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Visualization Concepts to Improve Spatial Perception for Instrument Navigation in Image-Guided Surgery

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ABSTRACT

Image-guided surgery near anatomical or functional risk structures poses a challenging task for surgeons. To this end, surgical navigation systems that visualize the spatial relation between patient anatomy (represented by 3D images) and surgical instruments have been described. The provided 3D visualizations of these navigation systems are often complex and thus might increase the mental effort for surgeons. Therefore, an appropriate intraoperative visualization of spatial relations between surgical instruments and risk structures poses a pressing need. We propose three visualization methods to improve spatial perception in navigated surgery. A pointer ray encodes the distance between a tracked instrument tip and risk structures along the tool's main axis. A side-looking radar visualizes the distance between the instrument tip and nearby structures by a ray rotating around the tool. Virtual lighthouses visualize the distances between the instrument tip and predefined anatomical landmarks as color-coded lights flashing between the instrument tip and the landmarks. Our methods aim to encode distance information with low visual complexity. To evaluate our concepts' usefulness, we conducted a user study with 16 participants. During the study, the participants were asked to insert a pointer tool into a virtual target inside a phantom without touching nearby risk structures or boundaries. Results showed that our concepts were perceived as useful and suitable to improve distance assessment and spatial awareness of risk structures and surgical instruments. Participants were able to safely maneuver the instrument while our navigation cues increased participant confidence of successful avoidance of risk structures.

Keywords: Intraoperative visualization, distance assessment, instrument navigation, image-guided surgery

1. INTRODUCTION

Patients undergoing image-guided surgery evidently experience less damage to healthy tissue, decreased infection risk, reduced pain and shortened recovery time compared to open surgery.[1] Therefore, a significant trend towards minimally invasive procedures can be seen in recent years. This trend is expected to continue into the near future as advances in technological development facilitate such procedures.

However, the use of image guidance often restricts surgeons' accustomed abilities, like hand-eye coordination and depth perception. This leads to response delay, increased cognitive workload and misjudgment of surgical instrument positions.[2,3] To this end, surgical navigation systems have been developed, which support surgeons through the visualization of navigational aids during image-guided procedures. Most of these systems augment camera images with virtual information and/or use 3D models reconstructed from preoperative image data to clarify spatial relations.[4] Yet the distance between surgical instruments and anatomical structures as well as between displayed 3D objects can often only hardly be correctly assessed.[5,6]

Bogdanova et al. reviewed depth perception of surgeons in minimally invasive surgery and found the lack of binocular disparity to be one of the main reasons for misjudged spatial relations. Therefore, they propose to

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capture and display stereoscopic images.[2] Stereoscopy has been used in surgical navigation before, but is often not applicable in practice because the required hardware is either not available or inconvenient to use (e.g. heavy video see-through glasses).[7]

Other approaches try to optimize the visualization of 3D models to improve the perception of spatial relations and distances. Kersten-Oertel et al. proposed different visualization techniques to enhance depth perception in cerebral vascular imaging and assessed their usefulness. Pseudo-chromadepth, a rendering technique where distance is represented by colors, was shown to particularly improve relative depth perception.[8] Lawonn et al. proposed illustrative rendering techniques, which encode shape and distance of vascular structures with different styles of hatching lines.[9] Similar approaches were presented by Wang et al. who applied contour enhancing, occlusion and depth color-coding to improve perception of vascular structures.[10] However, these rendering methods were developed to better assess relative depth of static representations of complex 3D models. While aspects like color-coding can be applied to visualizations for intraoperative procedures, the interpretation of 3D models increases surgeons' mental effort, thus increasing the risk of inattentional blindness.[11,12]

A different approach to visualize distances between various objects projects 3D data of anatomical or pathological structures onto 2D map displays, thus reducing the complexity of perceived information. Lamata et al. developed a concept for visualization of 2D maps for open liver surgery. They proposed to project risk structures on the planned resection surface and make use of multiple views.[13] Hansen et al. proposed a similar approach to facilitate risk assessment in liver surgery. The authors presented methods for the identification and classification of critical anatomical structures in the proximity of a preoperatively planned resection surface. Distances were mapped to a 3D model of the resection surface to visualize safety margins for surgeons.[14,15] While these techniques help to visualize distance information of risk structures with less mental effort, they may not be applicable for simultaneously displaying additional information like the distance between surgical instruments and anatomical structures.

Such information can be directly visualized as text output using labeling techniques.[16] De Paolis et al. presented an augmented reality system to help surgeons avoid risk structures and prevent erroneous injuries. To this end, they displayed distance information between a surgical instrument and specified organ structures in a label box on the screen.[17] However, displaying labels can quickly lead to visual clutter, occluding most relevant information. To avoid increased visual complexity, the use of auditory displays was investigated. The system of De Paolis et al. emitted acoustic signals in form of an impulse with varying frequencies depending on the distance between surgical instruments and anatomical structures.[17] Black et al. developed auditory feedback modalities for the use in medical needle placement tasks. While their method allowed view-free instrument guidance, they showed that using auditory displays alone leads to increased task completion time and subjective workload.[18] Additionally, acoustic feedback is not always applicable for surgeries because of general noise in operating rooms.

Bork et al. combined both auditory and visual feedback to encode distance information between a surgical instrument and regions of interest. Their method includes a propagating shape around the instrument tip which increases in size over time.Regions of interest are rendered when a collision with the shape is detected. Additionally, easy-to-distinguish acoustic signals are emitted upon collision.[19] While this method facilitates the correct perception of distance regarding specified small regions of interest, e.g. risk structures, the visualization of propagating shapes is not applicable to display the distance to larger areas, e.g. resection surfaces.

