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Effect of Knitting Textures on Perceived Color Differences

Zhenhua Luo *PhD*

Under direction: **Renzo Shamey** *PhD*

Color Science and Imaging Laboratories

Wilson College of Textiles

North Carolina State University, USA

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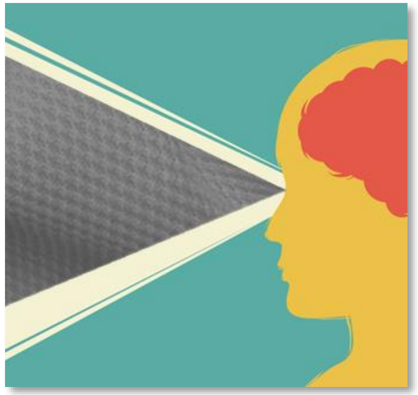
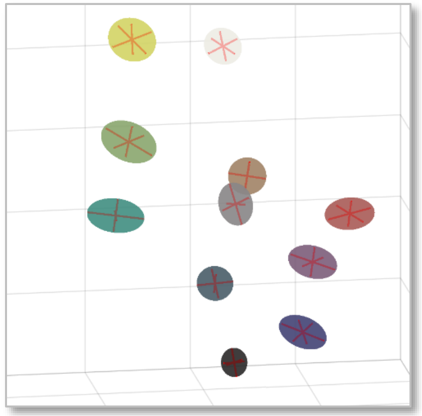
Research objectives



- Evaluate how selected knitting textures influence visual color difference assessments.

- Develop an experimental database that represents the visual tolerances of a population to small color differences in textured samples.

- Construct a tolerance dataset with an extensive sampling of the color space and a broad covering of the knitting texture patterns.



Reference viewing conditions

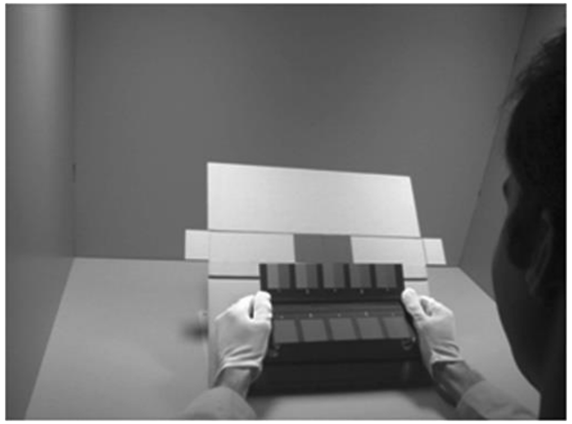


Fig 1. Visual assessment of color difference using a gray scale [*Shamey, et al., 2010*].

Reference viewing conditions

- Same size
- Homogeneous samples → Textured samples
- Hairline separation
- Same shape
- Mid-grey surrounding
- Etc.

Shamey, R., Cárdenas, L. M., Hinks, D., & Woodard, R. (2010). Comparison of naïve and expert subjects in the assessment of small color differences. JOSA A, 27(6), 1482-1489.

Current practice

$$\Delta E = \sqrt{\left(\frac{\Delta L^*}{k_L S_L}\right)^2 + \left(\frac{\Delta C^*_{ab}}{k_C S_C}\right)^2 + \left(\frac{\Delta H^*_{ab}}{k_H S_H}\right)^2}$$

- ΔL^*, ΔC^*_{ab}, and ΔH^*_{ab}: CIELAB metric lightness, chroma, and hue differences, respectively.
- S_L, S_C, and S_H: Weighting functions for the lightness, chroma, and hue components, respectively, to consider the positional dependencies.
- k_L, k_C, and k_H: **Parametric factors** to be adjusted according to different experimental viewing conditions.

Implicit assumptions

- Texture in textiles affects only lightness tolerances but not chroma or hue tolerances.
- Different textures in textiles affect the lightness tolerances to the same extent.

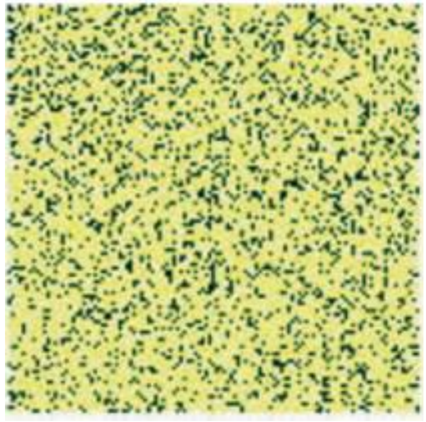
Parametric Factors (2:1:1) for Textiles?

- ❑ CMC(2:1) is recommended by the ISO for quantifying the colorfastness of textiles (*ISO 2009*), and the BSI (*1988*) and the AATCC (*2015*) for calculating small color differences.
- ❑ CIE94(2:1:1) and CIEDE2000(2:1:1) have been widely used in the color difference assessments of textile samples [*Becerir, 2011; Heggie, et al., 1996; Mangine, et al., 2005; Shamey, et al., 2014*].

Previous studies

Montag & Berns, 1999

- **Texture:** Simulated texture of thread wound on a card.
- **Color center:** Six neutral color centers at CIELAB L* = 10, 20, 40, 60, 80, and 90.
- **Major findings:** Texture had an effect of increasing the lightness tolerance thresholds by a factor of almost two as compared to the uniform stimuli.



Huertas, et al., 2006

- **Texture:** Simulated random dots varying in colors, size, and percentages of surface coverage.
- **Color center:** Five CIE centers as the background of stimuli.
- **Major findings:** Random-dot textures increase the tolerances on lightness, chroma, and hue, and usually the lightness tolerances were increased more than chroma or hue ones.

Montag, E. D., & Berns, R. S. (2000). Lightness dependencies and the effect of texture on suprathreshold lightness tolerances. Color Research & Application, 25(4), 241-249.
Huertas, R., Melgosa, M., & Hita, E. (2006). Influence of random-dot textures on perception of suprathreshold color differences. JOSA A, 23(9), 2067-2076.

Template samples

- **Physical samples:** 110 cotton knitted fabric samples with **10** varied textures and **11** distinct colors.

