group 2 subjects traveled shorter distances with these two shape information displays than with the Compass Only and the Radar Only displays ($p < .008$, based on a Bonferroni correction, to accommodate the large number of pair-wise comparisons carried out). That is, for Group 2, the RRC was significantly more efficient than the CO ($t(13) = -3.854$, $p = .002$) and the RO ($t(13) = -3.577$, $p = .003$), while the RE was significantly more efficient than the CO ($t(13) = -3.138$; $p = .008$), and the RO ($t(13) = -4.046$, $p = .001$). This finding thus further emphasizes the potential importance of shape information for navigating in a nonrigid environment.

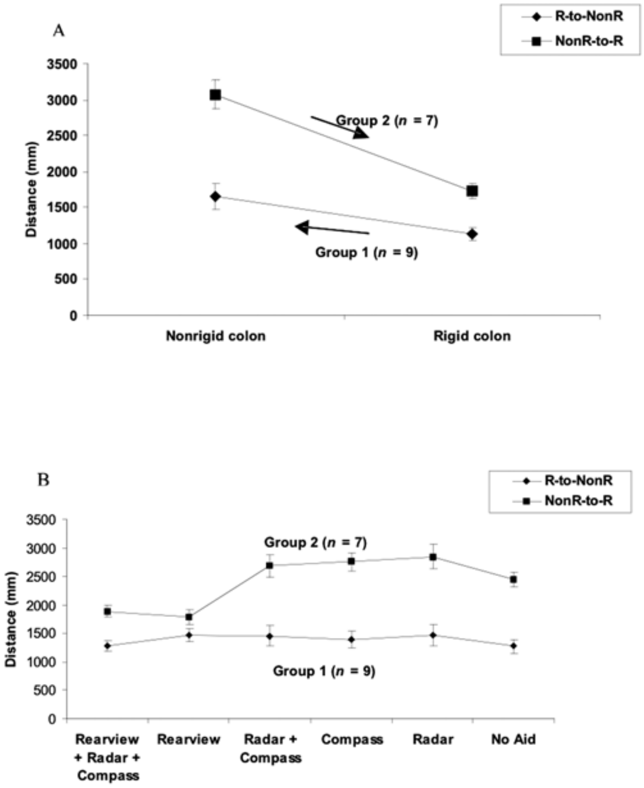

Figure 8. *(a) Averaged over subjects, total distance traveled was shorter for Group 1. The nominal distance along the midline of the colon was 400 mm. (b) Averaged over subjects, the total distance traveled was shorter in the Rearview + Radar + Compass and the Rearview display conditions for both colons.*

Interestingly, there was no difference between the two displays containing shape information (RRC and RE) and the No Aid display. One may surmise that this result suggests that having no information is better than having partial information for navigating in the colon. The fact that Group 1 subjects' results showed no effect of displays is also puzzling. In having learned from first working in the rigid environment, these subjects may have also learned to navigate without the use of the displays. Nevertheless, they traveled three times longer than the actual distance of the colon (approximately two times more efficient than Group 2 subjects).

4.3 Localization Error and Confidence

In general, localization errors averaged approximately 197 mm. Contrary to expectation, the accuracy of spatial localization did not differ across the two colon conditions, as there was no significant difference for this variable.

There was, however, a significant main effect with respect to the display factor in terms of subjects' *confidence* in their localization estimates. See Table 2 for a summary of mean confidence ratings. A post-hoc Tukey HSD multiple pair-wise test showed that the confidence levels with the various displays were not significantly different from one another.

4.4 Direction Error and Confidence

In general, direction judgment in spatial orientation was poor, with errors ranging from 60° to 110° from the true direction of the endoscope. This large error was most likely due to the fact that direction was coupled to location within the colon. That is, referring to Figure 6, a forward-facing scope in the descending colon would be directed at 90° (relative to the global frame of reference), and a forward-facing scope in the transverse colon would be directed at 180°. Thus, if the subject misjudged the location of the tip of the scope to be in the descending colon, but correctly judged the scope to be facing forward, the direction error could be as large as 90°. Indeed, on several occasions the subjects thought that the scope was still in the descending colon when in fact the scope was in the transverse colon.

Surprisingly, no significant effect of display condition on location and direction errors was found, in spite of the fact that the very nature of the displays strongly suggested that performance on the RRC condition would surpass the others. One reason for this result is that subjects had not learned to map the spatial frame of reference provided by the displays to the 2D drawing of the colon. As evident in Figure 9, the errors in judging direction showed a significant interaction between rigidity and order ($F(1, 14) = 6.97$, $p = .019$). The trends for both groups suggest that error in directional judgment improves with practice, regardless of the type of navigational aid display used.

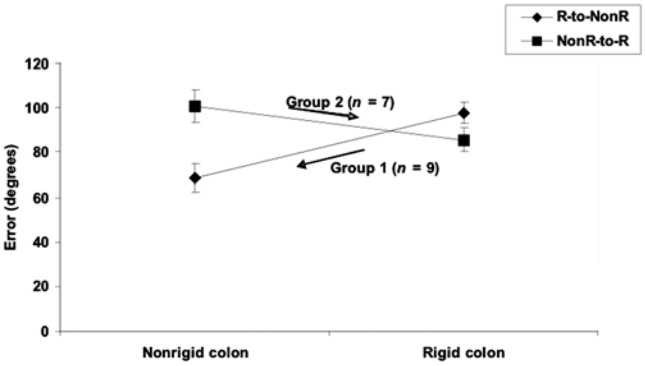

Figure 9. *Direction error. Direction errors are coupled to location errors (see discussion in text).*

There was a significant main effect of display on the confidence of direction judgment ($F(5, 70) = 7.50$, $p < .001$). See Table 2 for a summary of confidence rating results. In particular, a post-hoc Tukey's HSD test confirmed that subjects' confidence was higher in the RRC and the RC displays over the NA display. This supports the contention that the compass appeared to be providing useful directional information. In addition, the fact that performance with the Compass Only display was not different from the No Aid display suggests that subjects felt more confident about their directional estimates when positional information was simultaneously available.

