CHI2025

# Seeing Through the Overlap: The Impact of Color and Opacity on Depth Order Perception in Visualization

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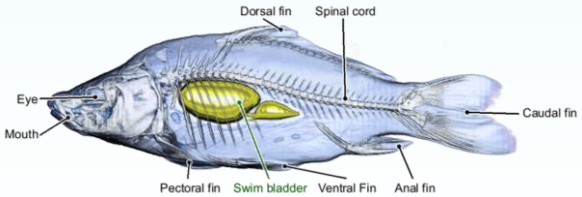
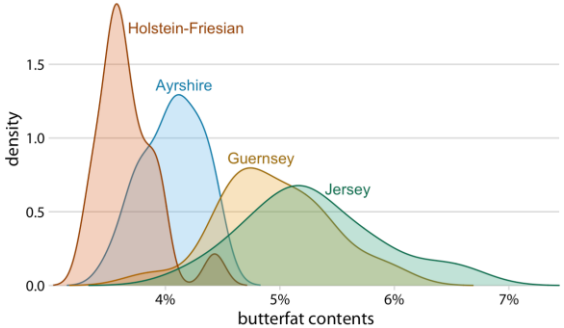



Bruckner et al. 2005

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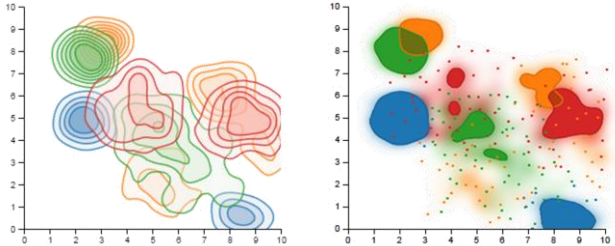
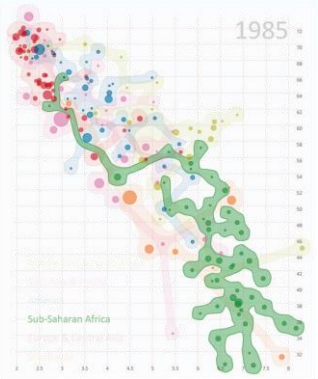
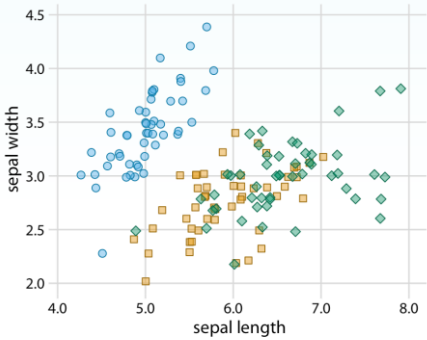


Sarikaya et al. 2018




Collins et al. 2009

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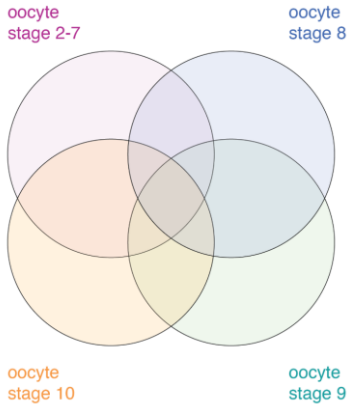
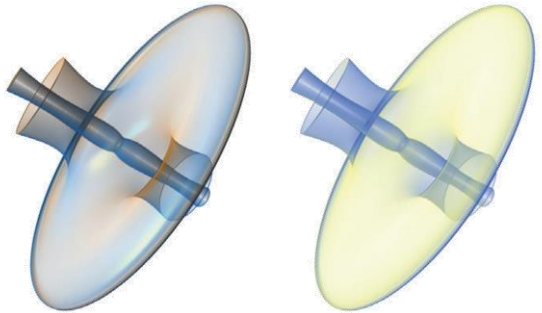
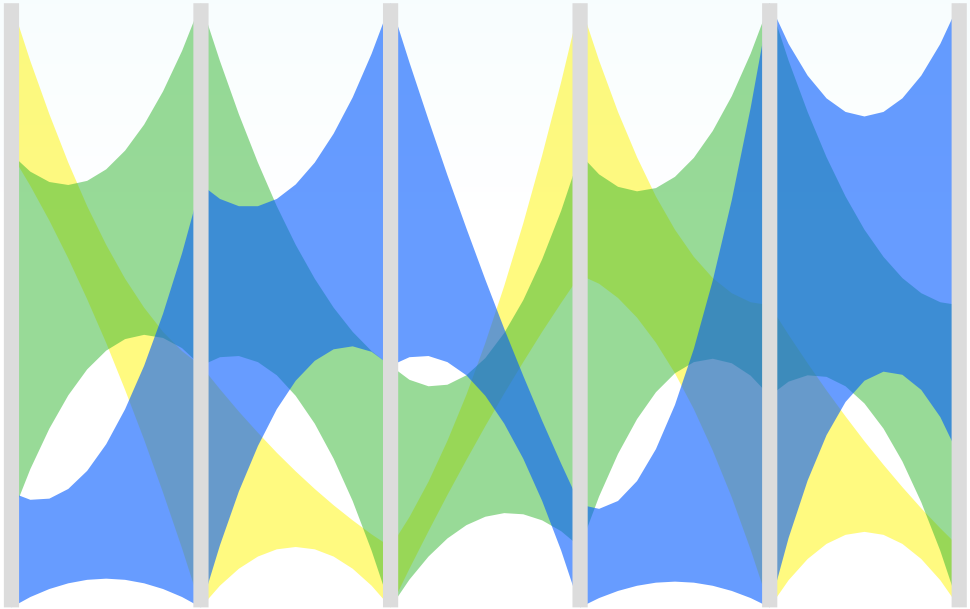