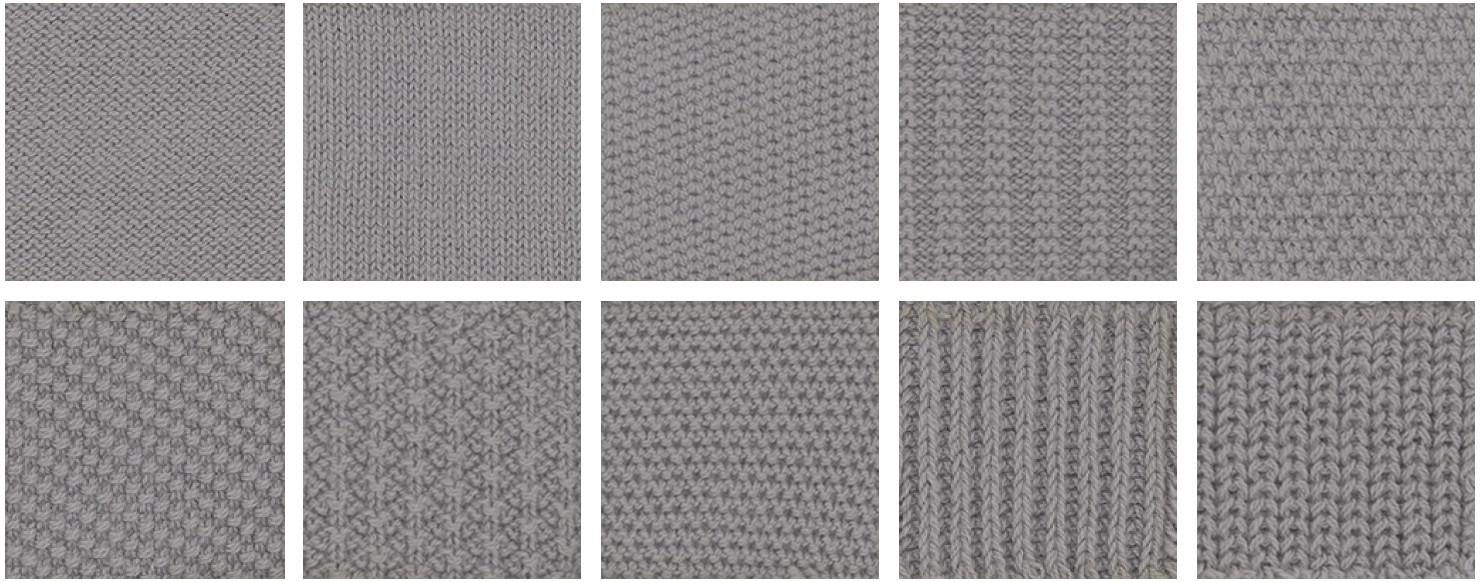


Fig 2. Ten selected texture patterns for the experiment.

Fig 3. Knitted textile samples in the colors approximating black, white, and nine CIE-recommended color centers.

S. K. Kulappurath, "Color evaluation of textured samples on LCD," in Investigating the Role of Texture on Visual and Instrumental Color Difference Assessments, Raleigh, NC, 2018, pp. 283–317.

Color-to-texture fusion

- **Fusion of color and texture:** A process that transforms the color of a source texture image into another target color to perceptually match the target image.
- Special consideration was given to the degree of **color fidelity** provided by the fusion models.
- **Color fidelity:** The degree to which the colors in a reproduced image match those of the target image.

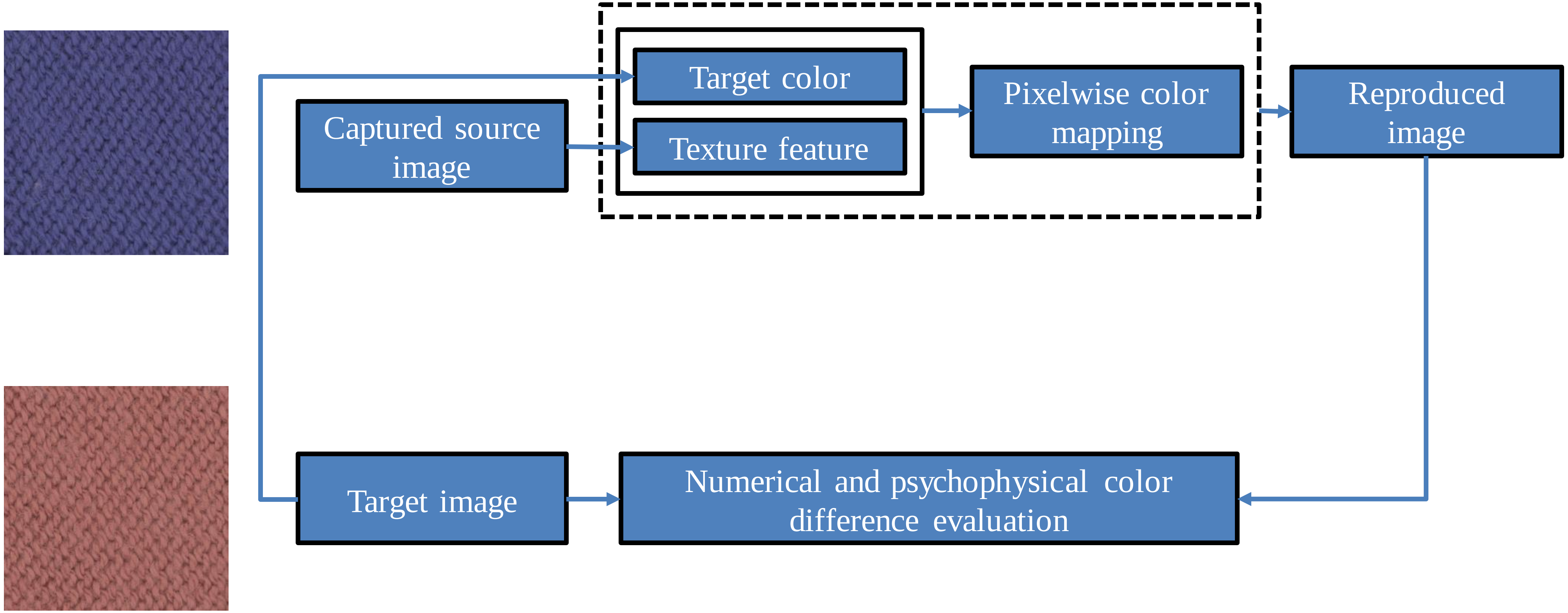


Fig 4. Schematic of the color-to-texture fusion process.

