Effects of Accuracy-to-Colour Mapping Scales on Needle Navigation Aids visualised by Projective Augmented Reality

F. Heinrich[1], *F. Joeres*[1], *K. Lawonn*[2], *C. Hansen*[1]

[1] *University of Magdeburg, Faculty of Computer Science & Research Campus STIMULATE, Germany*
[2] *University of Koblenz-Landau, Faculty of Computer Science, Germany*

Contact: hansen@isg.cs.uni-magdeburg.de

Abstract

Instrument navigation in needle-based interventions can benefit from augmented reality (AR) visualisation. Design aspects of these visualisations have been investigated to a limited degree. This work examined colour-specific parameters for AR instrument navigation, that have not been successfully researched before. Three different mapping methods to encode accuracy information to colour and two colour scales varying different colour channels were evaluated in a user study. Angular and depth accuracy of inserted needles were measured and task difficulty was subjectively rated. Result trends indicate benefits of mapping accuracy to discrete colours based on thresholds and using single hue colour scales that vary in the luminance or saturation channel. Yet, more research is required to validate the exposed indications. This work can constitute a valuable basis for this.

Keywords: projective augmented reality, needle navigation, intra-operative visualisation, colour mapping

1 Problem

Surgical navigation systems that guide tracked instruments towards their target positions have beneficial effects on needle-based minimally invasive interventions, such as improved targeting accuracy, decreased procedure time and less required imaging scans [1], [2]. Augmented reality (AR) can be used to visualise this navigation information directly on the patient, thus overcoming issues of commonly used monitor-based systems, e.g., increased mental load, complicated hand-eye coordination and disrupted attention to the patient [3], [4].

Diverse examples of such AR instrument navigation systems can be found in the literature. These system use different display modalities to convey navigation information, like video see-through monitors [5], optical see-trough glasses [6] and projection systems [4]. Most publications in the field primarily focus on the technical realisation and evaluation of navigation systems, while visualisation aspects are only marginally discussed. Yet, a few works explicitly address this topic. Seitel et al. [7] compared four navigation concepts presented on a monitor. Chan and Heng [8] examined different access path visualisations and Mewes et al. [9] investigated effects of two projected visualisation concepts on needle insertions inside an MRI scanner. In previous work [10], we analysed existing visualisation approaches to support needle navigation tasks and compared three projected concepts in terms of accuracy measures and subjectively perceived task difficulty. We also varied between two methods of indicator scaling (i.e. how changes in accuracy translated to changes in the visualisation concepts shape) and three different accuracy-to-colour mapping schemes. However, no clear conclusions could be drawn regarding the latter factor due to a considerably large amount of data that needed to be excluded from the analysis. This topic has also not been discussed elsewhere, to the best of our knowledge. Thus, there is still need for an extensive investigation of different accuracy-to-colour mapping methods for AR needle navigation. This work presents a user study that addressed this topic. Building on our previous results [10], three different colour mapping methods and two colour scales to convey accuracy information for projective AR needle navigation were compared using similar measures.

2 Material and Methods

To achieve comparable results to [10], a similar experimental apparatus was implemented. The work carried out a three factor test to evaluate navigation visualisations. These factors were the general navigation visualisation concept, the indicator scaling method and accuracy-to-colour mapping. To focus more on colour-specific visualisation aspects, the concept and indicator scaling factors were held constant for this experiment. Instead, different accuracy-to-colour mapping methods have been investigated. Additionally, the underlying colour scale was varied.

2.1 Apparatus

Out of our previously examined concepts, we determined a crosshairs shaped visualisation to be the most effective in terms of accuracy, task completion time and subjective difficulty ratings [10]. Moreover, similar concepts are already implemented by navigation systems in surgical use [1]. Therefore, this concept was used to support needle navigation in this experiment. Figure 1 shows the visualisation's functionality. The needle handle position is projected onto a circular grid in the form of a small crosshairs marker. Angular accuracy is visualised by the distance between the marker and the centre of the grid. For perfect needle orientation, both are aligned. Depth information is visualised by a circular filling of the grid. The filling's diameter represents depth accuracy. The correct insertion depth is reached when the diameter matches with the outer circle of the grid.