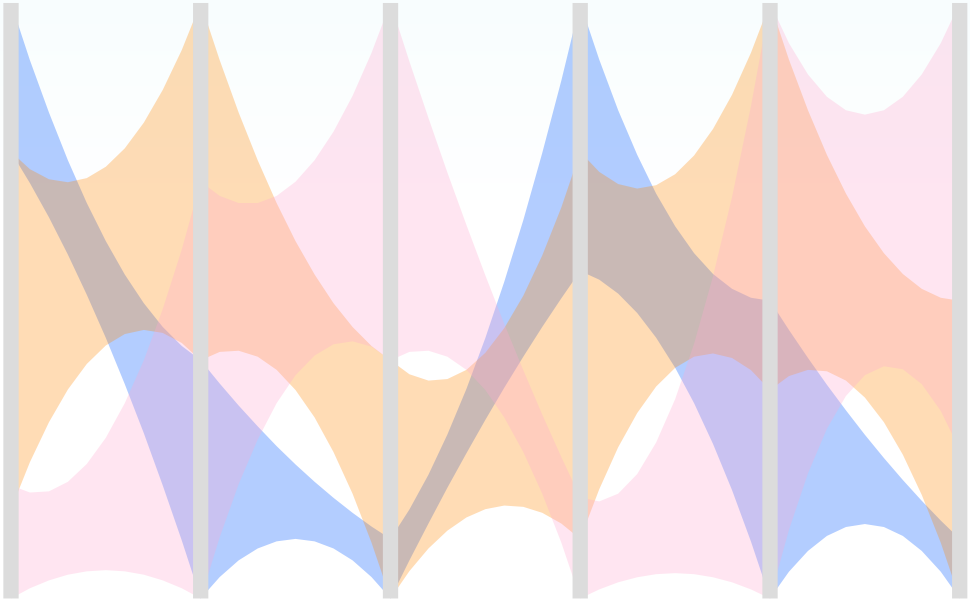

https://thenode.biologists.com



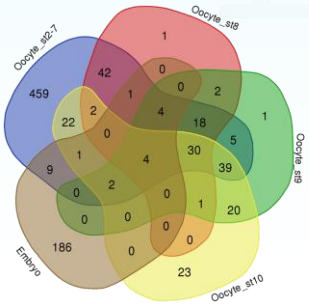
Hummal et al. 2010



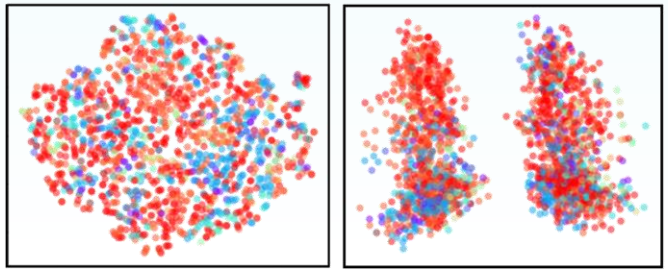
Reasonable color and opacity settings can show correct depth layers in overlapped spaces and improve data understanding.



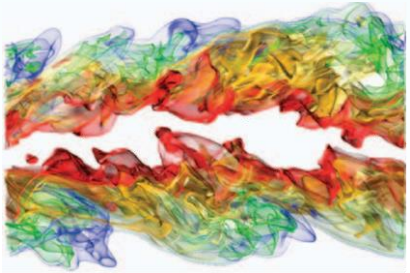
Inappropriate settings may show wrong depth layer perception and cause **visual clutter**.



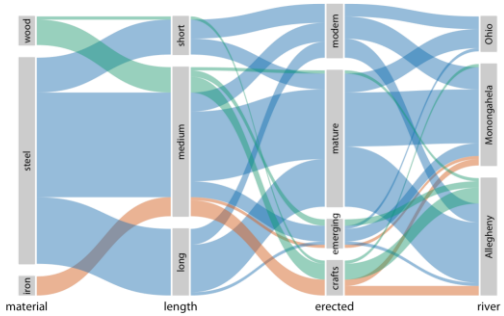

https://thenode.biologists.com



Tyagi et al. 2019



Han et al. 2020

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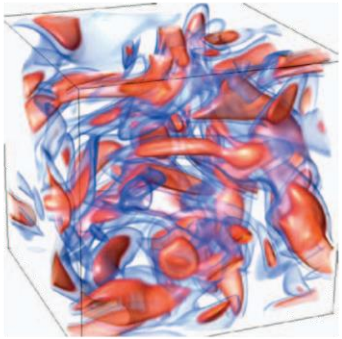
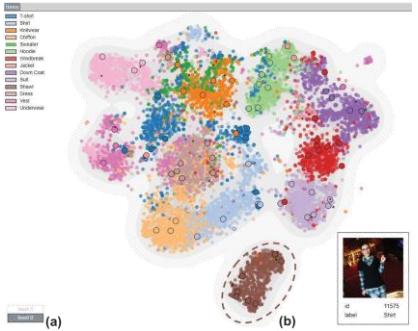


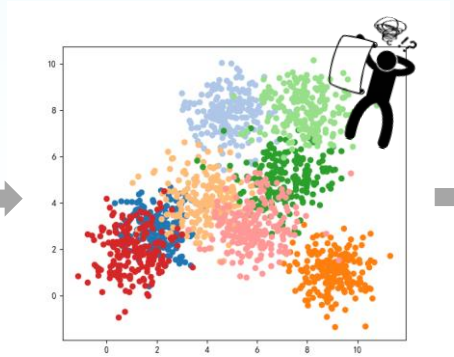
Han et al. 2020



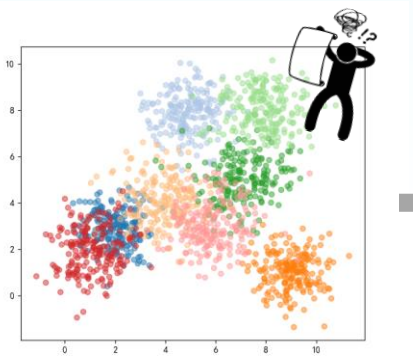

Xiang et al. 2019

This problem becomes more severe in realistic visualization applications.

