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Cross-Modal Associations Between Color and Touch: Mapping Haptic and Tactile Terms to the Surface of the Munsell Color Solid

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Abstract

This study investigated cross-modal associations between color and touch using a matching task. Participants matched colors drawn from the surface of the Munsell color solid to antonym pairs of haptic/tactile adjectives. For most of the term pairs assessed (*soft*/*hard*, *smooth*/*rough*, *flat*/*uneven*, *slippery*/*not slippery*, *light*/*heavy*, *thin*/*thick* and *round*/*sharp*) matching appears predominantly influenced by lightness, with the first term from each pair matched to light colors and the other to dark colors, a result in close agreement with previous research. For two terms, *warm* and *wet*, there were clear influences of hue on task performance. There were also similarities between patterns of color matching to several of the haptic/tactile terms assessed and color matching to another term, *dislike*. This suggests valence may play a mediating role in cross-modal associations involving touch and color.

Keywords

Color, touch, cross-modal correspondences

1. Introduction

Cross-modal correspondences involve associations between different perceptual modalities. One reason for investigating such associations, which have been noted across almost every possible pair of modalities, and the mechanisms that give rise to them is that such research contributes to understanding of multisensory integration, the process by which information from different modalities is integrated in the nervous system.

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Several mechanisms have been proposed to explain cross-modal associations (see Spence, 2011). Structural explanations propose that some cross-modal associations are caused by intrinsic properties of perceptual systems. Other explanations suggest associations can be learned. One potential mechanism involves linguistic/semantic correspondences, as in the association between the pitch of sounds and the location of objects, both of which can be described using a high to low continuum. Another proposed mechanism involves learning about regular co-occurrence of properties in the environment. Emotion may also play a role in cross-modal associations, with different attributes being associated on the basis of similar emotional responses (e.g., Marks, 1975; Palmer *et al.*, 2013).

A wealth of research indicates that haptics interact with vision in multisensory integration (Spence, 2011). Previous work shows that a multi-modal network is activated in the brain during haptic or visual exploration, suggesting common haptic and visual representation of object shape (Amedi *et al.* 2001; James *et al.* 2002). For attributes other than shape, such as texture, some have suggested that vision and touch are not integrated (Whitaker *et al.*, 2008). Others propose the integration of arbitrary signals from vision and touch, such as brightness and stiffness, can be learned (Ernst, 2007).

However, links between haptics and color vision specifically have been somewhat neglected. Color is known to be associated with music (Palmer *et al.*, 2013), taste (Tromasik-Krotki and Strojny, 2008) and smell (Deroy and Spence, 2016; Kim, 2013; Schifferstein and Tanudjaja, 2004), as well as to the tactile experience of temperature (Ho *et al.*, 2014a, b) and haptic experience of weight (Monroe, 1925). But, until recently, little was known about the involvement of color in cross-modal associations involving other haptic sensations. Studies showing that low-level visual mechanisms for contour and volume detection are color sensitive (Gheorghiu and Kingdom, 2007a) raise questions about how color might be involved in multisensory interactions with various object attributes. For example, assuming common haptic and visual representation of object shape, if color is involved in contour and volume detection, then does it play a role in object shape representation?

Three recent studies investigating color–touch associations using matching tasks, summarized in Table 1, provide evidence of color–touch associations. All studies show consistent effects of brightness (referred to henceforth using the term lightness), with stimuli on one extreme of a haptic/tactile dimension being associated with lighter colors and stimuli on the other extreme associated with darker colors. The studies provide less consistent results with respect to color's other two dimensions, hue and saturation. Ludwig and Simner (2013) found saturation influences children's, though not adults', associations. By contrast, Slobodenyuk *et al.* (2015) provide evidence that saturation influences associations in adults, though in a direction opposite to that reported

Table 1.
Summary of three recent studies investigating associations between color and touch. Haptic terms and color terms are shown in italics. Because color stimuli in all three studies were luminant, the term ‘brightness’ is used in the table. Elsewhere in the text, the term ‘lightness’ is used to refer to both brightness and lightness