Choi et al. presented a minimum distance visualization between a tool tip and anatomical 3D data. The surface point closest to the instrument was highlighted by a spherical representation and a line was drawn between said point and the tool tip position. A label displayed the actual distance values. The visualization was shown to be useful for reducing the number of collisions as well as minimizing targeting errors.[5] However, the concept could only emphasize the distance to the closest object. During more complex image-guided surgery tasks, e.g. tumor resections, or at rather narrow regions of interest, the visualization of only one distance does not suffice.

To overcome limitations of previous advances towards depth perception and distance assessment this work presents three visualization concepts encoding distance information of surgical instruments during image-guided surgery. We focused on simplified line-based concepts to augment surgical views without occluding anatomical structures. The visualizations were evaluated in a comparative user study. We measured user performance data as well as subjective usefulness and usability data. In the following, a detailed description of developed techniques is given. Afterwards the evaluation and its results are depicted.

2. METHODS

During our research, we identified three key information that are crucial while maneuvering instruments in image-guided surgery: the anatomical structure and potential hit position towards which the instrument is currently oriented, the positions of critical risk structures with respect to the instrument and the distance of the instrument tip to its surroundings. We developed three visualization concepts to encode each of these information. Thereby we aimed to reduce visual complexity of displayed navigation cues. All methods were implemented using the game engine Unity (Unity Technologies, USA) for its wide-ranging amount of available computer graphics functionalities, e.g. rendering pipeline and ray casting. Video 1 presents all developed concepts in a generic use case.

2.1 Pointer Ray

Since surgical instruments are usually inserted from a certain angle, structures facing the instrument tip are pertinent to help navigate the tool. To support users recognizing distances to and potential intersection points with anatomical structures along the instrument's trajectory, we decided to implement a *pointer ray* cast from the instrument tip aligned with the tool axis.

Similar approaches that visually extend the instrument can be found in related work supporting needle placement tasks.[20] While these techniques often color-code the needle extension according to targeting tasks for single targets, e.g. translational or angular offset, our aim was to visualize distance information between the instrument tip and all relevant anatomical or functional structures. Therefore, we implemented a color scale that adapts to the length of the pointer ray itself. Since we were mostly interested in illustrating proximity ranges, we used a discrete scale stretching from green (large distance) over yellow (medium distance) to red (small distance). The corresponding thresholds can be adjusted for each use case. Fig. 1 shows the concept with a virtual instrument pointing towards a target structure. The ray changes in appearance with respect to the distance to the structure.

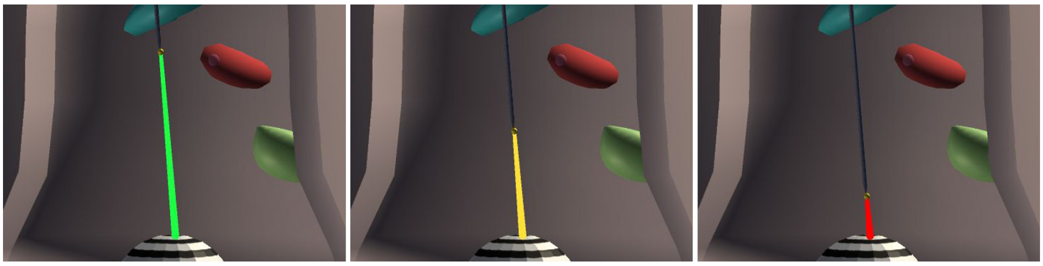


Figure 1. Pointer Ray. An instrument is virtually extended by a ray pointing at potential collisions along the trajectory. The distance to detected objects is encoded by the line color.

2.2 Side-looking Radar

Besides structures directly facing surgical instruments, the relative position of objects surrounding them can be crucial for navigation tasks. Especially when risk structures that must not be injured are in the proximity of the instrument trajectory, their distances to the instrument are crucial information.

To this end, we were inspired by the *side-looking* airborne *radar* as used in aviation and implemented a ray that is traced from the tool tip with an adaptable angle to the instrument's main axis. This angle can be adjusted according to the specific surgical corridor and view cone. The ray rotates around the tool and measures the distance to surrounding structures. The distance is again mapped to a discrete color scale, where red indicates very small, yellow indicates medium and green indicates large distances. The actual distance ranges for each color can be defined as needed. A full 360° rotation is completed after 3 s. Together with our clinical partners, we found faster rotational movement to be confusing and slower movement to be too slow to use. The concept can be seen in Fig. 2.

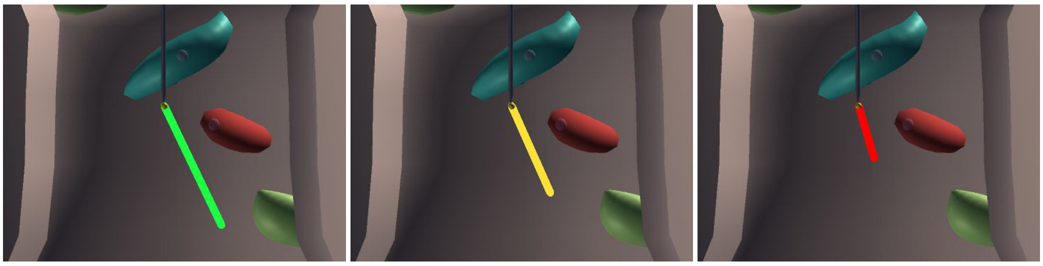


Figure 2. Side-looking radar. A radar rotates around an instrument at an adaptable angle. It ends when a collision with an object is detected. The color of the line is determined by the distance to the detected collision.

2.3 Virtual Lighthouses

Image-guided surgery tasks, like the resection of tumors in neurosurgery, are often carried out in a piecemeal fashion, requiring the operating surgeon to frequently move his/her instruments inside the patient. Thereby the position of critical risk structures often gets lost. In order to help surgeons being aware of nearby risk structures, we developed navigation cues inspired by lighthouses signaling maritime hazards.