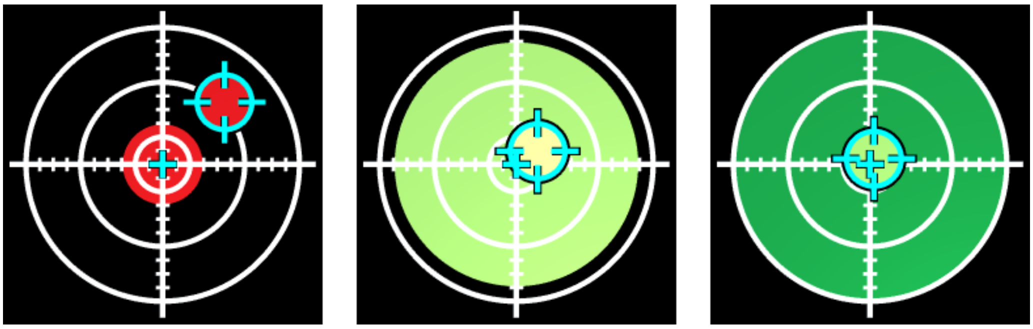

Figure 1: Needle navigation visualisation. A crosshairs grid is projected onto the injection site. A smaller crosshairs marker (blue) represents the needle handle position and the filling of the grid represents insertion depth information. From left to right the insertion angle is steadily improved and the needle is inserted further. Colours encode accuracy information.

The movement of the depth and angle indicators (i.e. filling diameter and marker-to-centre distance) were scaled logarithmically in this experiment. In [10], we compared a linear and and a logarithmic scaling method and concluded that the logarithmic method yielded higher depth accuracy results. Therefore, we implemented a similar method for this experiment, as well. This resulted in more sensitive indicator changes at higher than at lower accuracy levels and thus caused a higher resolution when precision is required.

To get a deeper insight into accuracy-to-colour mapping methods, this factor was adopted from [10]. Hence, a discrete and a continuous colour mapping method were implemented. Figure 2 shows the differences between both alternatives and depicts the threshold levels used for colour changes. Besides a red-yellow-green colour scale using a traffic lights metaphor, a green single hue scale was implemented. The first variant was adopted from [10]. However, the hue channel is best used to differentiate categorical attributes. Accuracy values rather represent quantitative ordered data which is better encoded by the saturation or luminance channel of single hue colour scales [11]. Therefore, the second variant was implemented, as well. Both scales are based on colour maps from *www.ColorBrewer2.org* [12]. In case of colour vision deficiency, scales using blue hues instead of green were provided.

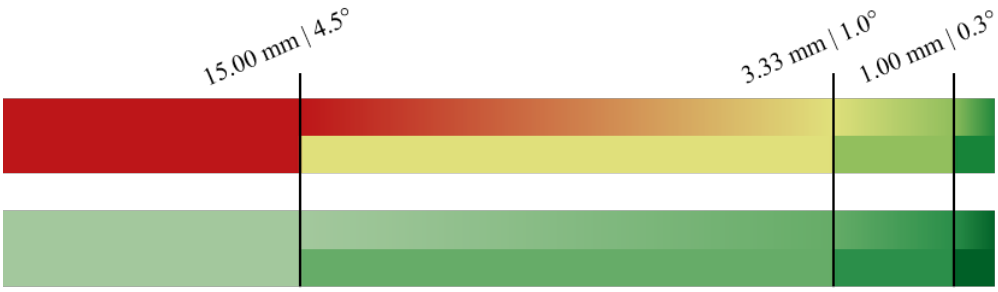

Figure 2: Accuracy-to-colour mapping methods and colour scales used to encode angular and depth accuracy information. Continuous and discrete mapping methods were investigated for each colour scale. Top scale varies by hues and the bottom scale varies by luminance. Thresholds for accuracy levels are reported at the separator lines.