Study	Haptic stimuli	Main findings			
		Brightness	Saturation	Hue	Color categories
Ludwig and Simner, 2013	Smooth	Brighter	Higher*	N/A	*Pink*, *white* and *yellow*
– Haptic sensations	Rough	Darker	Lower*		*Black* and *brown*
– Monitor emulated colors	Soft	Brighter	Higher*	N/A	*Pink* and *yellow*
– Matching color to sensation	Hard	Darker	Lower*		*Black*
– Conducted in UK	Round	Brighter	No effect	N/A	No evidence
– Child and adult participants	Pointed	Darker	No effect		*Black* and *Red*
Slobodenyuk *et al.*, 2015	Smooth	Brighter	Lower	No effect	N/A
– Simulated haptic sensations	Rough	Darker	Higher	Violet–red, red	
– Monitor emulated colors	Soft	Brighter	Lower	Yellow, yellow–green	N/A
– Matching color to sensation	Hard	Darker	Higher	Violet–red, red	
– Conducted in Lebanon	Light	Brighter	Lower	No effect	N/A
– Adult participants	Heavy	Darker	Higher	Violet–red	
	Elastic	Brighter	Lower	Yellow, green–yellow	N/A
	Inelastic	Darker	Higher	Violet–red, red	
	Non-adhesive	Brighter	Lower	Violet, red	N/A
	Adhesive	Darker	Higher	Violet–red, red, blue–violet	

Table 1.
(Continued)

Study	Haptic stimuli	Main findings			
		Brightness	Saturation	Hue	Color categories
Jraissati *et al*., 2016	*Smooth*	Brighter	Lower	Red–purple	No evidence
– Haptic terms	*Rough*	Darker	Higher	Yellow	
– Monitor emulated colors	*Soft*	Brighter	No effect	Blue–purple	No evidence
– Matching color to terms	*Hard*	Darker	No effect	Yellow	
– Conducted in Lebanon using Arabic speakers	*Light*	Brighter	Lower	Red–purple	No evidence
– Adult participants	*Heavy*	Darker	Higher	Yellow	
	Cold	No effect	Lower	Blue–green	No evidence
	Warm	No effect	Higher	Red	
	Thin	Brighter	Lower	Green	No evidence
	Thick	Darker	Higher	Purple	

* Effects of saturation found only in children.

in children. Results are similarly inconsistent with respect to hue, though all studies imply hue is involved. Establishing hue's role in cross-modal associations is of particular interest because hue is a circular dimension. Consequently mechanisms underlying cross-modal correspondences involving hue may differ from those that drive correspondences involving *prothetic* perceptual dimensions, which vary in intensity, such as lightness and saturation.

Inconsistencies in the findings of studies summarized in Table 1 may stem from differences in stimuli. Jraissati *et al*. (2016), for instance, used haptic/tactile *adjectives*, whilst Ludwig and Simner (2013) and Slobodenyuk *et al*. (2015) used haptic/tactile *sensations* of varying intensities. Further, Jraissati *et al*. used a limited range of colors, drawn from the surface of the Munsell system (see Note 1). The other studies specified colors using a different metric and did not constrain the range of colors available for matching.

There were also differences in the structure of the tasks used across studies. In Jraissati *et al*., each trial involved matched haptic/tactile terms to a single presented color. In the other two studies a single haptic/tactile sensation was presented and participants used a color picker to navigate through color space to choose a matching color. Though this method offers the widest possible choice of color it can be a challenging process (Schwarz *et al*., 1987), as it presupposes that participants know both the color they are searching for and how to find it. One similarity between all three studies was the emulation of colors on a monitor. This raises questions about both the accuracy of color rendering and ecological validity: most colors in the environment involve reflected rather than luminant light.

The study reported here also investigated correspondences between color and touch, though differed in several respects in its aims and the methodology employed. The basic goal was to map associations between haptic/tactile terms and colors drawn from the surface of the Munsell color solid. Color stimuli were physical Munsell chips, rather than emulated colors, ensuring accuracy in stimulus specification and providing more natural colors. Colors were presented in an array, making it easy for participants to select them for matching.