Our *virtual lighthouses* are represented by spheres that surgeons can place at pre- or intraoperatively acquired positions. These points emit rays towards the instrument tip position, which are color-coded analogues to the *pointer ray* and *side-looking radar*. Red lines indicate that the instrument is very close, while yellow signifies a medium distance and green indicates that the instrument tip is far away. If they exceed a certain maximum distance, the rays are not shown at all. The exact distance values can be configured as needed. To further support the spatial perception of the emitted rays, they get larger the closer they are to the lighthouse positions. When using multiple lighthouses, the view gets quickly obscured. To solve this problem, the virtual lighthouses emit their rays periodically in a circular fashion. Additionally, the lines are rendered semi-transparently and only shown for a few seconds before fading out. Fig. 3 shows three lighthouses positioned on risk structures in different time steps.

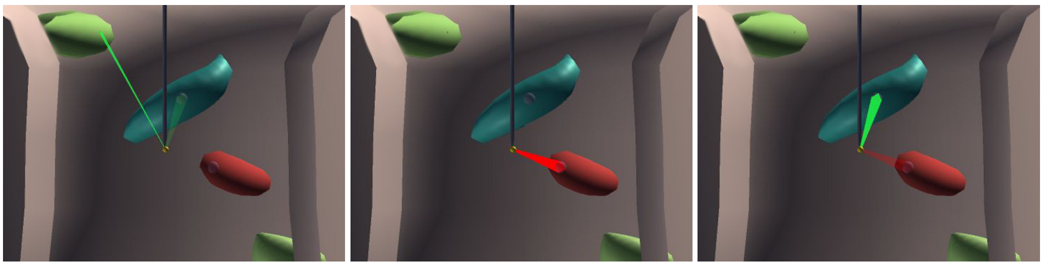


Figure 3. Virtual lighthouses. Each lighthouse emits a color-coded signal pointed towards an instrument (green and red lines). Displayed rays appear one after another and then slowly fade out.

2.4 Navigation Environment

In order to be able to utilize our visualization concepts, we created a prototypic navigation application. Our application had the requirement to enable a full overview of a given dataset, thus supporting users to successfully maneuver displayed instruments. The use of multiple views has been shown to help restore three-dimensionality of 2D images, thus improving anatomical interpretation and surgical performance.[2,21] Therefore, we decided to split up our application into the following separate views, which can be seen in Fig. 4:

- The left half of the display, called *surgical view*, shows the image of a steerable virtual camera tool. The view aims at providing the user with detailed images of the currently most relevant regions.
- The top right view shows a three-dimensional *overview* of the dataset from a predefined viewing position. Its purpose is to clarify the spatial relations of instruments and surrounding structures.

- The lower right view is again split up into two separate views. They display the dataset from different predefined directions and hold a collateral clipping plane to hide occluding structures and to better display spatial relations of inner objects. Therefore, the view is called *cross-sectional view.*

To help users identify the views' perspectives, a small cube is displayed in each views' top right corner. The cubes are rotated analogous to each respecting camera position and their faces are labeled accordingly.

Instrument positions were retrieved using an optical tracking system. To register the tracking system to our applications' global coordinate system, we implemented a method using a tracked reference marker at a known position. In order to reduce registration errors caused by noise, we averaged all incoming data packages for 3 s. Surgical instruments were represented by a needle-shaped model. To reduce noise, the tracking data was weighted with the current virtual needle position and rotation using linear interpolation.

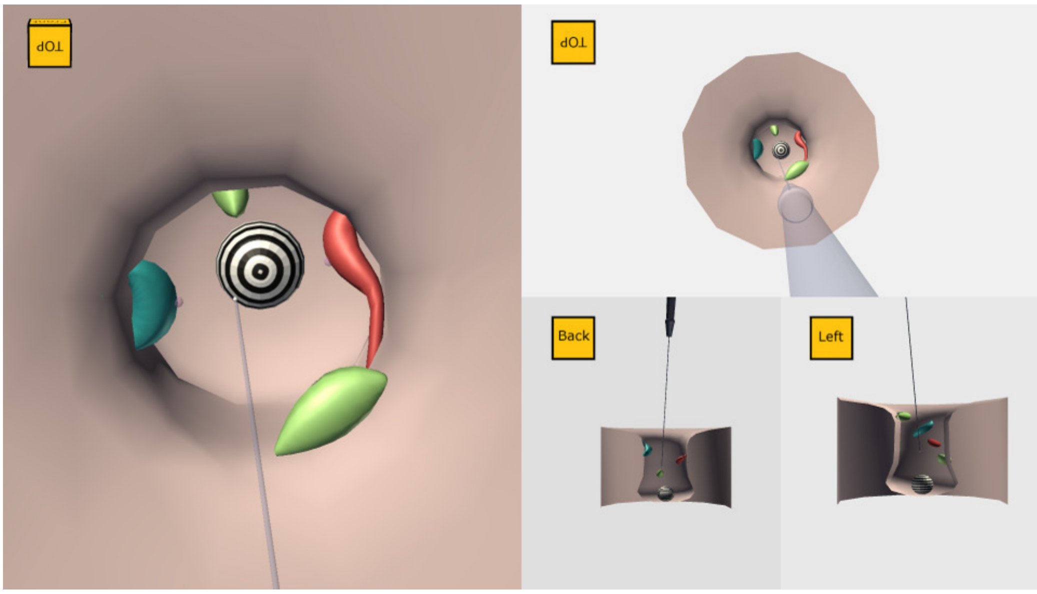


Figure 4. Navigation Environment. The surgical view (left) displays a dataset from a user defined camera position. The overview (right, top) displays the scene from above and the cross-sectional view (right, bottom) shows clipped images of the dataset from two predefined viewing positions. Currently no additional navigation cues are displayed.

3. EVALUATION

After developing described navigation cues, a user study was conducted. The study's goal was to assess the individual and combined usefulness and usability of developed visualization concepts. Additionally, we wanted to evaluate their overall user acceptance and find out how well each concept could serve the purpose it was developed for. This section describes the selected independent and dependent variables, participant tasks, and the experimental procedure.