Shen, H. L., & Xin, J. H. (2005). Computational models for fusion of texture and color: a comparative study. Journal of Electronic Imaging, 14(3), 033003-033003.

Monitor-based visual assessment

- **Observers:** 26 participants (mean age: 23.5 years) with normal color vision.
- **Stimuli:**
  - **Comparison pair:** Textured or solid color samples.
  - **Anchor pair:** Homogeneous near-neutral stimuli with a fixed color difference of 2.1 ΔE^*_{ab} unit.

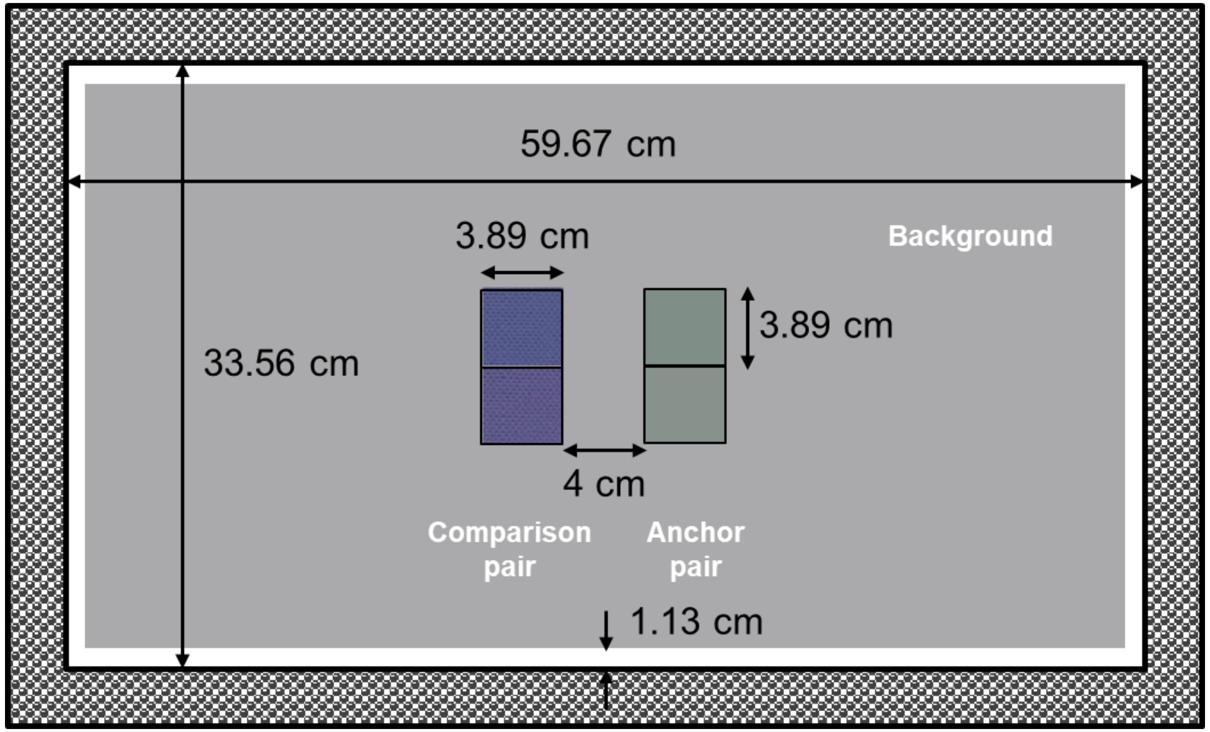


Fig 5. Arrangement of sample pairs used in the psychophysical experiment.

Monitor-based visual assessment

Experimental

- **Psychophysical method:** The method of adjustment (MOA)
- **Task:** The observers progressively adjust one sample of the comparison pair until its perceived color difference matches or comes closest to that of the anchor pair.
- **Visual response:** The comparison pair was established to have a color difference visually equivalent or approximate to that of the anchor pair (2.1 ΔE^*_{ab}).