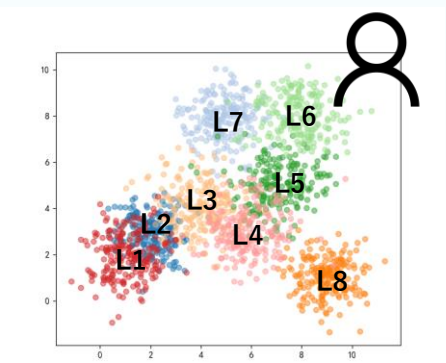
**Mark Selection**
(point, face, line)



**Color Design**
(color palette, color assignment, color fine-tune)



**Opacity Design**
(opacity assignment)




*What colors and opacities should I use to make people perceive correct depth orders?*
*What depth orders might be perceived by users?*

Using warmer colors in the foreground and colder colors in the background.

- Bailey et al. 2006; Sundet JM et al. 1978

Using cold colors in the foreground, overlapped with warm colors in the background.

- Wang et al. 2008

Increasing the lightness contrast between foreground and background layers can further emphasize depth ordering.

- Chuang et al. 2009; Englund et al. 2016

Increasing the opacity of foreground objects can enhance depth ordering accuracy.

- Edward et al. 1990; Wang et al. 2008

Excessively high opacity should be avoided in contexts where transparency conveys critical information or when subtle layering effects are needed.

- Sakano et al. 2018

Opacity has only a limited influence on the accuracy of depth perception.

- Kersten et al. 1992;Kersten et al. 2006

Combining highly saturated colors with lower opacity to enhance visual prominence.

- Chan et al. 2009

Placing cold colors in the foreground and warm colors in the background can improve depth perception even at low opacity levels.

- Wang et al. 2008

| Top Layer | | Back Layer | | Supported Papers |
|---|---|---|---|---|
| **Color** | **Opacity** | **Color** | **Opacity** | |
| Warm color | / | Cool color | / | Bailey et al. 2006 |
| Cool color | Low opacity | Warm color | / | Wang et al. 2008 |
| / | High opacity | / | / | Adelson et al. 1990 |
| High contrast | / | Low contrast | / | Chuang et al. 2009 |
| High saturation | Low opacity | / | / | Chan et al. 2009 |

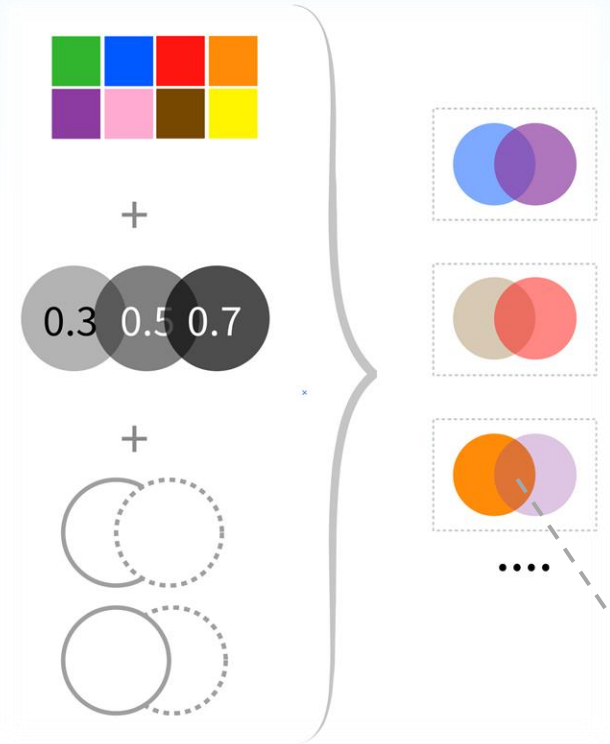
However, existing considerations often overlook interaction effects, and may produce conflicting design recommendations.

*What are the impacts of color, opacity, and their interaction on depth order perception?*

8 representative colors

3 opacity levels

4 layer order and arrangments

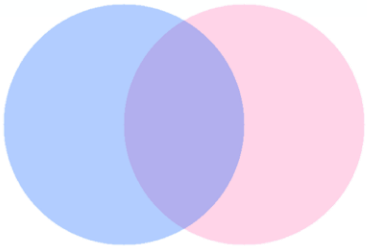



$$C_8^2 \times 3^2 \times 4 = 1008$$

$$\alpha_{\text{MIX}} = 1 - (1 - \alpha_t)(1 - \alpha_b)$$

$$C_{\text{MIX}} = \frac{C_t \alpha_t + C_b \alpha_b (1 - \alpha_t)}{\alpha_{\text{MIX}}}$$

**Please click and select the disk on the FRONT**



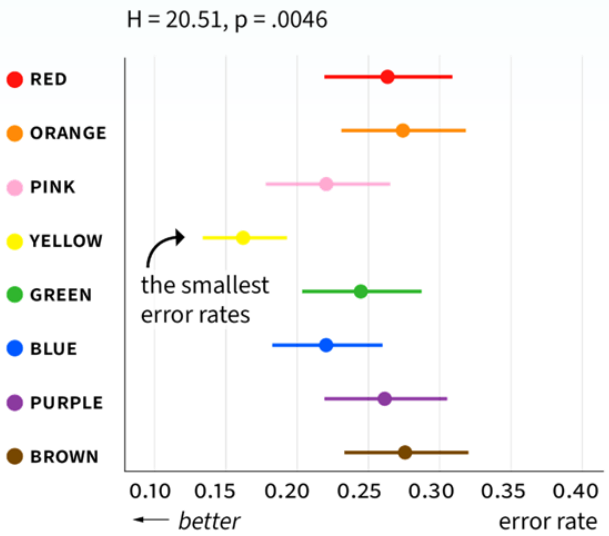
Left | Uncertain | Right

| | Pilot Study | Main Experiment |
|---|---|---|
| Participant No. | 24 | 180 |
| Trials/person | 252 | 112 |
| Total | 6,048 | **20,160** |