Like Jraissati *et al*. (2016), haptic terms rather than actual sensations were used. Individual trials involved matching colors to haptic/tactile terms, rather than matching haptic/tactile terms to individually presented colors, hence allowing the bi-directionality of previously noted effects to be gauged. We also tested Turkish speakers, permitting assessment of potential cultural and linguistic effects on performance. Finally, in order to investigate the possible involvement of valence in correspondences involving color and touch, color preference was also assessed (see e.g., Marks, 1975; Palmer *et al*., 2013).

2. Matching Task

2.1. Method

2.1.1. Participants

Fifty native Turkish speakers (44 women and six men; mean age = 21 years 4 months; SD = 18 months), recruited from Bahçeşehir University's student population, took part in the study. They received course credits for participation.

2.1.2. Stimuli

Stimuli consisted of 64 Munsell color chips and 22 Turkish words (hereafter terms). In referring to terms, English equivalents are used. The terms consisted of 11 pairs of antonyms, shown in Table 2. Ten pairs described tactile/haptic sensations (e.g. *soft/hard*). The remaining pair consisted of the terms *like* and *dislike*. The procedure used to derive Turkish terms from a list of English term pairs is described in Appendix A. Each term was printed on a piece of white card.

Color stimuli were 64 Munsell chips, a subset of those used in the World Color Survey (Kay *et al.*, 2009), each mounted in a grey-bordered 35-mm slide case. Sixty were chromatic, the remaining four achromatic (see Note 2). Chromatic chips were selected at five 5 hue unit intervals at six different lightness

Table 2.
Turkish term pairs used in experiment (*italics*), with equivalent English terms

Touch			Haptics		
soğuk cool	↔	*sıcak* warm	*hafif* light	↔	*ağir* heavy
yumuşak soft	↔	*sert* hard	*kalın* thick	↔	*ince* thin
pürüzsüz smooth	↔	*pürüzlü* rough	*yuvarlak* round	↔	*sivri* pointed
kuru dry	↔	*ıslak* wet	Preference		
engebeli uneven	↔	*düz* flat	*begendiginiz* like	↔	*beyenmeyediniz* dislike
yapışkan sticky	↔	*yapışmayan* not sticky			
kaygan slippery	↔	*kaymayan* not slippery			

levels. Chips of lower lightness levels appear darker, those of higher levels lighter. Chromatic chips were of maximum available saturation at each hue and lightness level selected, forming a lattice arranged on the surface of the Munsell solid. Achromatic chips represent locations on a vertical axis running through the center of the solid. Munsell notations of the chips are shown in Table 3.

2.1.3. Apparatus, Design and Procedure

Participants were screened for color vision deficiencies using an online test (Barbur *et al.*, 1994). One participant failed the test. His data were excluded from analyses. The procedure was explained to each participant (see Appendix B), with each of 11 trials taking the following form. The 64 Munsell chips were spread randomly on the center of a table covered with a sheet of dark grey card. A pair of terms (e.g., *warm*/*cool*) was placed on the table, flanking the chips. The task involved matching colors to each term by placing chips next to the term they matched. When finished, participants' selections were recorded and the next trial initiated.

Each term pair featured in one trial. Trial order was randomized, with the exception of the first and last trials which used, respectively, *warm*/*cool* and *like*/*dislike* pairs. Participants were allowed to match as many chips as they wished to each term, though the task's structure prevented matching the same chip to both terms used in a trial. Participants were also required to match at least one chip to each term. If they felt unable to do so, they were asked to select a chip at random. Participants took between 20 minutes and 1 hour to complete the task, conducted in a windowless room using a broad spectrum 6500K illuminant.