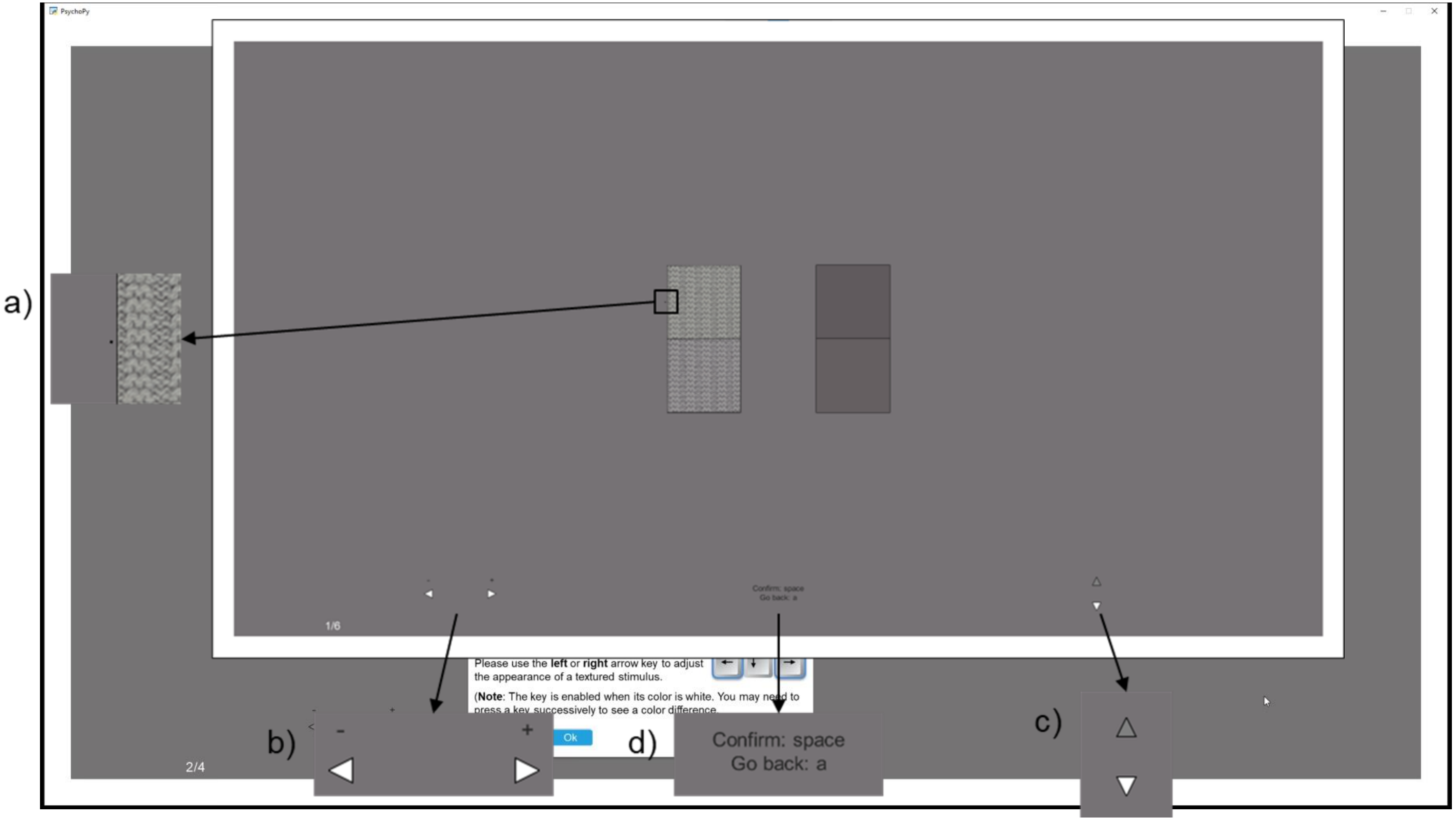


Fig 6. Screenshot of the monitor-based MOA experiment, showing **a)** the dot indicating the adjustable stimulus, **b)** arrow symbols representing color difference adjustment actions, **c)** arrow symbols indicating the order of the anchor pair, and **d)** prompts reminding observers of the keys for confirming or revising their decisions.

Color centers of textured stimuli

- **Color centers:** Approximations of 9 CIE-recommended color centers, black, and white.

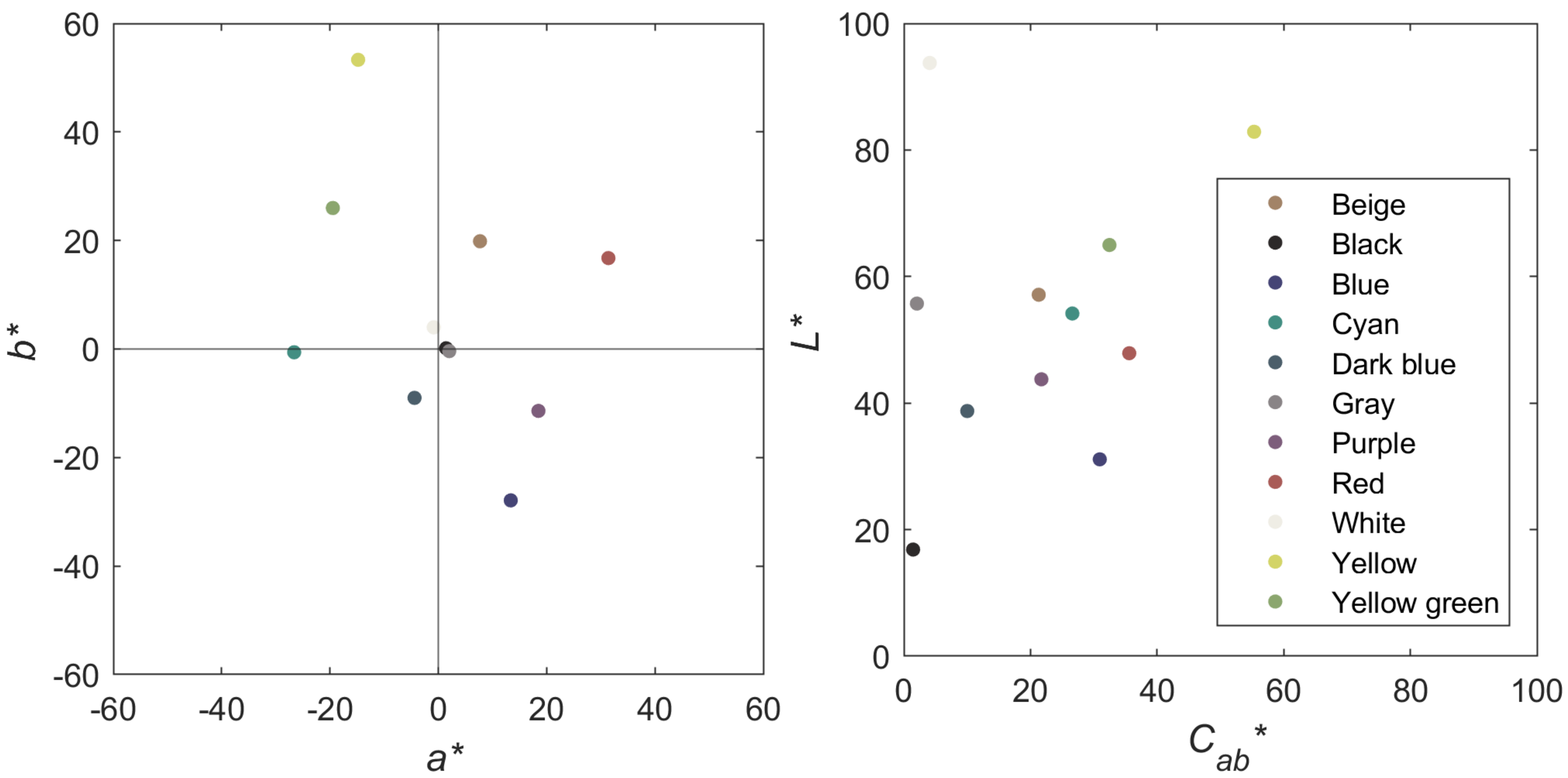


Fig 7. Distribution of the selected color centers in the CIELAB color space.