3.1 Tasks

During the study, our participants were asked to navigate two tracked pointer instruments inside a phantom. One tool represented an endoscope, while the other was used as a pointer that had to be navigated to a virtual target structure. That target was positioned inside a virtual cylindrical cavity which should only be accessed through its circular entry on top of the phantom. Additionally, virtual risk structures were placed along the cylindrical path determined by the cavity. During the insertion process, users had to stay as far away as possible from these risk structures as well as the cavity's boundaries. This resulted in a total of three different subtasks: precisely reaching the target structure, avoiding risk structures and keeping as far away as possible from the cavity boundaries. In order to fulfill these tasks, users could make use of our developed navigation system, displayed in Fig. 4. The figure shows the virtual cavity with target and risk structures, as well.

3.2 Sample Design

We recruited medical students for this study because we considered novice users with medical background to be the ideal choice of participants because all tested alternatives were newly developed and require no prior knowledge in order to successfully use them. If participants were familiar with alternative navigation systems, like experts would be, their answers to questions regarding rather subjective topics would inherent the chance of being biased. At this point, however, we solely aimed at rating our new concepts without considering methods that are already in use. Sixteen (16) medical students (12 female, 4 male) participated in the study. Their age ranged from 20 years to 31 years old (median: 24) and they were between their first and sixth year of university.

3.3 Independent Variables

To compare the presented concepts, a two-factor test was carried out. The factors was were defined by the independent variables *visualization concept* and *task difficulty*. The first factor's levels were a blank tool visualization without any additional cues, the *pointer ray*, the *side-looking radar*, the *virtual lighthouses* as well as a combination of the three concepts. For the task difficulty we considered three levels determining the arrangement of the virtual structures inside the phantom. The easiest level meant a cavity radius of 30 mm while three additional risk structures were placed at 20 mm distance from the cavity's center. The second difficulty level used a cavity of 25 mm radius and 4 risk structures at center distance of 15 mm. Finally, the hardest difficulty level consisted of a cavity of 20 mm radius and 5 risk structures positioned at 10 mm distance from the cavity's center.

3.4 Dependent Variables

During each trial we measured various dependent variables including performance data and subjective feedback. Each frame, we determined the current distance between the pointer tip and the other virtual objects. At the end of the trial, we averaged the collected data of the pointer to cavity boundary distances as the *mean boundary distance*. For the pointer to risk structure distances, we searched for the minimum distance for each respective risk structure and then calculated their average. We called this variable the *mean smallest distance*. In order to be able to compare the results between the difficulty levels, we normalized the *mean boundary distance* with the size of the cavity's radius and the *mean smallest distance* with the risk structure distances defined by the current difficulty level. This resulted in values between 0.0 and 1.0. Furthermore, we measured the final distance between the instrument tip and the center of the target structure as the *target distance* and the *time* it took our participants to position the instrument.

Regarding the investigated subjective feedback, we asked our users to fill out various questionnaires after completing each trial. We measured *subjective workload* using the Raw TLX questionnaire where different workload dimensions were assessed on a scale from 0 to 100. Ratings were then averaged, resulting in an overall task load index.[22] Additionally, we used the meCUE questionnaire for measuring user experience.[23] We only used the dimensions *usefulness*, *usability* and *overall assessment* because the other dimensions did not match our purposes. Finally, we were interested in the participants' level of confidence in their performance during the three defined subtasks. Moreover, we wanted to know how suitable the presented visualizations were perceived for these subtasks. Therefore, participants answered the following questions on a 7-point Likert scale: "How confident are you that you reached the target precisely?", "How suitable was the application for precisely reaching the target?", "How confident are you that you touched no risk structures?", "How suitable was the application for avoiding the risk structures?", "How confident are you that you kept as most distance to the boundaries as possible?" and "How suitable was the application for keeping distance to the boundaries".

3.5 Experimental Procedure

During the study, each user was asked to insert the pointer tool once for every combination of difficulty levels and visualization concepts, resulting in a total of 15 trials. We first randomized the order of visualization concepts. Next, we randomized the order of difficulty levels within each visualization concept. Therefore, the participants completed every difficulty level for a given visualization before proceeding with the next randomized concept. Before a new visualization concept started, participants were given the chance to try out the navigation aids inside a testing environment. After participants felt confident with the technique, we proceeded with the actual trials.

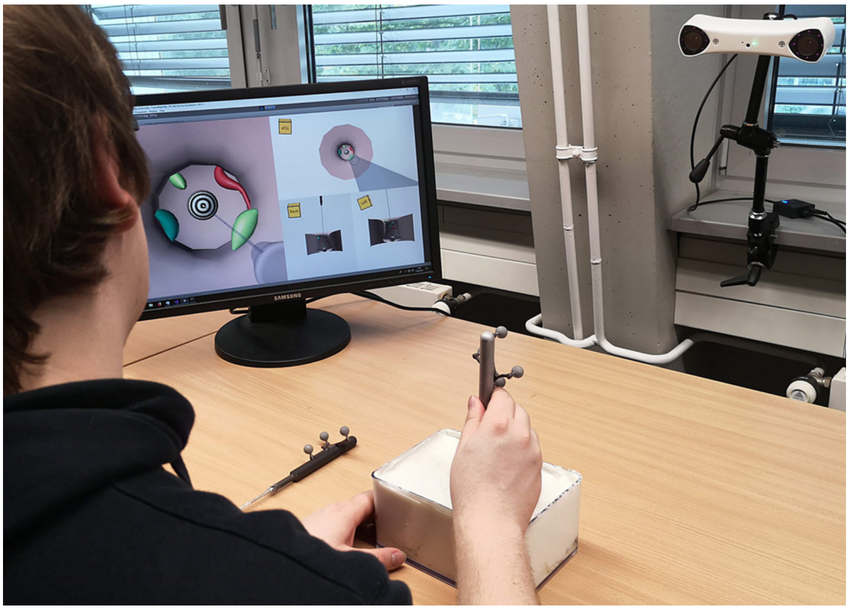
At the beginning of each trial, participants had to position their hand-held endoscopic tool which was responsible for generating the virtual images of our system's *surgical view*. The users first had to locate the cavity inside the phantom and adjust the camera at a convenient position. Afterwards, the participants could make use of a foot switch to fix the virtual camera position. The actual instrument could then be laid down. The position of the camera could later be adjusted by tapping the foot switch again and moving the instrument. After positioning the endoscopic camera, participants had to navigate the pointer tool through the virtual cavity while accomplishing the three previously described subtasks. Video 1 shows an example of a user maneuvering the pointer tool. When participants felt confident in the final pointer position, they tapped a second foot switch, whereupon we logged all relevant data. Next, our participants were asked to fill out our questionnaires. Afterwards, the next trial started with a different difficulty level and/or visualization concept. This procedure was repeated until all trials were completed.