The needle navigation aids have been implemented using the game engine *Unity* (Unity Technologies, USA) and were displayed by a projector-camera-system. Three Barco F22 WUXGA Digital Light Processing projectors (Barco GmbH, Germany) were mounted above a table and aligned over a common projection area. The projectors were calibrated with the photogrammetric measurement system *ProjectionTools* (domeprojections.com GmbH, Germany). To obtain instrument position data, the IR-based optical tracking system fusionTrack 500 (Atracsys LLC, Switzerland) was installed facing the projection site. Coordinate systems of the projector-camera-system and the tracking camera were registered using an optical IR marker with a known transform in projection space. A mannequin phantom filled with candle gel served as the projection surface. Covered by a sheet of paper, the candle gel created skin-like haptic when inserting a needle. An overview of the setup can be seen in Figure 3.

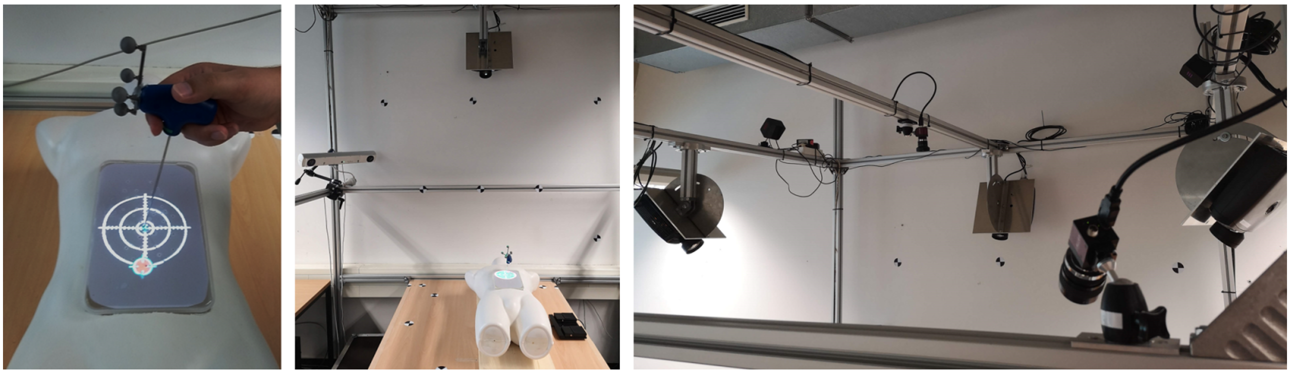

Figure 3: Experimental apparatus. Three projectors augmented a candle gel filled phantom with navigation visualisations. An IR-based optical tracking camera was used to obtain instrument position information.

2.2 Evaluation

During the experiment, participants were asked to repeatedly insert a tracked needle into the candle gel filled phantom. Each insertion was guided by the AR navigation visualisation and defined by preset insertion angle and depth parameters, that had to be reached as closely as possible. Participants were asked to keep an accurate insertion angle throughout the insertion process and not to over-insert the needle.

This task did not require specific clinical experience. However, a general understanding of the medical motivations may have been helpful. Therefore, we recruited twelve medical students (10 female, 2 male) for this study. Additionally, three students with a technical background and experience with AR (2 female, 1 male) participated in the experiment. The subjects were between their first and fifth year of university and their age ranged from 21 to 27 years old (median: 24 years). No participant reported colour vision deficiencies.

Two independent variables were regarded for this within-subject design study. First, the discrete and continuous accuracy-to-colour mapping methods were investigated as levels of the factor *Mapping Method*. Additionally, a monochromatic factor level was included. For this variant, angular and depth accuracies were always mapped to the same colour, which was set to the respective colour of the second accuracy level. Secondly, the two colour scales depicted in Figure 2 were considered as levels of the factor *Colour Scale*.

The dependent variables of this experiment were chosen and measured identically to [10]. Throughout each needle insertion, the angle between the current and the planned needle trajectory was calculated. Angular deviation was measured after each $1mm$ of insertion. At the end of each trial, these data points were averaged resulting in a *mean angular deviation*. *Absolute depth deviations* were measured as the absolute value of the difference between the current and the planned insertion depth at the end of each trial. Participants had control of the start and end times of trials by pressing a single-button switch near their standing position. The time in between was measured as the *task completion time*. After each needle insertion, participants rated the subjectively perceived difficulties to find the correct insertion angle and depth on a 6-point Likert scale (i.e. *subjective difficulty rating angle* and *subjective difficulty rating depth*).