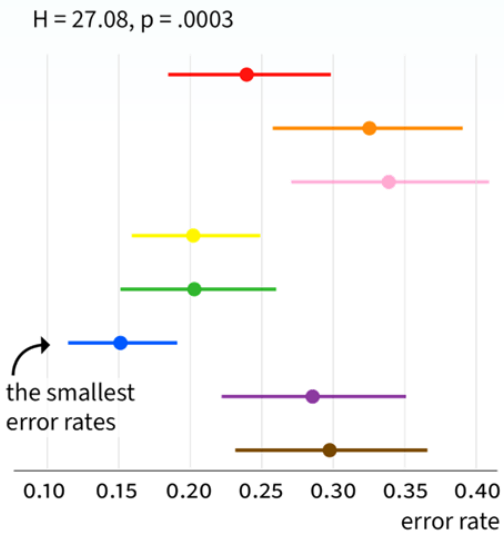
- **Inferential Analyses**
- **Predictive Analyses**
- **Exploratory Analyses**

- **Inferential Analyses**
- Predictive Analyses
- Exploratory Analyses

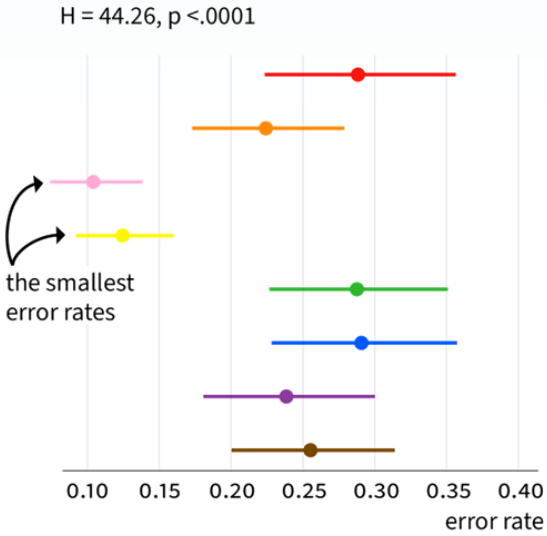
# Results | Effect of Color Hue




(a) overall effects of color hues