Robertson, A. R. (1978). CIE guidelines for coordinated research on colour-difference evaluation. Color Research & Application, 3(3), 149-151.
Witt, K. (1995). CIE guidelines for coordinated future work on industrial colour-difference evaluation. Color Research & Application, 20(6), 399-403.

Vector directions around color centers

Vector directions: 18 vector directions were sampled for each combination of color center and texture pattern.

Synthesis of stimuli

- For each combination, 100 stimuli (excluding the color center) were prepared along each pair of vectors.
- The target color of the stimuli varied in color difference relative to the center point, ranging from -12.5 ΔE^*_{ab} units to +12.5 ΔE^*_{ab} units in small steps of 0.25 units.
- **Homogenous stimuli:** The uniform samples displayed the target colors.
- **Textured stimuli:** Each texture pattern was mapped to those target colors using the selected fusion method.

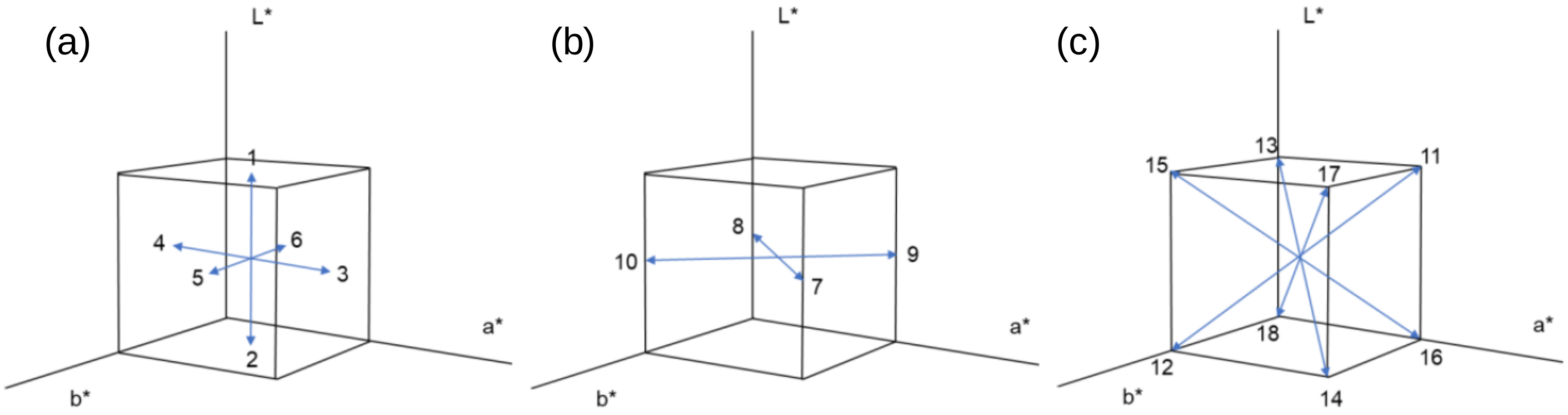


Fig 8. (a) Vectors 1-6 varying independently in L^*, a^*, and b^*, respectively; (b) vectors 7-10 simultaneous sampling chromaticness (a^* and b^*); (c) vectors 11-18 simultaneously sampling L^*, a^*, and b^*.

Statistical analysis

$$\Delta E = \sqrt{\left(\frac{\Delta L^*}{k_L S_L}\right)^2 + \left(\frac{\Delta C^*_{ab}}{k_C S_C}\right)^2 + \left(\frac{\Delta H^*_{ab}}{k_H S_H}\right)^2}$$

ΔL^*, ΔC^*_{ab}, and ΔH^*_{ab}: CIELAB metric lightness, chroma, and hue differences, respectively.

Isolating texture effects: Investigating texture effects independently on the lightness, chroma, or hue components.

Three datasets of visual tolerance

- Lightness tolerances:
  - Visual responses for the comparison pairs vary in directions 1 and 2.
  - ΔL^* accounted for 99.97% of the total color differences ΔE_{ab}.
- Chroma tolerances: On average, 92.73% of the total color differences were exclusively in ΔC^*_{ab} for the selected directions.
- Hue tolerances: ΔH^*_{ab} on average accounted for 91.00% of the total color differences for the selected directions.