Each participant performed a total of twelve needle insertions. Every factor combination between the two independent variables was evaluated twice per user. Before the actual trials began, a training session was conducted, where participants were instructed with the overall needle navigation concept, the colour scales and their tasks during the study. During this session, participants could freely practise the navigated insertion process. Afterwards, the twelve trials began. The order of presented alternatives was partially randomised. First, all six possible factor level combinations were presented in random order. After the completion of these trials, every alternative was presented a second time in the same order as before. By pressing the aforementioned switch, a new trial began. Participants could then freely select a desired injection site and begin the insertion process. Planned insertion angle and depth were generated randomly for each trial with angles ranging from 0° to 30° around the perpendicular to the injection site and depths between 70mm and 90mm. When participants felt confident to have completed the needle insertion, they pressed the switch again and rated the perceived task difficulty dimensions.

3 Results

The two factors' effects were analysed with two-way ANOVAs for all dependent variables. Results of the *Mapping Method* factor are summarised in Figure 4 and results of the *Colour Scale* factor are shown in Figure 5. No statistical significance could be shown except for the *Mapping Method* main effects on both subjective difficulty variables. However, the descriptive data reveal some trends worth noticing.

Regarding the *Mapping Method* factor, discrete accuracy-to-colour mapping seems to have yielded the least angular deviation but highest depth deviation. This may be due to the choice of accuracy thresholds and easier noticeable differences between final colours. The most accurate threshold may have been low enough to cause advantageous effects for angular accuracy, but may have been too great for depth accuracy (see Figure 2). Using the monochromatic and continuous methods achieved similar accuracy results. This may indicate that the navigation concept alone was helpful enough to accurately orient and insert needles. Yet, monochromatic accuracy-to-colour mapping was rated to be significantly more difficult compared the other factor levels, which was probably caused by a higher degree of confidence due to additional feedback. The *Colour Scale* factor plots suggest higher achievable accuracies when using the single hue scale. This is consistent with the general classifications of Munzner [11] and may confirm that luminance is a more suitable colour channel to convey accuracy information in projective AR needle navigation than hue.