2.2. Results

2.2.1. Descriptive Statistics

On trials involving tactile/haptic terms participants made, on average, 17.7 matches per trial, with wide variation between participants (min. = 3.6, max. = 58.7). Participants made most matches on the *warm*/*cool* trial (mean selections/participant = 20.1) and fewest on the *sticky*/*not sticky* trial (12.4). For the term pair *like*/*dislike*, participants matched an average of 17.3 chips (min. 2, max. 62). Figure 1 shows, for each term pair, the average number of selections of chromatic (Fig. 1a) and achromatic (Fig. 1b) chips.

Table 4 shows the relative frequency with which each Munsell chip was matched to *haptic*/*tactile* terms across all trials involving these terms. Values in the table are ratios, with values larger than one indicating chips chosen more frequently than expected, assuming random matching, and smaller values the reverse. Producing these ratios involved calculating, separately for each participant, the percentage of matches made using each chip and dividing each value

Table 3.
Notations of Munsell chips used in matching task. Shaded areas indicate chips used. Numbers in shaded areas indicate saturation level (higher values indicate higher saturation) of individual chips. Hue is indicated at the bottom of the table, lightness at left (higher values indicating lighter colours)

Chromatic

Lightness		R		YR		Y		GY		G		BG		B		PB		P		RP	
		2.5	7.5	2.5	7.5	2.5	7.5	2.5	7.5	2.5	7.5	2.5	7.5	2.5	7.5	2.5	7.5	2.5	7.5	2.5	7.5
H	9	2		2		4		6		2		2		2		2		2		2	
	8		6		8		12		10		6		4		4		4		6		6
M	6	12		16		10		10		10		8		8		10		8		10	
	5		14		10		8		10		10		8		8		10		10		14
L	3	10		8		4		4		8		6		6		10		10		10	
	2		8		4		2		4		6		4		6		10		6		8

Hue

Achromatic

Value	
9.5	0
7	0
4	0
1.5	0

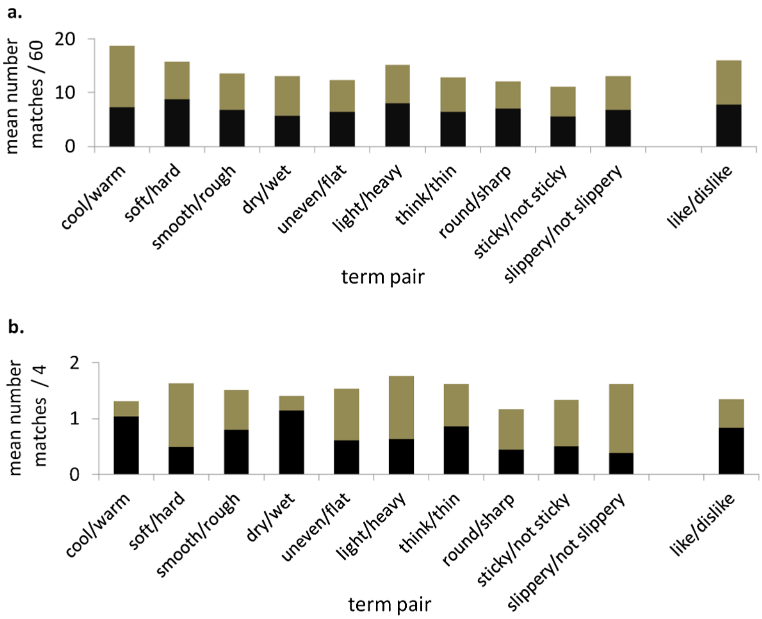

Figure 1. Mean number of matches made by participants on trials involving each term pair, for chromatic (a) and achromatic chips (b). For each term pair, darker section of bar represents the first term listed.

by 1.56 (the expected percentage of matches made using each chip assuming random matching behavior). For each chip, individual participant ratio values were averaged to give the value shown in Table 4. The least matched chip was 7.5BG/5 (ratio = 0.38). The most frequently matched chip was Acr/1.5, the darkest achromatic chip (ratio = 2.72).