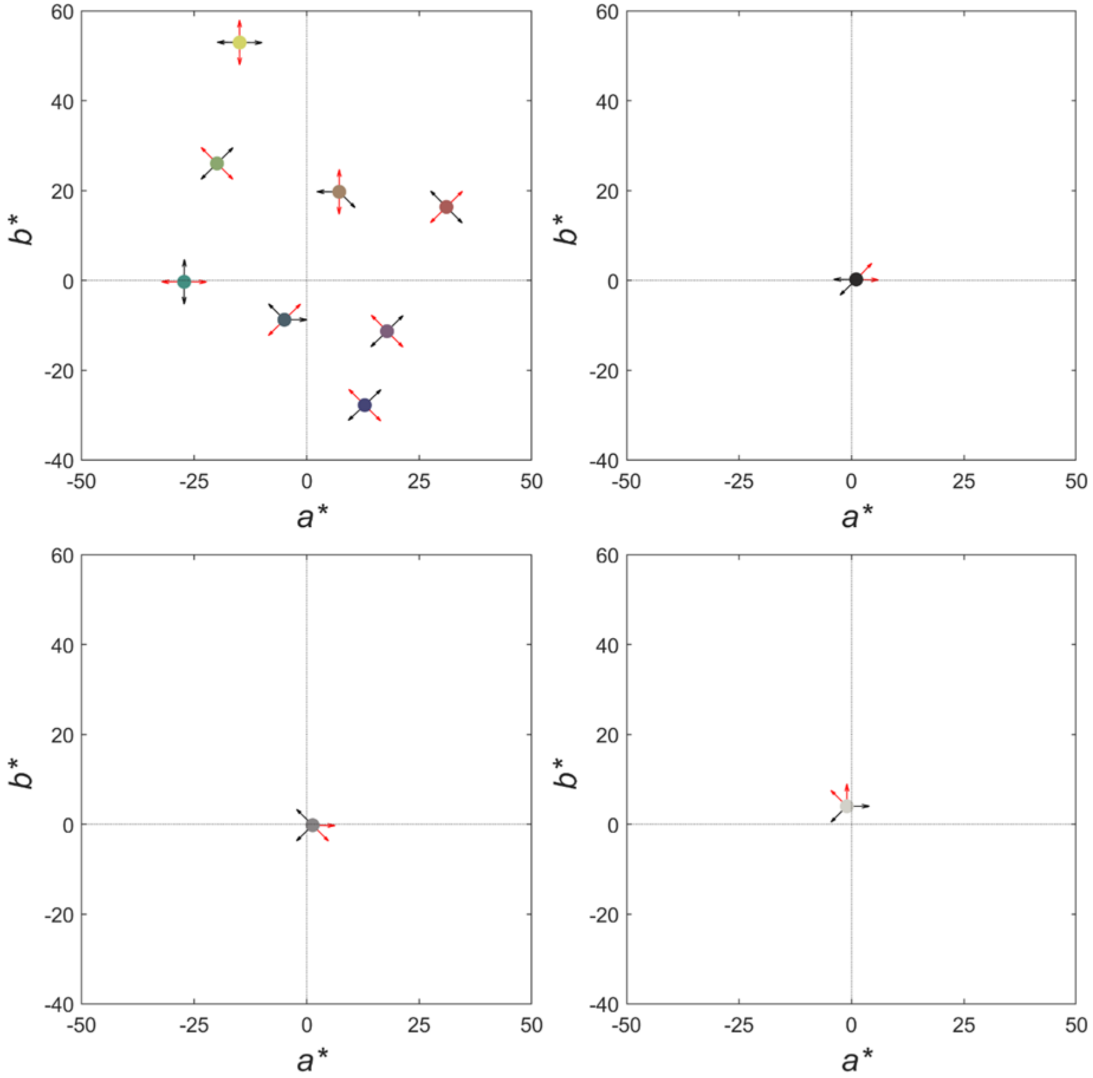


Fig 9. Vector directions with predominant color differences in ΔC^*_{ab} (red) and ΔH^*_{ab} (black) for 11 color centers: chromatic, black, gray, and white (arranged from left to right and top to bottom).

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Statistical analysis

- **Dependent variable:** Three datasets of color-difference tolerances computed in CIELAB units.
- **Independent variables:**
  - Color center (11 color centers)
  - Texture pattern (homogeneous and 10 texture structures)

Table 1. ANOVA results testing the effects of color center, texture pattern, and their interaction.

Dataset	Effect	df	*F*	*p*-value
Lightness tolerances	Color	10, 239.4	13.89	<0.0001***
	Texture	10, 232.1	5.24	<0.0001***
	Color × texture	100, 2308	1.64	<0.0001***
Chroma tolerances	Color	10, 246.1	53.96	<0.0001***
	Texture	10, 263.9	3.46	0.0003***
	Color × texture	100, 3372	1.01	0.45
Hue tolerances	Color	10, 238.3	23.32	<0.0001***
	Texture	10, 236.5	3.66	0.0001***
	Color × texture	100, 2820	1.37	0.01**

Note: The number of asterisks indicates the level of significance: * denotes p-value < 0.05, ** denotes p-value < 0.01, and *** denotes p-value < 0.001.