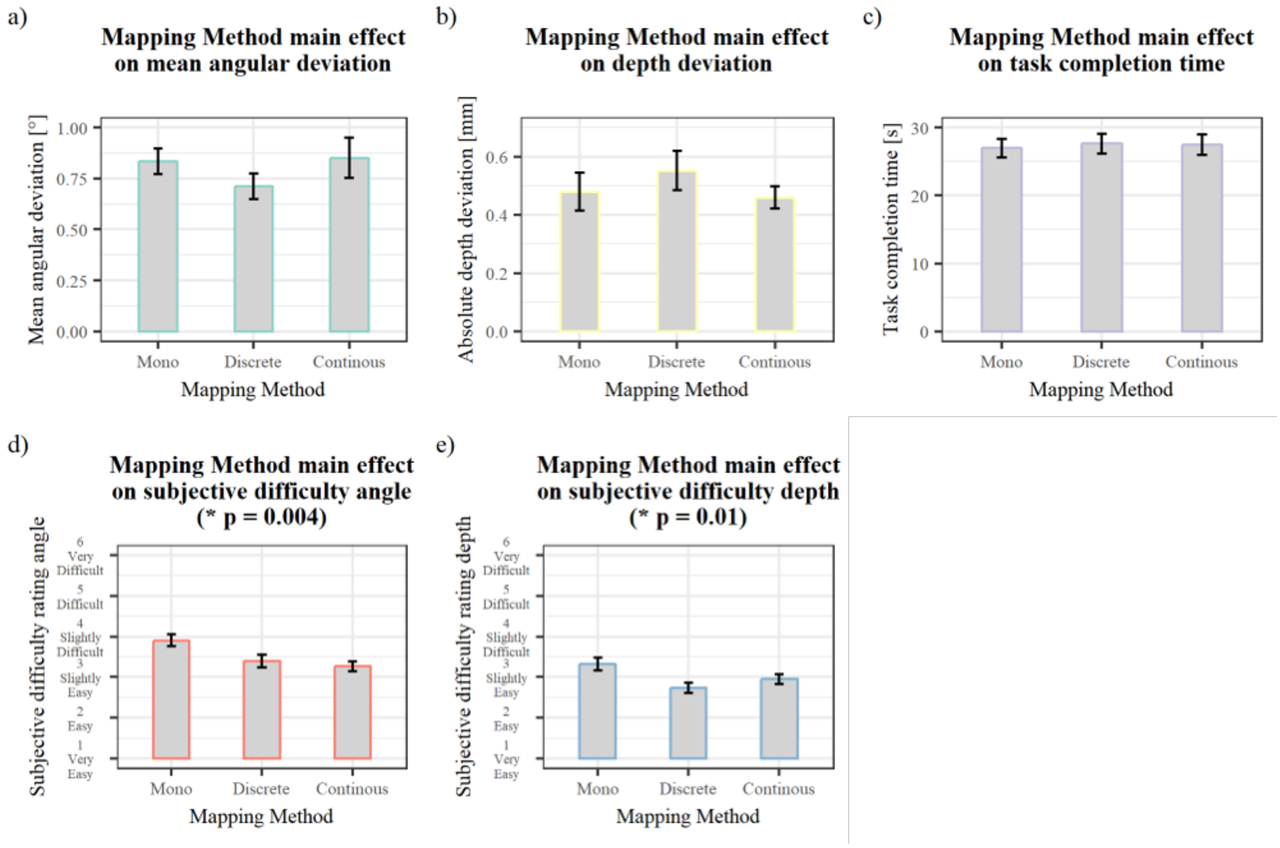

Figure 4: Main effects of the *Mapping Method* factor on: a) angular deviation, b) absolute depth deviation, c) task completion time, d) subjective difficulty angle, and e) subjective difficulty depth. (Error bars represent standard error. * denotes statistical significance.)