2.2.2. Inferential Statistics

Our initial approach involved using ANOVAs to assess differences between matches made using chips from different areas of the Munsell array. However, results were difficult to interpret, particularly since post-hoc testing revealed very many significant differences. In consequence, we adopted a cruder but simpler approach, primarily using Bonferroni corrected one-sample tests. These tests examine whether chips from different areas of the color array are matched to terms more or less than would be expected assuming participants match chips to terms at random. Two sets of analyses are described below.

2.2.2.1. Analyses of Data From Individual Trials. These analyses consider data from each trial separately. Three analyses were conducted. The first examined matching of terms to specific areas within the Munsell array. Further analyses examined matching to chips of differing hue codes and lightness levels. It is important to stress that neither of the latter two analyses can definitely

Table 4.
Relative frequency of matching of Munsell chips to haptic/tactile terms. Numbers within the table are ratios indicating how much more (numbers > 1) or less frequently (numbers < 1) each chip was matched compared to distribution assuming chips are matched at random

Chromatic

Lightness		R 2.5	R 7.5	YR 2.5	YR 7.5	Y 2.5	Y 7.5	GY 2.5	GY 7.5	G 2.5	G 7.5	BG 2.5	BG 7.5	B 2.5	B 7.5	PB 2.5	PB 7.5	P 2.5	P 7.5	RP 2.5	RP 7.5
H	9	1.3		1.6		1.2		1.1		0.9		1.1		1.1		1.4		1.3		1.2	
	8		1.3		0.9		1.2		1.0		0.9		1.0		1.4		0.8		0.8		1.2
M	6	0.8		1.4		0.7		0.5		0.6		0.5		0.9		0.9		0.6		0.4	
	5		1.2		0.6		0.6		0.5		0.5		0.4		0.7		0.6		0.4		1.0
L	3	0.8		1.1		1.6		0.9		0.6		0.4		0.5		0.9		0.5		0.6	
	2		1.3		2.2		2.2		1.1		0.8		0.9		0.8		0.9		0.7		1.1

Hue

Achromatic

Value	
9.5	2.1
7	1.1
4	1.6
1.5	2.7

Key: matched more than average; matched less than average determine the independent contributions of hue and lightness to matching, because saturation levels vary as hue and lightness change (see Table 3). Rather, the analysis of lightness examines whether the longitudinal location of chips on the surface of the Munsell color solid affects matching. The analysis of hue examines whether matching is influenced by latitudinal location. Individual analyses are reported in the following three sections, followed by a section summarizing the results.

2.2.2.1.1. Analyses 1: Munsell Array Area. The Munsell array was divided in 32 areas, each represented by two chips. For example, the six chips of hue R were split into three groups based on lightness levels. The same procedure was followed for chips of other hue notations, dividing the chromatic array into 30 areas; 10 hue regions, each containing three different lightness levels (high, medium and low), shown in Table 4. For the four achromatic chips, data from the two lightest and two darkest chips were combined, giving two further areas.

Data was prepared for analysis as follows. For each participant's data on each trial, chips matched to one term (e.g., *warm*) were assigned a value of $+1$, chips matched to the other term (e.g., *cool*) -1, and chips not matched to either term 0. For the pair of chips contained within each of the 32 Munsell areas participant responses could thus take the following values; 0/0, 0/1, 1/0, 1/1, $1/{-1}$, $-1/{-1}$, $0/{-1}$ or $-1/0$. To create a single value representing each area, the average of the two values was used. If participants match chips to terms at random, then (on trials involving any given term pair) the average for each of the 32 areas of the Munsell array should be 0. Data from each of the 32 areas was analyzed using the Wilcoxon one-sample signed rank tests (critical p-value $= 0.00156$, test value $= 0$).

Figure 2 summarizes the results. Shaded regions show areas within the array significantly associated with particular terms (min. sig. $z = 3.2$, $p = 0.00144$, $r = 0.46$). Significant results were found on all but one trial, that involving term pair *sticky*/*not sticky*. For example, the upper left section of Fig. 2 deals with the *warm*/*cool* trial. The four darkest shaded areas within the array are significantly associated with matches to the term *warm*, whilst the lighter shaded area (dark achromatic chips) is associated with matches to the term *cool*. Shaded letters representing Munsell hue codes (R, RY etc) and lightness (H, M, L) relate to further analyses, described next.