Texture effects on **lightness** tolerances

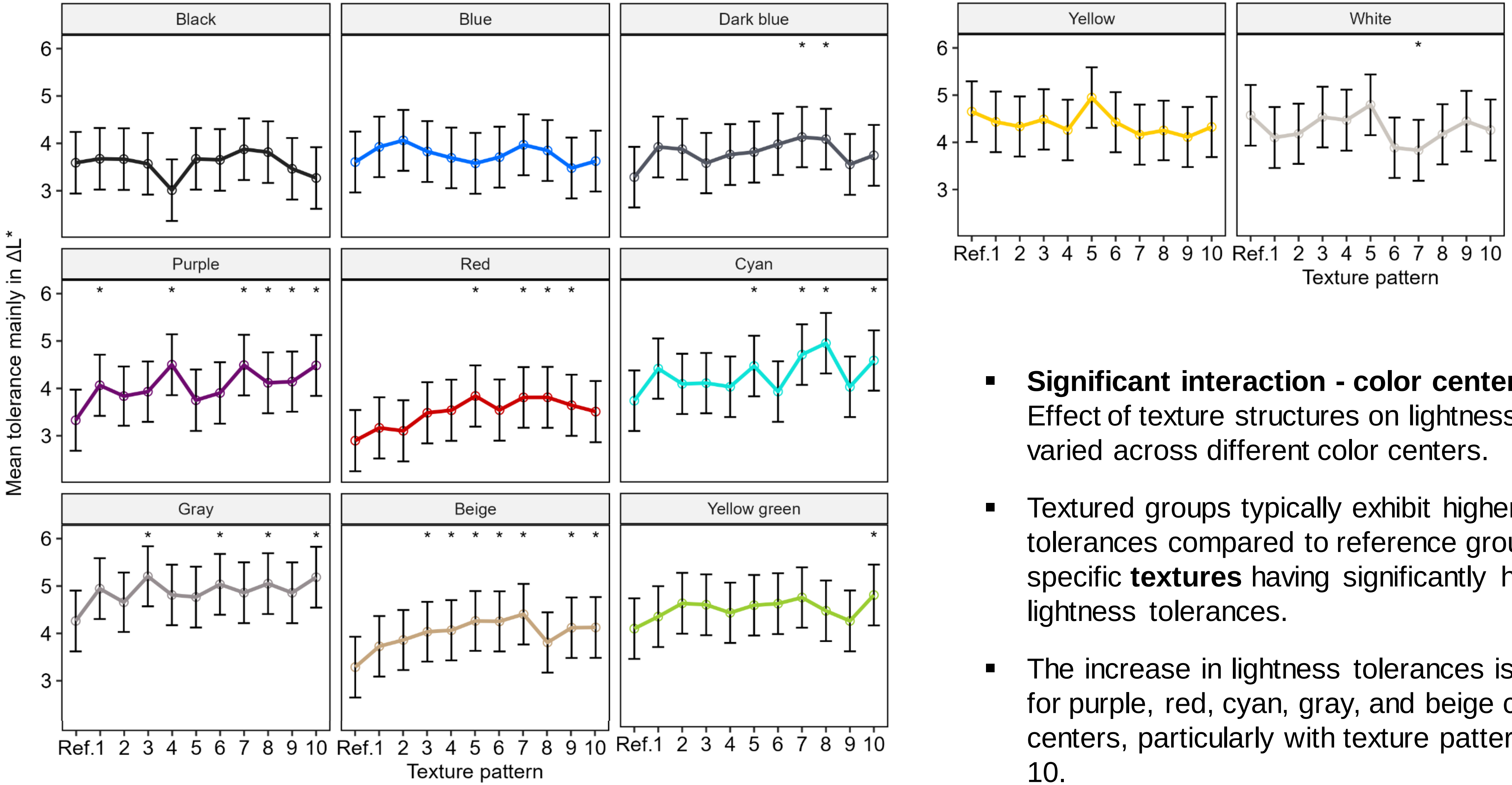

Fig 10. Mean visual tolerances primarily in *ΔL** as a function of stimuli's color center and texture pattern.

Notes: Error bars represent 95% confidence intervals; asterisks "*" indicate texture structures with significantly different mean tolerances than the corresponding references.

- **Significant interaction - color center × texture:** Effect of texture structures on lightness tolerances varied across different color centers.
- Textured groups typically exhibit higher lightness tolerances compared to reference groups, with specific **textures** having significantly higher lightness tolerances.
- The increase in lightness tolerances is prominent for purple, red, cyan, gray, and beige color centers, particularly with texture patterns 7, 8, and 10.

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Texture effects on **chroma** tolerances

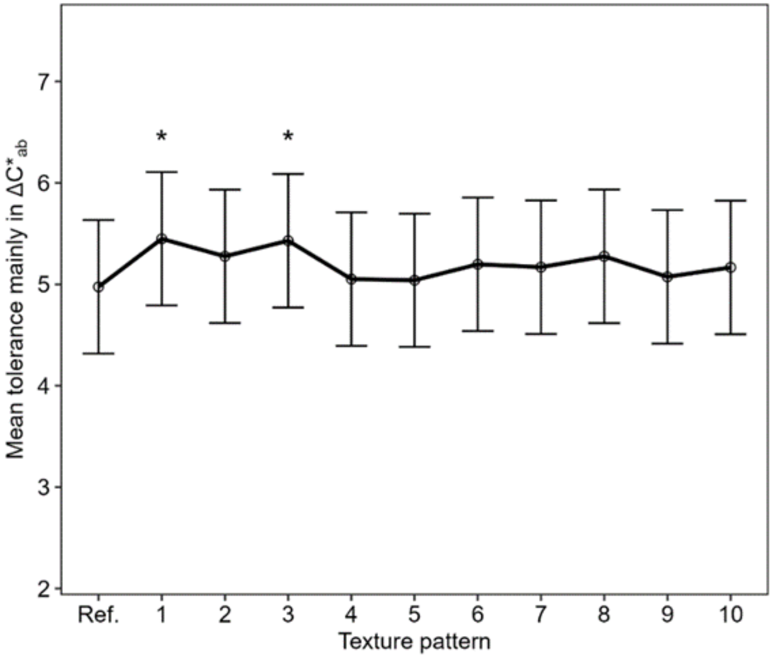

Fig 11. Mean visual tolerances primarily in ΔC^*_{ab} as a function of stimuli's texture pattern.

Note: Error bars represent 95% confidence intervals; asterisks "*" indicate texture structures with significantly different mean tolerances than the reference group.

Table 2. Comparisons between reference chroma tolerances with tolerances for stimuli with 10 texture patterns.

Texture	Mean difference	Adjusted *p*-value
1	0.47	0.001*
2	0.30	0.080
3	0.46	0.002*
4	0.08	0.996
5	0.06	0.999
6	0.22	0.349
7	0.19	0.508
8	0.30	0.088
9	0.10	0.977
10	0.19	0.523

Notes: The mean differences indicate the results obtained by subtracting the mean tolerance of the reference group from that of the textured group; asterisks indicate the textures with significantly different tolerances than the reference at the 0.05 alpha level.

- Texture patterns have a significant main effect on chroma tolerances.
- On average, chroma tolerances are higher for textured stimuli compared to the reference group.
- Textures 1 and 3 significantly increase chroma tolerances, while textures 2 and 8 show marginal increases.

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Texture effects on **hue** tolerances