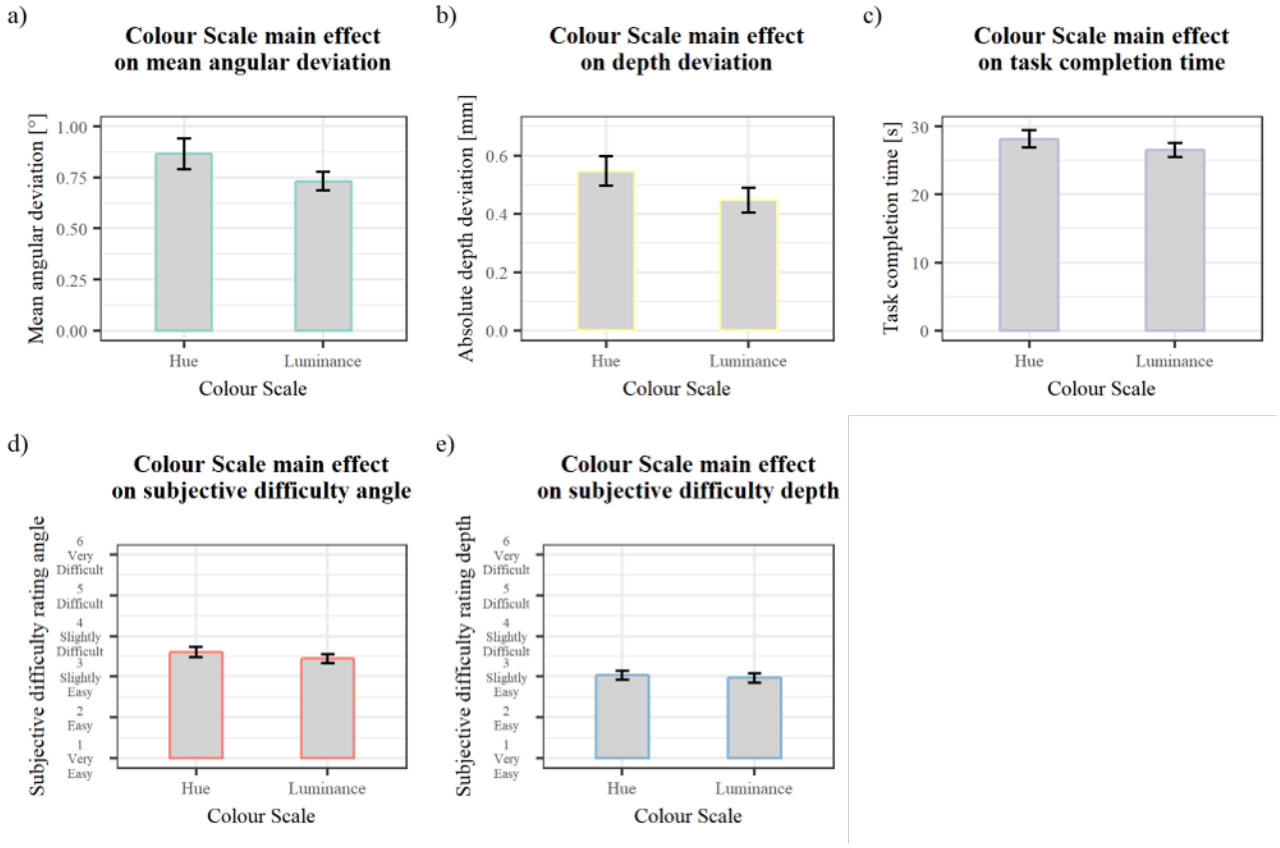

Figure 5: Main effects of the *Colour Scale* factor on: a) angular deviation, b) absolute depth deviation, c) task completion time, d) subjective difficulty angle, and e) subjective difficulty depth. (Error bars represent standard error.)

4 Discussion

Some statistically significant effects could be shown by the ANOVAs, although trends could be identified in the descriptive data. Various reasons may have contributed to this. The sample size of the study was rather small. Additionally, the overall navigation visualisation may have already contributed enough information to achieve high accuracy and therefore may have caused a ceiling effect. This is supported by the low angular and depth deviation results for the monochromatic factor level.

Results for the *Mapping Method* factor suggest, that colour is a useful tool to convey additional accuracy feedback and thus increase confidence of correctly performed needle insertions. Moreover, the position of final accuracy level thresholds seemingly influences the insertion precision for discrete colour mapping and may cause higher accuracy than monochromatic or continuous methods. This needs to be further investigated in a future experiment, especially because no statistically significant effects could be shown, yet.

The *Colour Scale* factor yielded results that are consistent with the literature. However, no clear conclusions can be drawn regarding this factor because no statistically significant effects could be shown for this factor either. The trends visible in the descriptive data may also be due to differently perceived navigation support from both monochromatic colour scales, which is indicated by the raw data to a certain degree. The monochromatic colour of the luminance scale (light green) may have been easier to differentiate from crosshairs grid (white) compared to the monochromatic colour of the hue scale (light yellow). Therefore, more research is required to find definitive answers to the question which colour scale yields the best results.

The selected colour scales may have influenced the experiment, as well. Different colours may have been easier to differentiate. For example, more nuances may have been noticeable on a red single hue scale, thus creating benefits for a continuous mapping method. High contrast between colours is especially important for projection systems, that are known to be sensitive to this property. Future research should focus on finding and evaluating suitable colour scales for this display modality.

Moreover, colour anchors in this work were not evenly distributed along the accuracy intervals, which resulted in non-linear colour scales. This was done to facilitate a higher colour resolution at higher accuracy levels, but may have ultimately influenced the experiment. More research could therefore be conducted to explore effects of linearisation of colour scales. This could also include an investigation of how including more discrete colour steps influences needle insertion accuracy.

5 Conclusion

This work investigated colour-specific visualisation parameters for projective AR instrument navigation. These included different methods of accuracy-to-colour mapping and variations of the channel that was used to create a colour scale. The factors were evaluated in a user study with simulated needle insertion tasks. Measured variables were objective performance parameters (angular and depth accuracy ans task completion time) and subjectively perceived task difficulty. Results suggest that discrete accuracy-to-colour mapping has to potential to convey accuracy information the most effectively. This highly depends on the choice of thresholds used for colour mapping. Moreover, for instrument navigation visualisations, colour scales varying the luminance or saturation channel seem to be more expressive than colour scales varying the hue channel. However, extended research is required to find specific answers to the identified open questions regarding instrument navigation visualisation. This work can constitute a solid basis for this.

6 Acknowledgements

This project was funded by the DFG (HA 7819/1-2 and LA 3855/1-2).

7 References

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