4.5 Workload

Assessment of weighted overall workload using the NASA-TLX questionnaire showed that, contrary to expectation, workload was not significantly different between the rigid and nonrigid colon conditions. Averaged over order and colon conditions, the workload measures as a function of display were significantly different ($F(5,70) = 2.71$, $p = .027$). See Table 2 for a summary of results. However, a post-hoc Tukey HSD multiple pair-wise comparison showed that there was no significant difference between any of the pairs of displays. These results may have been due to the relatively simple and short length of the colon models, which were similar in length to a sigmoidoscopy rather than a colonoscopy. Had the colons been longer and more complex, the effects may have been more pronounced. Subjects' workload while using the No Aid display was not higher, which was not surprising (although somewhat counterintuitive). Indeed, it has been shown that sometimes, when a task load is too high, subjective workload decreases (Tulga & Sheridan, 1980).

4.6 Usefulness Rating and Preference Ranking

Usefulness ratings concurred with our hypothesis, with the No Aid display rated 1 ("very useless") on an 11-point scale (0 to 10), while the RRC display was rated at 8.5 (close to "very useful"). The perceived degree of usefulness decreased as the amount of information provided decreased. These ratings also concurred with the order of preference ranking for the displays. All subjects preferred the RRC display the most, while 75 percent of the subjects preferred the No Aid display the least. Interestingly, one subject preferred the No Aid to the Compass, while three others preferred it to the Radar display. It is possible that these subjects found the Compass and the Radar displays to be more distracting than helpful, and thus more demanding in terms of their interpretation.

5 Conclusion

Unlike navigating in large scale rigid environments, where typically there are invariant features to specify the spatial configuration of the environment, even if it is a dynamic environment (as characterized by other moving bodies within the space), the nonrigid colon is an enclosed self-contained environment, which makes it difficult for the endoscopist to maintain an accurate cognitive map of the environment. There are no external anchors, such as the sun, sky, magnetic north, or gravitational force to maintain spatial orientation. As colonoscopy is a primarily visually guided procedure, visualization of spatial information, and in particular, explicit shape information, was proposed as a solution that can help support spatial orientation in colonoscopy. In addition, the proposed navigational aid display, illustrated conceptually in Figure 5, may also reduce the cognitive load in orientation and navigation while performing colonoscopy. Furthermore, it could be used as a training tool for novice endoscopists to visualize the outcomes of their scope manipulations, especially given the lack of haptic feedback, to aid learning. Such visual feedback might be particularly useful for first-year fellows who are learning to perform colonoscopies for the first time (Mahmood & Darzi, 2004).

Even though the effect of displays in our simulated colonoscopy was not present in all performance measures, the results of this experiment have practical implications for the design of colonoscopy systems and training. The navigational aid prototype designed and evaluated here proved to be useful in that the total distance traveled in the nonrigid colon was significantly reduced, or efficiency of motion was increased, when the navigational aid provided shape information (RE and RRC) to untrained subjects. Subjective ranking of preference and rating of usefulness further confirmed that more information was better, therefore supporting the conclusion that a useful navigational aid display for colonoscopy should provide information about the shape of the endoscope inside the colon.

Confidence in the spatial orientation task was also higher with the navigational displays containing shape information, and highest with all three: direction, location, and shape. One cautionary note in designing any display enhancement is that it may lead to a false sense of confidence, which could be especially dangerous when accurate spatial estimation is important, as in localizing tumors for surgery.

Even though such a display may not necessarily reduce the total time required for an experienced endoscopist to perform an examination, it would at least be likely to reduce the number of painful manipulations of the scope (Saunders et al., 1995), and the uncertainty in locating lesions and tumors. Even so, the cost of providing a navigational aid for colonoscopy must be compared to the potential benefit of prior training with a rigid model. As this research shows, subjects who were first exposed to the rigid model performed better when switched to the nonrigid model, and with the particular short colon model used, it would appear that initial training should take place in a rigid model.

Clearly, an important consideration in evaluating this research is the fact that our subjects were not experienced endoscopists. Our reasoning, however, was that, in light of our global objectives, which were related to one's ability to comprehend and make use of the different types of spatial information provided by the different display options, the absence of surgical experience on the part of our subjects should not invalidate our findings relative to those objectives. Nevertheless, it is also clear that, as a first evaluation of a conceptual prototype, any transfer of the validity of our results to actual colonoscopy procedures remains to be demonstrated. Clearly, the next logical step in future research would be to test the usefulness of the navigational aid display for expert endoscopists, first in a simulated colon, then in real patients. The next step would be to examine its usefulness for training novice endoscopists, as well as its value for patient outcome.

The general conclusion to be drawn from this research, therefore, is that in a nonrigid environment, shape/form information is just as, if not more, important as location and direction. This research provides evidence that points to the importance of spatial layout, or shape information, for successful navigation and orientation in nonrigid egocentrically viewed environments. Nonrigid environments have not been the focus of investigations in the past, perhaps due to their relatively specialized nature. However, technology has created a new genre of complex environments in which humans must act and work. These environments are becoming increasingly common as more diagnostic and surgical procedures are done minimally invasively.

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