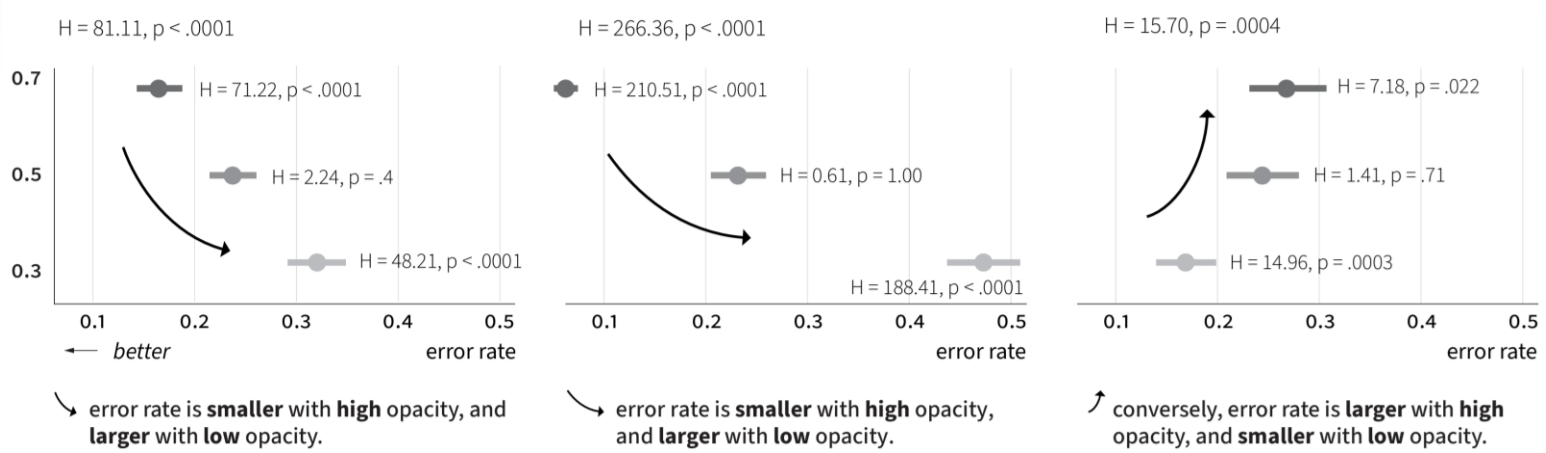



(b) effects of color on *front* layers



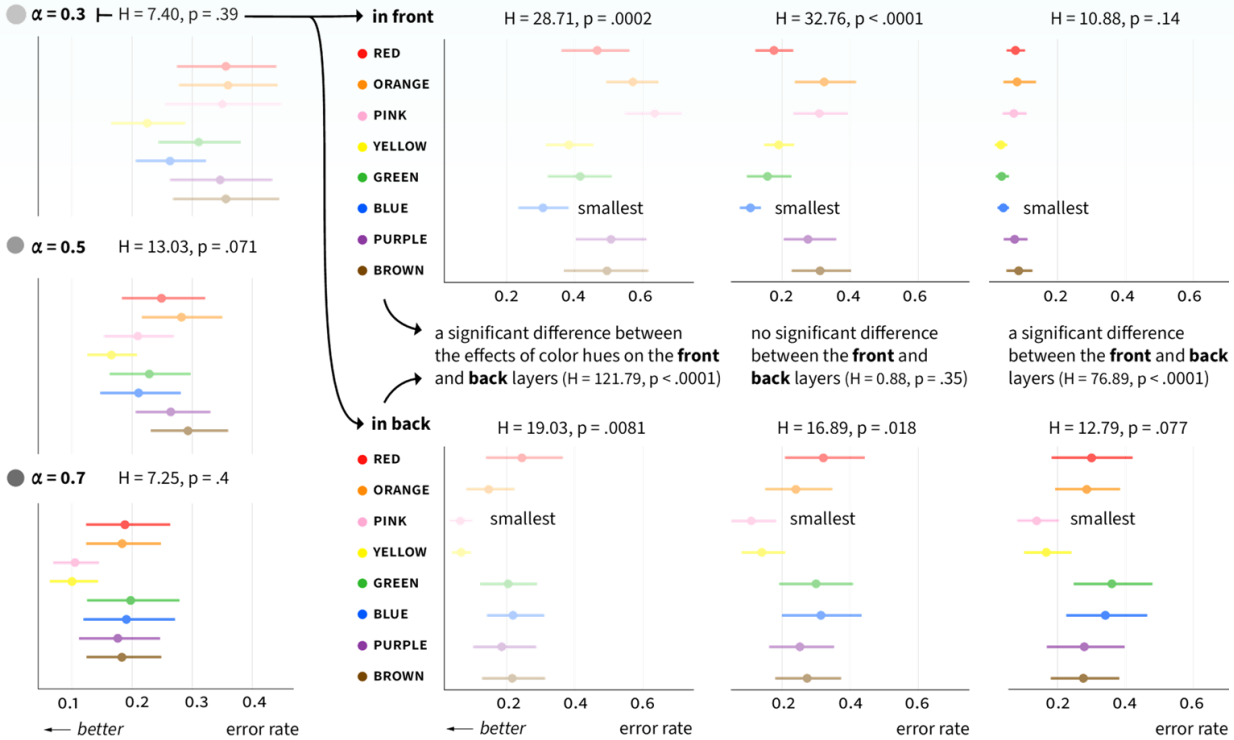

(c) effects of color on *back* layers

# Results | Effect of Opacity




(a) overall effects of opacity levels (b) effects of opacity on *front* layers (c) effects of opacity on *back* layers