3.6 Experimental Setup

The experimental setup included the optical tracking system spryTrack 180 (Atracsys LLC, Switzerland) with two unique optical marker shields and pointer tools, two USB foot switches (Scythe Co., LTD., USA), a custom made phantom and a computer with our navigation application running at 45 frames per second (Intel (R) Core (TM) i5-4690 CPU 3.50GHz, 16.0 GB RAM, NVIDIA GeForce GTX 560 Ti).

For the study, our virtual scene was composed of a cylindrical cavity which included various risk structures and one spherical target structure. For each difficulty level, we developed one base level as described above. Afterwards we slightly translated, rotated and tilted these base levels in different directions so that each trial could use a distinct but comparable cavity design. We assumed these changes to be enough for our participants having to rethink their insertion strategy for each trial, thus reducing learning effects.

Before the experiment, we defined several parameters of our navigation environment. Concerning the views, the *surgical view* was generated by a tracked tool as described earlier. We fixed the camera position of the *overview* above each levels' cavity so that the camera's direction vector and the main axis of the cylindrical cavities' aligned. Thus we wanted to help our participants find a correct trajectory for the instrument insertion task.



Video 1. Experimental Setup. A user is navigating a tracked instrument inside a virtual cavity within a curd filled phantom. A Monitor shows the developed navigation environment. Different visualization concepts are presented in the video: http://dx.doi.org/doi.number.goes.here

Table 1. Summary of the ANOVA results (statistically significant effects only, $\alpha < .05$).

Variable / Effect type	Factor	df	F	p	η^2	Effect	Figure
Mean Smallest Distance							
Main effects	*Concept*	4	6.34	0.011	0.043	small effect	Fig. 5a
	Difficulty	2	20.34	<0.001	0.133	medium effect	Fig. 8a
Interaction effect	*Concept * Difficulty*	8	3.48	<0.001	0.091	medium effect	Fig. 7
Mean Boundary Distance							
Main effects	*Difficulty*	2	29.59	<0.001	0.200	large effect	Fig. 8b
Time							
Main effects	*Difficulty*	2	6.52	0.002	0.054	small effect	Fig. 8c
Subjective Workload							
Main effects	*Concept*	4	5.81	<0.001	0.086	medium effect	Fig. 5d
	Difficulty	2	7.96	<0.001	0.059	small effect	Fig. 8f
Usefulness							
Main effects	*Concept*	4	6.67	<0.001	0.104	medium effect	Fig. 5c
Overall Assessment							
Main effects	*Concept*	4	6.38	<0.001	0.101	medium effect	Fig. 5b
Target Confidence							
Main effects	*Concept*	4	3.74	0.006	0.061	medium effect	Fig. 6a
Risk Confidence							
Main effects	*Concept*	4	2.59	0.038	0.039	small effect	Fig. 6a
	Difficulty	2	12.18	<0.001	0.091	medium effect	Fig. 8d
Boundary Confidence							
Main effects	*Difficulty*	2	7.04	0.001	0.057	small effect	Fig. 8e
Target Suitability							
Main effects	*Concept*	4	15.04	<0.001	0.209	large effect	Fig. 6b
Risk Suitability							
Main effects	*Concept*	4	13.68	<0.001	0.193	large effect	Fig. 6b
Boundary Suitability							
Main effects	*Concept*	4	9.10	<0.001	0.137	medium effect	Fig. 6b

The viewing directions of the *cross-sectional view* were set to a sagittal and transversal perspective, respectively, while the clipping planes were fixed right before clipping into the target structure. That way, users could better perceive the instrument position inside the cavity and extract valuable information like trajectory and insertion depth. Regarding the visualization concepts, we decided on color coding thresholds of 10 mm between red and yellow and 20 mm between yellow and green. The angle between *side-looking radar* and instrument trajectory was set to 45 °, in order to scan for both frontal and lateral structures. Additionally, we defined the positions of all *virtual lighthouses* before conducting the study. For each risk structure, we placed a lighthouse at the hull position nearest to the cavity center.

Since the displayed cavity, target and risk structures only existed inside our virtual environment and users were to only use the provided system as navigational aids, the insides of our phantom should not be visible. Simultaneously, our participants should be able to move the given instruments freely inside the phantom in order to be able to fully explore the virtual scene with the endoscopic tool. Therefore, we decided on using a curd-filled box, since curd has the desired properties regarding its opaque appearance and viscosity.

4. RESULTS

After measuring and collecting all desired data, we performed two-way ANOVAs for all dependent variables. Table Table 1 summarizes all statistically significant effects. Statistical parameters for non-significant effects are not reported.