2.2.2.1.2. Analyses 2: Hue. This analysis investigated matching involving chips of different hue codes. The array was divided into 10 areas corresponding to Munsell hue codes (R, RY, Y etc). Data from the 6 chips in each area was then combined as described previously. Data from each trial was again analyzed using Wilcoxon one-sample signed rank tests (critical p-value $= 0.005$, test value $= 0$).

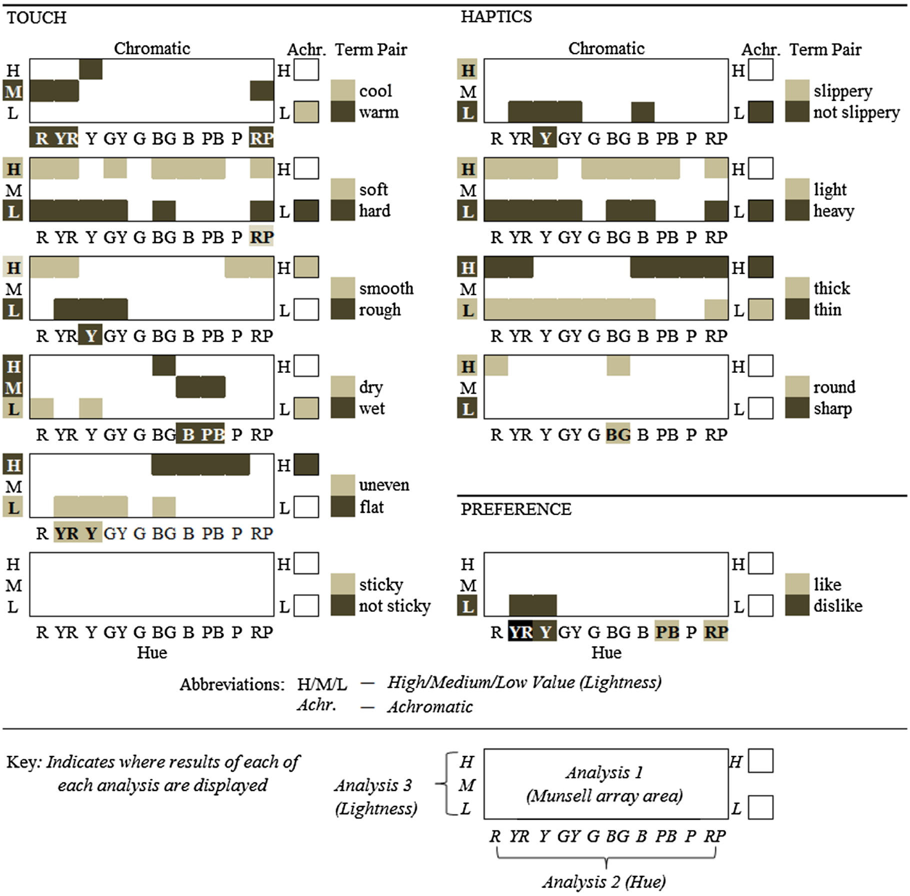

Figure 2. Results of analyses of matches using each term pair. Shaded areas indicate areas of Munsell array (analysis 1), and hues (analysis 2) or lightness levels (analysis 3) significantly associated with terms. See text (Section 2.2.2.1 and following) for details.

There were numerous significant results (min. sig. $z = 2.89$, $p = 0.004$, $r = 0.41$), indicated by shaded Munsell hue code letters in Fig. 2. On seven trials one of the terms involved was associated with one or more hues. *Warm* was associated with R, YR and RP hues, *soft* with RP, *rough* with Y, *wet* with B and PB, *uneven* with Y and YR, *not slippery* with Y and *round* with BG. On 3 trials *sticky/not sticky*, *light/heavy* and *thick/thin* there were no associations. Only on the *like/dislike* trial were both terms associated with specific hues, *dislike* with Y and YR hues, *like* with PB and RP hues.