# Results | Interaction Effect between Color & Opacity



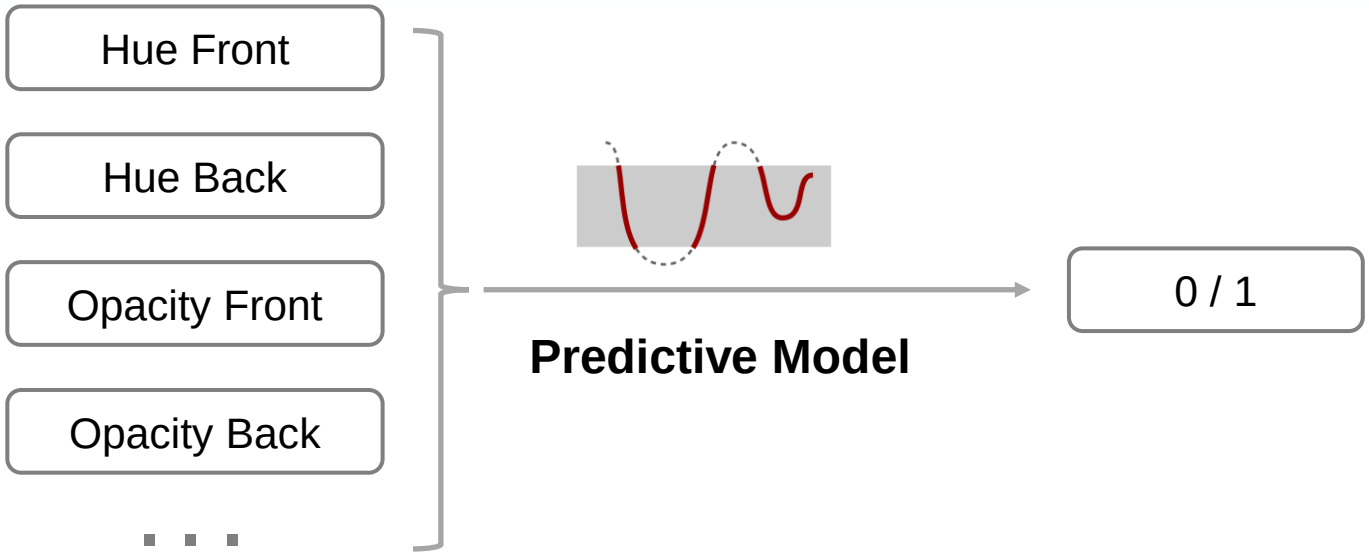

(a) overall effects of color and opacity

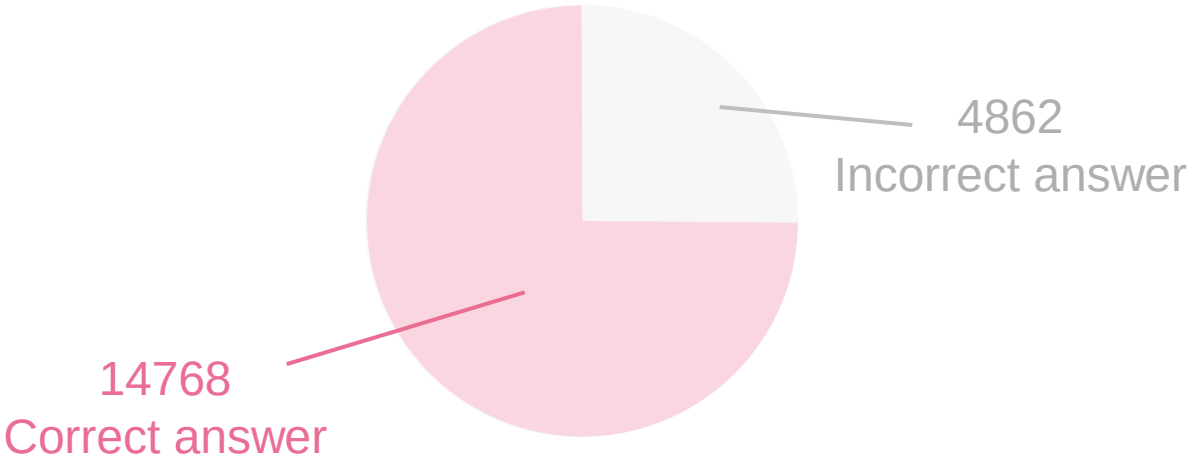
(b) Effects of color when α = 0.3

(c) α = 0.5

(d) α = 0.7

- Inferential Analyses
- **Predictive Analyses**
- Exploratory Analyses


Hue Front
Hue Back
Opacity Front
Opacity Back
. . .
Predictive Model
0 / 1

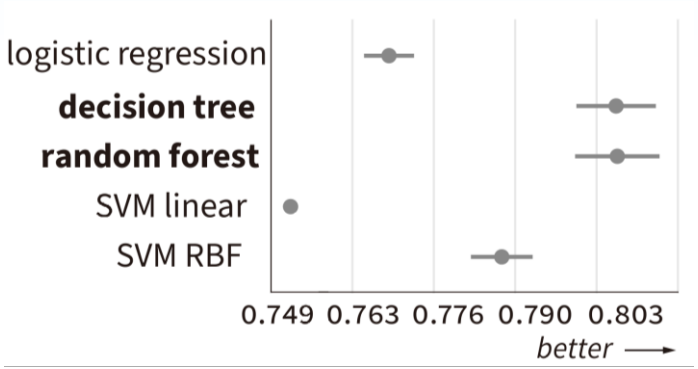

4862
Incorrect answer
14768
Correct answer

*HUE FRONT: color hue assigned to the front layer*
*HUE BACK: color hue assigned to the back layer*
*OPACITY FRONT: opacity assigned to the front layer*
*OPACITY BACK: opacity assigned to the back layer*
*HUE MIN: the smaller hue value between the two layers*
*HUE MAX: the larger hue value between the two layers*
*HUE MEAN: the average hue value between the two layers*
*HUE DISTANCE: the hue distance between the two layers*
*OPACITY MIN: the smaller opacity between the two layers*
*OPACITY MAX: the higher opacity value between the two layers*
*OPACITY MEAN: the average opacity value between the two layers*
*OPACITY DISTANCE: the opacity distance between the two layers*

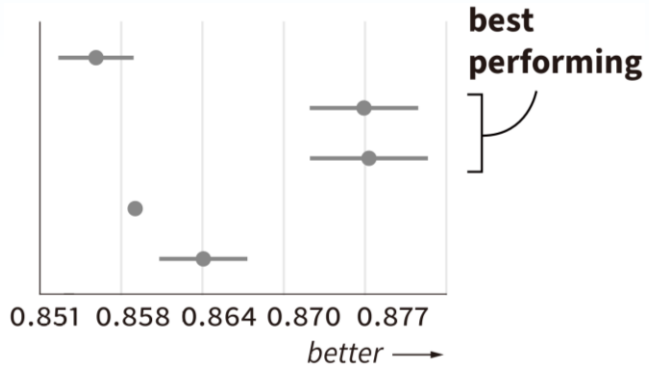
- Logistic regression
- Decision tree
- Random forest
- SVM with linear kernels
- SVM with radial basis function (RBF) kernels

- $Accuracy = \frac{TP+TN}{TP+TN+FP+FN}$
- $F1 = 2 * \frac{Precision*Recall}{Precision+Recall} = \frac{2TP}{2TP+FP+FN}$