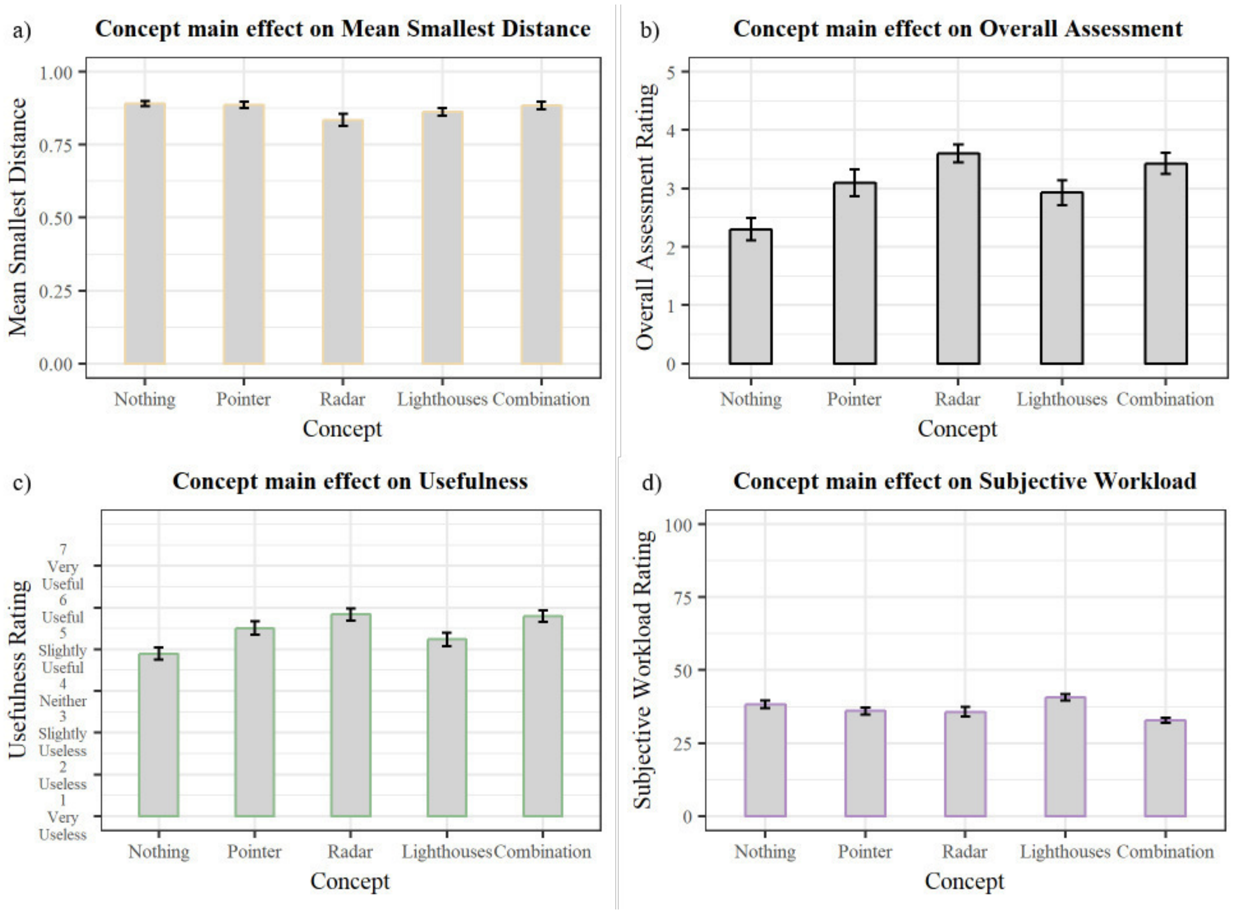


Figure 5. Main effects of the *Concept* factor on: a) mean smallest distance, b) overall assessment, c) usefulness and d) subjective workload. (Error bars represent standard error.)

4.1 Interpretation of Visualization Concept Results

The Concept factor results are summarized in Fig. 5 and Fig. 6. Overall assessment and usefulness ratings show consistent user preferences. In both variables, the *side-looking radar* is rated best and the navigation without additional cues (*Nothing*) is rated worst. The *pointer ray* and *combination* of concepts are rated similarly but the *virtual lighthouses* concept is rated slightly worse. Similar results are suggested by the subjective workload ratings. The low workload was measured for the*combination* of concepts, *side-looking radar* and the *pointer ray*. The navigation concept without additional cues was assessed to be of higher subjective workload while the *virtual lighthouses* received the highest workload score.

Concerning the mean smallest distance, similar values were calculated across concepts. However, usage of the *side-looking radar* resulted in significantly smaller distances. The two-way interaction plot (see Fig. 7) gives further insight into this effect. The interaction effect probably results from the low value of the *side-looking radar* in the *easy* difficulty level. Contrarily, all other factor level combinations are within a similar range. Participants may have maneuvered the tool more freely in the *side-looking radar - easy difficulty* configuration because of the radar's color being green more frequently compared to the other difficulty levels. At these levels, risk structures were located closer to the cavity main axis which results in more frequent yellow and red colors. Participants may have concentrated more on the radar's color than on the overall navigation environment, which was a need for most other concepts. This way, lower mean smallest distance values could have been recorded for the *side-looking radar*.