2.2.2.1.3. Analyses 3: Lightness. In these analyses chips were grouped by lightness (high, medium and low). Figure 2 again summarizes significant (critical p-value $= 0.017$, test value $= 0$) results (min. sig. $z = 2.81$, $p = 0.005$, $r = 0.40$), with shaded lightness codes (H, M and L). For eight term pairs, one term is associated with light chips (*soft*, *smooth*, *wet*, *flat*, *slippery*, *light*, *thin*, *round*), the other with dark chips (*hard*, *rough*, *dry*, *uneven*, *not slippery*, *heavy*, *thick* and *sharp*). Only terms *warm and wet* were associated with chips of medium lightness levels. On the *sticky/not sticky* trial, there were no associations based on lightness. On the trial using *like/dislike* there was an association between *dislike* and dark colors.

2.2.2.1.4. Summary: Analyses of Data from Individual Trials. A summary of the analyses reported above is presented in Table 5. For all trials except that involving *sticky/not sticky* at least one of the analysis produced significant results.

For most of the term pairs matches are consistently made to either light or dark stimuli, as shown in the table. For pairs *soft/hard*, *smooth/rough*, *flat/uneven*, *slippery/not slippery*, *light/heavy*, *thin/thick and round/sharp* the

Table 5.
Summary of main results from analyses of individual trial data

Term pair	Summary of matching
Cool	Dark achromatic
Warm	Saturated (medium lightness) RP–YR range hues
Soft	Light colors (of various hues)
Hard	Dark colors (of various hues)
Smooth	Light colors (P–YR hue range)
Rough	Dark colors (YR–GY hue range)
Dry	Dark colors (R and Y hues)
Wet	Light (BG hue) and saturated (medium lightness) B–PB range hues
Uneven	Dark colors (of various hues)
Flat	Light colors (BG–P hue range)
Sticky	No evidence of consistent matching to either term
Not Sticky	
Slippery	Light colors
Not Slippery	Dark colors (of various hues)
Light	Light colors (of various hues)
Heavy	Dark colors (of various hues)
Thick	Dark colors (RP–B hue range)
Thin	Light colors (B–YR hue range)
Round	Light colors (R and BG hues)
Sharp	Dark colors
Like	PB and RP hues
Dislike	Dark colors (YR–Y hue range)

first mentioned term is always associated with light colors and the latter term with dark colors. For term pair *wet/dry*, the pattern is similar though there are additional matches involving *wet* to colors of medium lightness. For the *warm/cool* pair, most associations to *warm* involve colors of medium lightness, whilst cool is only associated to dark achromatic stimuli.

The analysis by hue (analysis 2) revealed significant associations on trials involving seven of the 10 haptic/tactile terms pairs, though in each of these trials only one of the terms involved (*warm*, *soft*, *rough*, *wet*, *uneven*, *not slippery* and *round*) showed evidence of significant association with chips of specific hue. This contrasts with the patterns found in the analysis of lightness where, in most cases, both of the terms in any given pair show associations with colors of specific lightness levels. On trials involving term pairs *sticky/non-sticky*, *light/heavy* and *thick/thin* there were no significant results in the analysis by hue.

2.2.2.2. Relationship Between Matching to Haptic/Tactile Terms and Dislike *Term.* On the *like/dislike* trial, the only significant associations involving the term *like* are with chips of PB and RP hues, a pattern not replicated for any of the haptic/tactile terms. For the term *dislike*, there is a significant association with dark colors in general, with additional significant associations to dark YR and Y hues. Similar patterns of matching are found for many haptic/tactile terms. Of the eight haptic/tactile terms significantly associated with dark colors (*hard*, *rough*, *dry*, *uneven*, *not slippery*, *heavy*, *thick and sharp*), seven also show associations involving dark YR and/or Y hues (see Fig. 2). The exception is the term *sharp*, which is associated with dark matches, but not to dark chips of any specific hue. We therefore conducted further analyses to assess the similarity in matching between the term *dislike* and the eight haptic/tactile terms associated with dark matches.