# Results | Performance

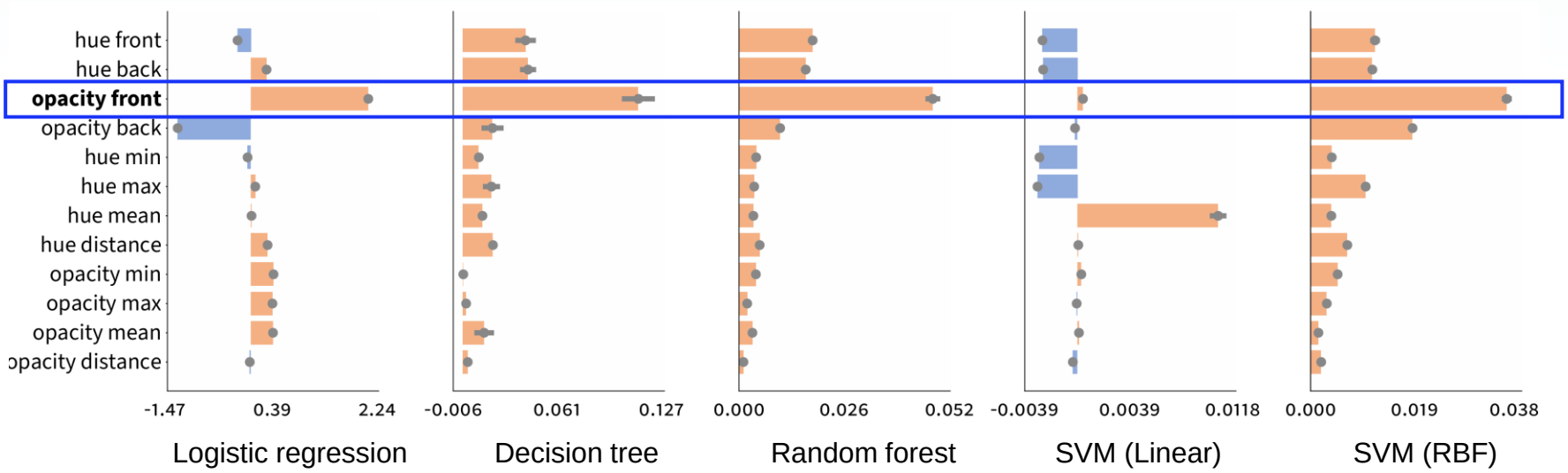



(a) accuracy of 12 features

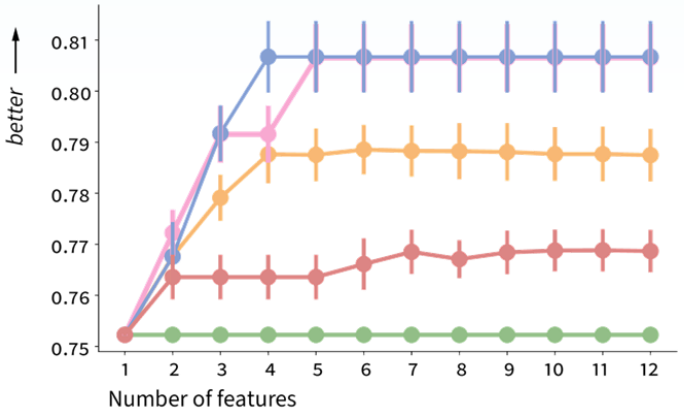



(b) F1 score of 12 features

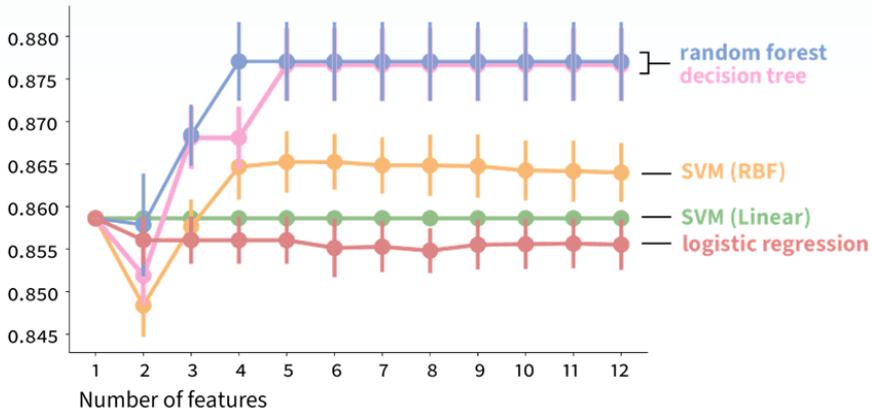
# Results | Feature importance



# Results | Sensitivity Analysis



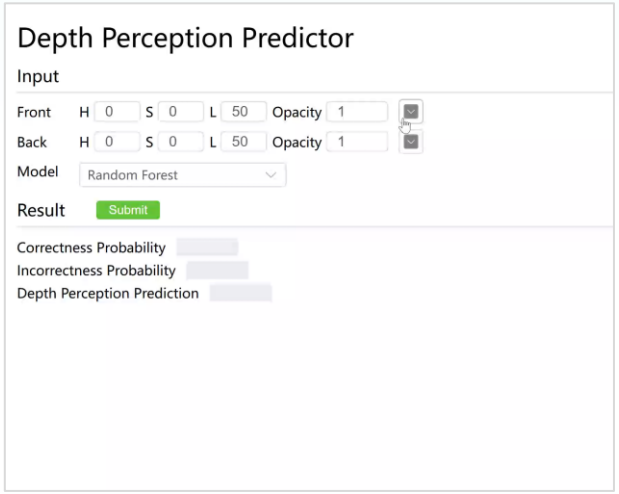

(a) accuracy changes

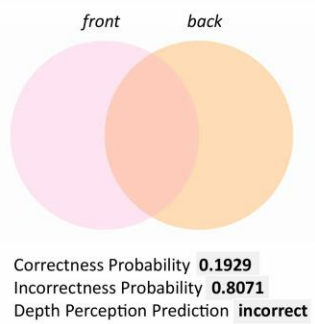


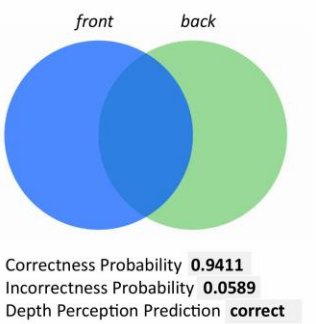

(b) F1 score changes

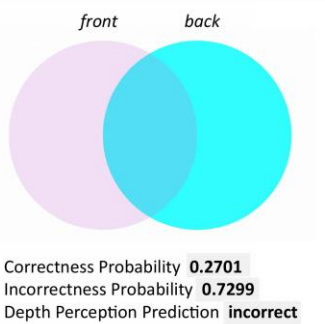
**Best performance model**: random forest with four features
(opacity front, hue front, hue back, opacity back)