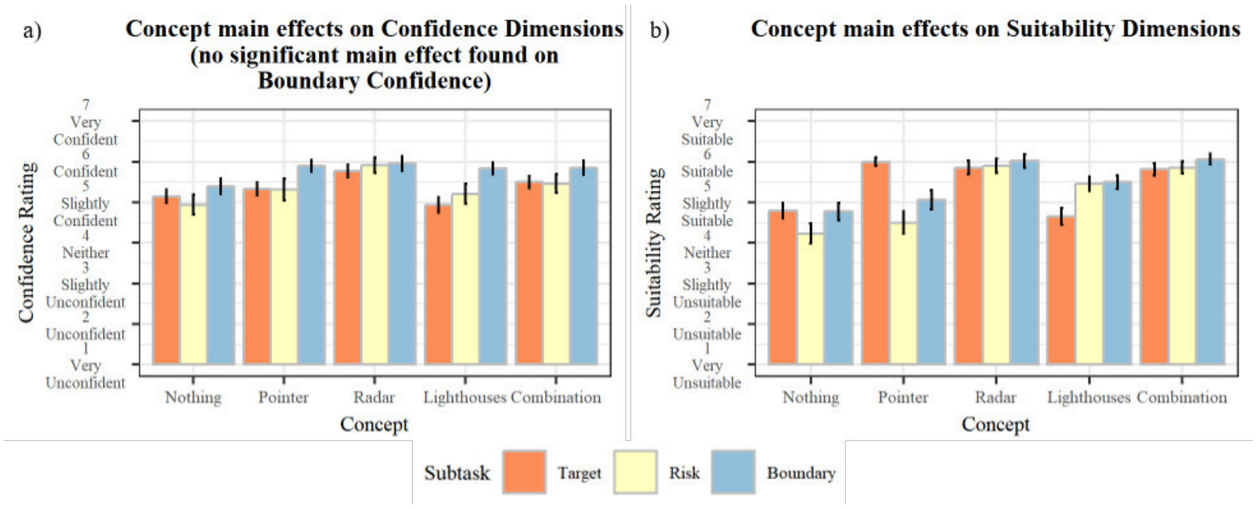


Figure 6. Main effects of the *Concept* factor on: a) target, risk and boundary confidence and b) target, risk and boundary suitability. (Error bars represent standard error.)

In contrast, participants felt the most confident in having avoided the risk structures and having kept the most possible distance from the cavity boundaries using the *side-looking radar* concept. Using this concept, participants also felt the most confident in having reached the target structure. Participants felt less confident regarding the risk structure and targeting subtasks with the *virtual lighthouses* concept and the navigation without additional cues. Additionally, the *side-looking radar* was rated as suitable for all three subtasks. The *combination* of concepts received suitability scores in a similar range. The navigation concept without additional cues was generally rated to be the least suitable for the given tasks. However, the *pointer ray* was rated the most suitable and the *virtual lighthouses* was rated the least suitable for the targeting subtask.

In general, the *side-looking radar* received the best scores or scores in similar ranges to the best rated concept across all subjective variables. The navigation concept without additional cues was almost always rates worst. However, the *virtual lighthouses* concept received ratings similar low ratings. These subjective results could not be replicated for our objective measures which may be due to a ceiling effect resulting from the general effectiveness of the overall proposed navigation environment concerning the given tasks.

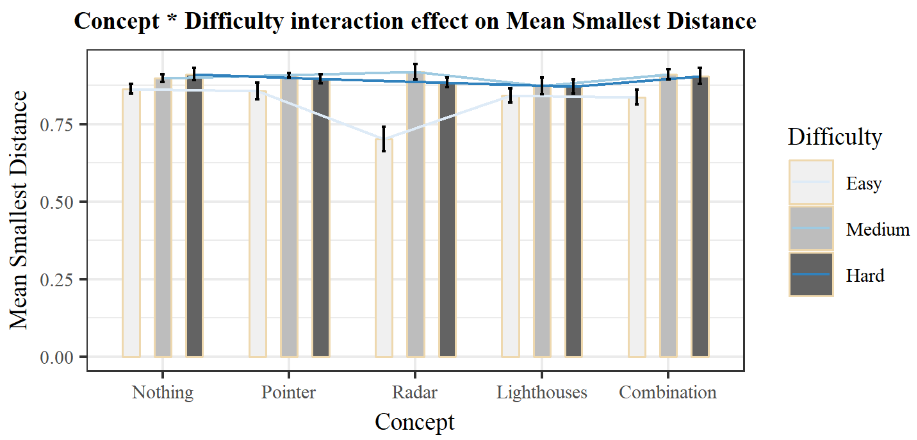


Figure 7. Two-way interaction effect on mean smallest distance. (Error bars represent standard error.)