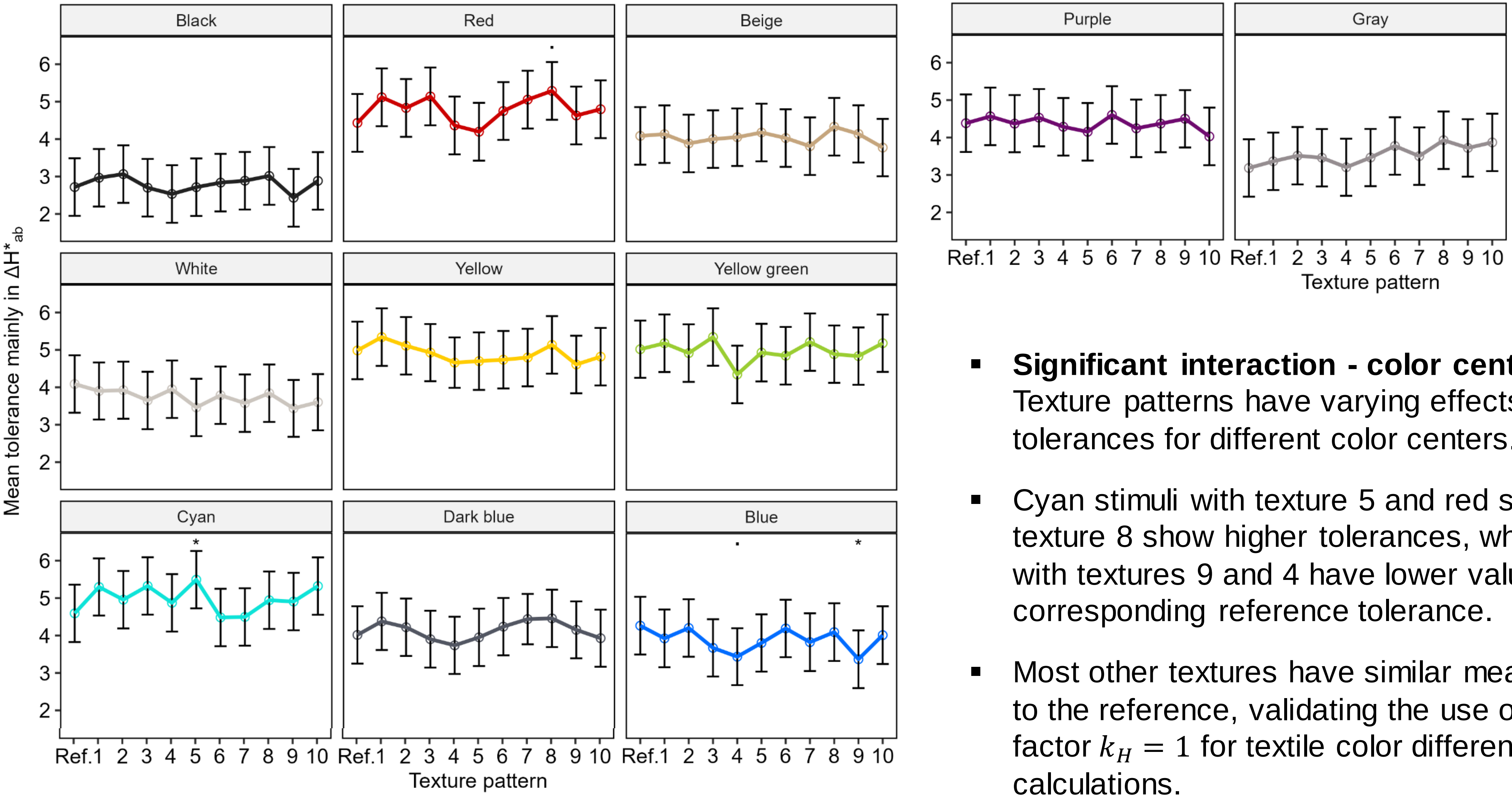

Fig 12. Mean visual tolerances primarily in ΔH^*_{ab} as a function of stimuli's color center and texture pattern.

- **Significant interaction - color center × texture:** Texture patterns have varying effects on hue tolerances for different color centers.
- Cyan stimuli with texture 5 and red stimuli with texture 8 show higher tolerances, while blue stimuli with textures 9 and 4 have lower values than the corresponding reference tolerance.
- Most other textures have similar mean tolerances to the reference, validating the use of parametric factor $k_H = 1$ for textile color difference calculations.

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Performance testing of color-difference metrics

STandardized **RE**sidual **S**um of **S**quares (STRESS)

Computed color differences (ΔE)

Visual color difference (ΔV)

Table 3. Statistical significance testing between each pair of color-difference formulas.

	Parametric factor	ΔE^*_{ab}	ΔE_{CMC}		ΔE^*_{94}		ΔE_{00}	
		-	1	2	1	2	1	2
ΔE^*_{ab}	-	1.00	**0.61**	**0.37**	1.21	0.94	0.97	**0.51**
ΔE_{CMC}	1	1.64	1.00	**0.61**	1.99	1.54	1.60	**0.83**
	2	2.71	1.65	1.00	3.28	2.54	2.63	1.37
ΔE^*_{94}	1	**0.82**	**0.50**	**0.30**	1.00	**0.77**	**0.80**	**0.42**
	2	1.07	**0.65**	**0.39**	1.29	1.00	1.04	**0.54**
ΔE_{00}	1	1.03	**0.63**	**0.38**	1.25	0.97	1.00	**0.52**
	2	1.98	1.20	**0.73**	2.40	1.86	1.92	1.00

Notes:

- Boldface values indicate a statistically significant improvement in performance for the formula in the respective row compared to that in the corresponding column.
- Gray-shaded cells denote that statistically worse performance for the formula in the row compared to that in the column.

Key findings:

- CIE94(1:1:1) significantly outperformed the other tested models.
- CMC(2:1) displayed the least favorable performance among the tested formulas.
- Formulas with parametric factors (2:1:1) exhibited significantly worse performance than their counterparts with (1:1:1) ratio.

Conclusions

- A dataset involving 11 color centers and 11 surface structures (homogenous and 10 textured patterns) was generated.
- The study confirmed that selected knitting textures have a substantial impact on visual color difference assessments, with significant effects on lightness, chroma, and hue tolerances.
- Specific textures led to significantly higher lightness tolerances compared to uniform stimuli, with variations observed across color centers and some texture patterns showing more prominent effects.
- Similar trends were observed for chroma, and hue tolerances influenced by texture, although these effects were generally more modest than those on lightness tolerances.
- Among the tested formulas, CIE94(1:1:1) emerged as the top performer in predicting visual color differences for stimuli with tested textures.
- Formulas with parametric factors (2:1:1) exhibited significantly worse performance than their counterparts with (1:1:1) ratio.

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Shamey, R., Cárdenas, L. M., Hinks, D., & Woodard, R. (2010). Comparison of naïve and expert subjects in the assessment of small color differences. *JOSA A*, *27*(6), 1482-1489.

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Thank You