# Results | Design Tool

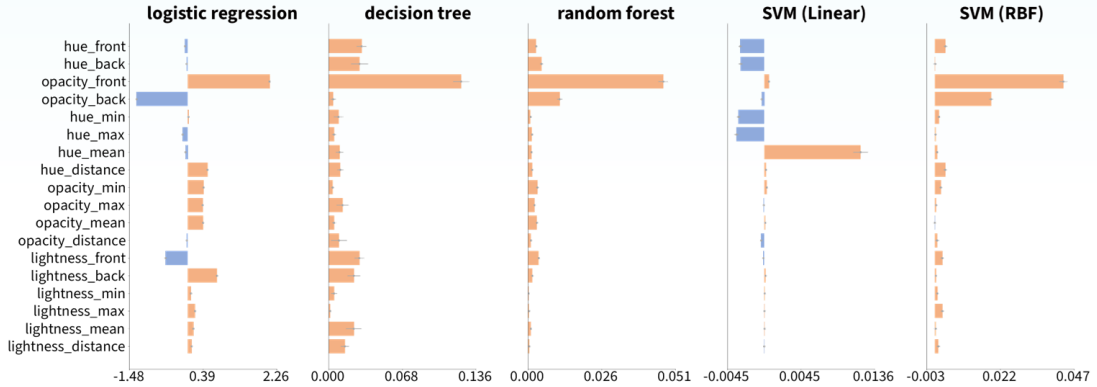


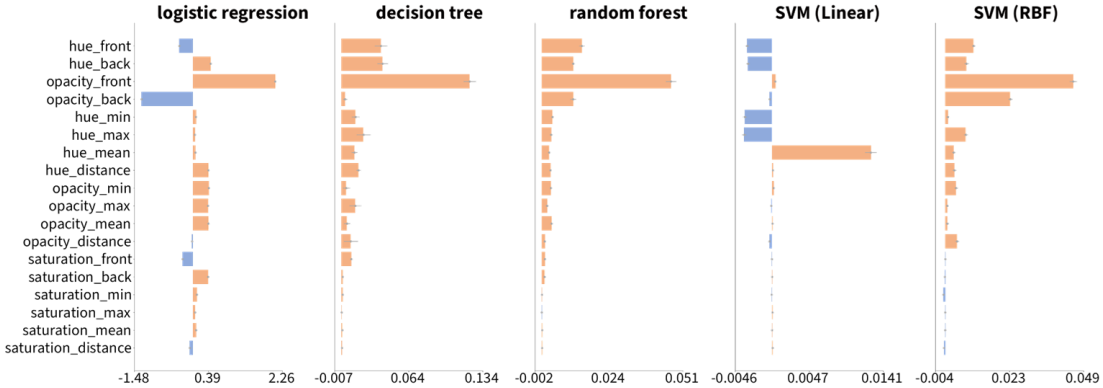



- Inferential Analyses
- Predictive Analyses
- **Exploratory Analyses**




Lightness has minimal influence

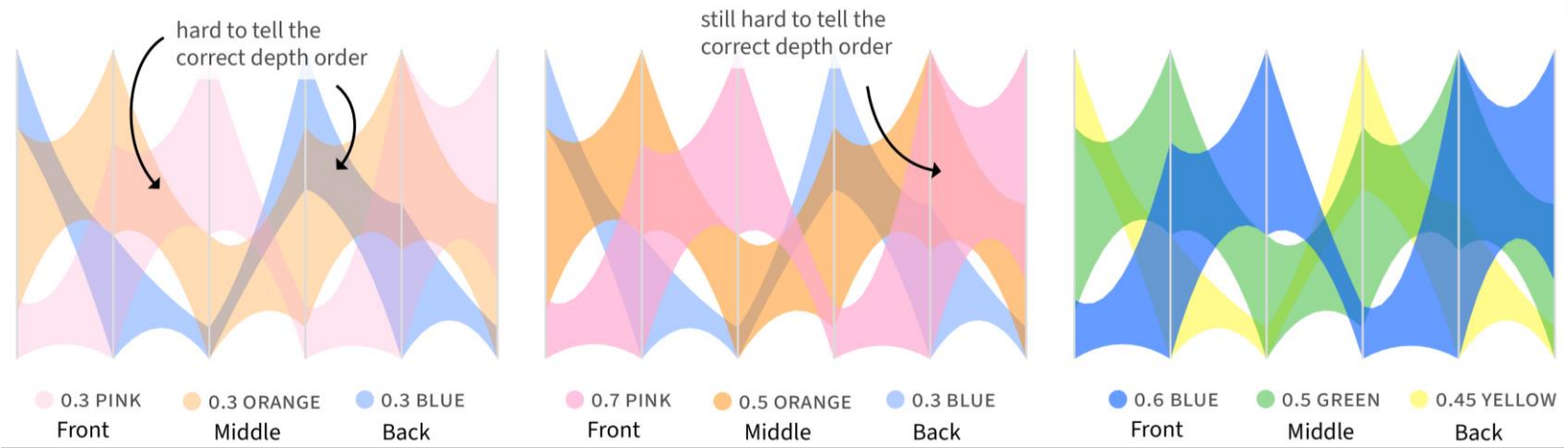



Saturation has minimal influence

# Design Guidelines

1. **Blue** and **pink** (or **yellow**) can be considered a priority in selecting colors for depth order perception tasks in the **front** and **back** layers, respectively.
2. **Cold** colors can be used for the front layer and **warm** colors for the back layer, except **red** and **purple**.
3. **Front** layers should be assigned to **higher** opacity, while **back** layers should be assigned to **lower** opacity.
4. In applications that require frequently adjusting opacity levels—such as medical imaging for exploring different organ structures—using colors like **red**, **blue** and **green** can be more effective.

# Practical Application




(a) Bad design case (b) Still bad after adjusting opacity (c) Easy to see the depth order

# Thanks for your attention!

More details and source code can be found on:
*https://amesholland.github.io/DepthOrderStudy/*