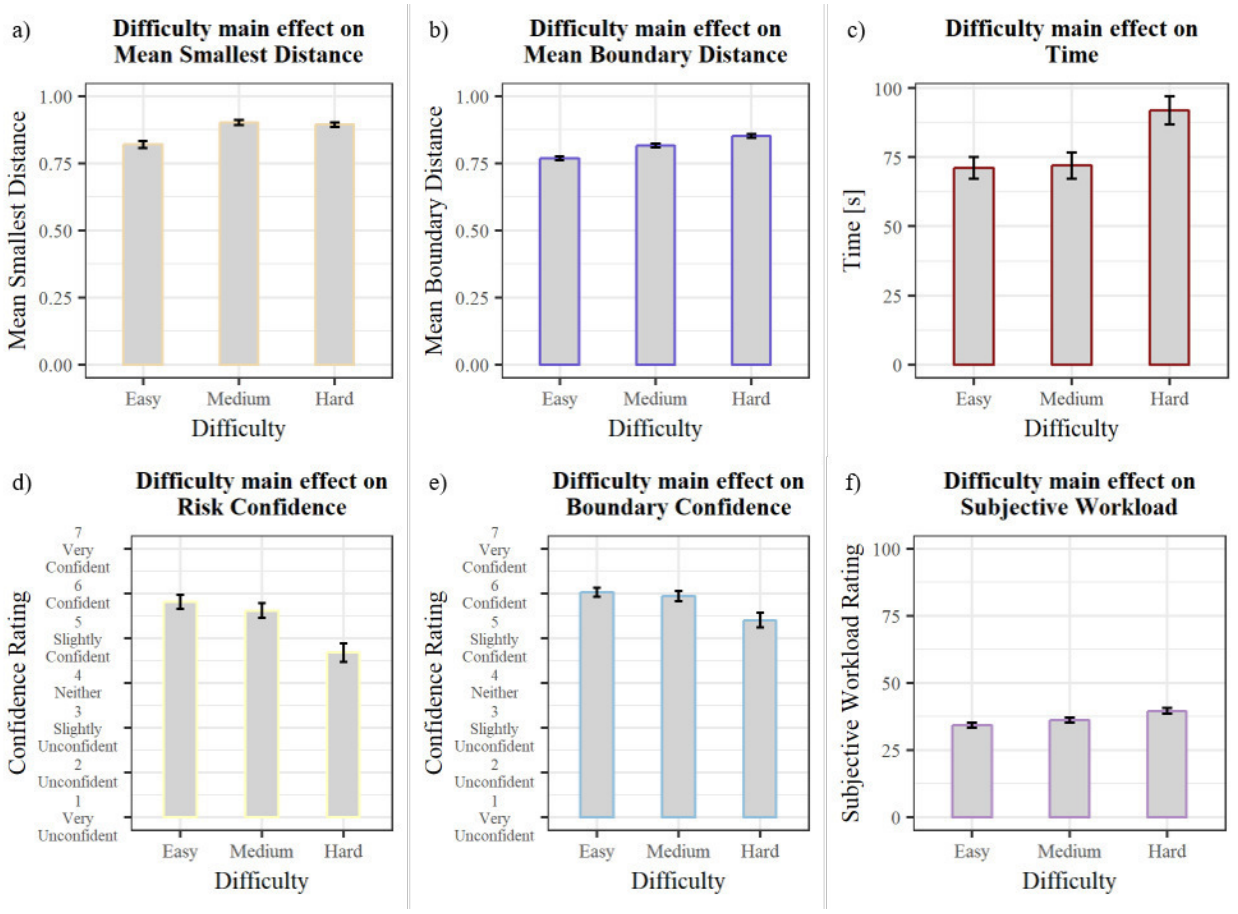


Figure 8. Main effects of the *Difficulty* factor on: a) mean smallest distance, b) mean boundary distance, c) time, d) risk confidence, e) boundary confidence and f) subjective workload. (Error bars represent standard error.)

4.2 Interpretation of Difficulty Level Results

The Difficulty factor results are summarized in Fig. 8. Main effects on the means smallest distance and mean boundary distance variables show, that participants held the least distance to risk and boundary structures during easy difficulty level trials. Besides the above given possible explanation regarding the color of navigation cues, this could also have happened because participants tried to always align the tool with the cavity main axis. This axis was easier to perceive, the smaller the cavity radius was. That way, it could have been easier for participants to keep greater distances to risk and boundary structures in harder difficulty levels.

In contrast, participants felt more confident in their performance regarding the risk structure and cavity boundary subtasks, the easier the difficulty level was. This again substantiates the theory that participants focused rather on color-coding than on the navigation environment thus maneuvering the tool more freely in easier difficulty levels.

Additional main effects could be shown on the variables time and subjective workload. Task completion time and workload both steadily increased with the difficulty level. This could also explain main effects on performance variables. Participants could have compensated difficulties in placing the instrument with a higher amount of effort and time.[24]

5. DISCUSSION

Based on these results, various assumptions can be made regarding the presented instrument navigation cues. All concepts received high, positive overall assessment scores (2.93 to 3.60 on a scale from -5.00 to 5.00) and were rated higher than the navigation concept without cues. User preference of using additional navigation cues over the mere navigation system is further implied by the results the usefulness questionnaire. Except for the concept without cues, which was said to be "insufficient" because of "too little feedback" and the *virtual lighthouses*, which were sometimes said to be "distracting" all concepts received similar usefulness scores. The similarity between assessed concepts can be explained by different user preferences, which also showed in partially contradicting feedback between participants. For example, the *virtual lighthouses* were said not to "distract" workflow by one user but their fading effect was "very distracting" for another one.

Regarding confidence and suitability variables, the *side-looking radar* was rated best for almost all dimensions. The *combination* of concepts received similar high ratings but was said to be "very distracting" and "confusing" by some participants. A more sparse combined visualization approach focusing on the *side-looking radar* thus seems to be an interesting topic for further research.

Similar measured data for some subjective and performance variables, like usability, led to non-significant results. This could be explained by a possible limitation of the conducted user study. The target and risk structures as well as the virtual cavities themselves were all planned around a linear main axis. Using the developed navigation environment alone, the participants were able to achieve similar duration measurements, target distances, mean boundary distances and mean smallest distances compared to the use of additional navigation cues. The navigation environment alone was helpful enough in to fulfill all given subtasks, thus resulting in a ceiling effect. More challenging tasks and phantom designs could reveal different results concerning these variables. This should be examined during future research.

As described above, effects on mean smallest distance could be explained by the discrete color-coding scales used for the navigation cues. As long as displayed lines were drawn in green, the participants could have relied on this information and thus were less careful. Using continuous color scales instead of discrete colors to encode magnitude information may have led to different results. Future work should therefore address more expressive color-coding scales, designed for specific tasks.

6. CONCLUSION

In this work, we present new visualization techniques to facilitate safe navigation of surgical instruments by supporting distance assessment to surrounding anatomical or pathological structures. We developed three navigation cues supporting different tasks. A *pointer ray* signalizes the distance to objects following the instrument trajectory. Distances to structures around the instrument are displayed with a rotating *side-looking radar* and the position of points of interest, like risk structures, get emphasized by *virtual lighthouses*.

Compared to a blank visualization, our concepts were perceived by our participants as useful and suitable for the respective tasks. Furthermore, they could increase the confidence in successfully keeping desired distances. However, no performance differences could be measured compared to the blank visualization, which may be due to a ceiling effect resulting from the general effectiveness of the overall proposed navigation environment concerning the given tasks. This should be further investigated in future research.

In conclusion, the proposed visualization concepts represent promising new approaches to facilitate distance assessment for instrument navigation tasks in image-guided surgery. They form an important basis for future research and development work in the field of intraoperative 3D visualization.

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