This analysis only considers matches involving dark chromatic chips. If such matches are made purely on the basis of lightness, they should be distributed evenly across dark chips of differing hue. Analyses reported above suggest this is not the case, though do not provide detailed comparison of similarities in matching patterns. To do this we first calculated, for each participant, the total number of matches made using dark chips (i.e., chips of Munsell value levels 2 and 3) to each term under consideration. Overall, most matches were made to *heavy* (mean = 5.5/20, SD = 6.0) and fewest to *not slippery* (mean = 1.6/20, SD = 3.2). Next, the region of the array containing dark chips was divided into five hue regions; PR/R hues, RY/Y hues, GY/G hues, BG/B hues and PB/P hues, each represented by four chips. Then, for each participant separately, the number of matches made using chips from each of the five regions to each term was calculated (see Note 3). Following this, the proportional difference between each participant's total matches in each of the five areas for each term and that expected if matches are made purely on the basis of (low) lightness was calculated.

These data, combined across participants, are shown in Fig. 3. The upper panel shows matching to the term *dislike*. As can be seen, participants are 25% more likely to match chips of RY/Y hues to *dislike* than would be the case

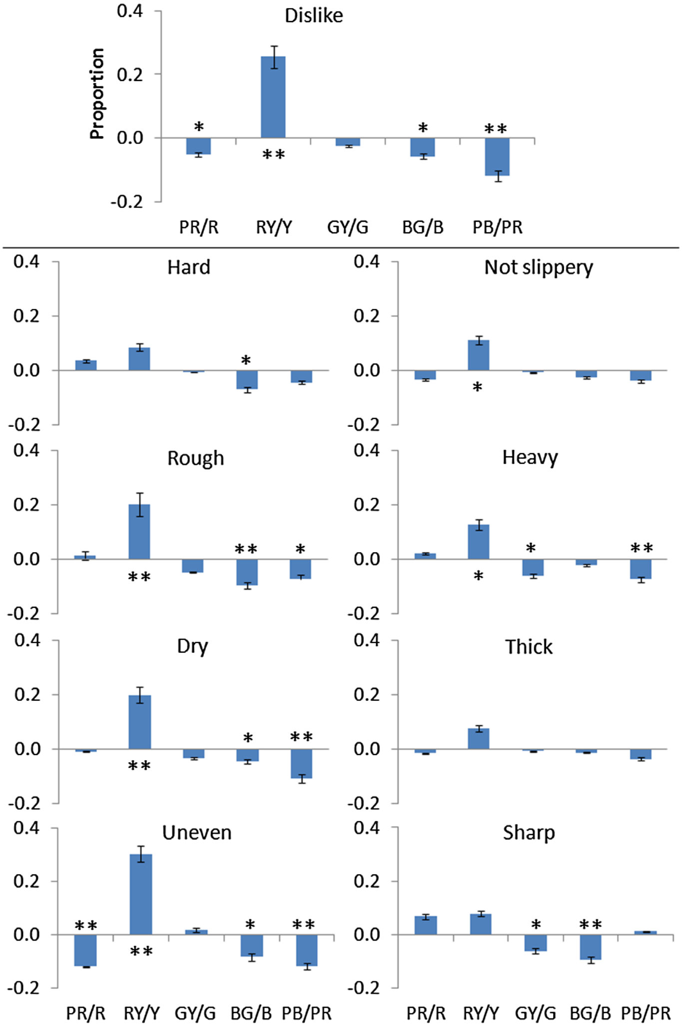

Figure 3. Top panel shows proportion of matches, as more or less than expected assuming matching is based on lightness alone, involving dark stimuli from different hue regions to the term *dislike*. Other panels show equivalent data for the eight haptic/tactile terms significantly associated with matches to dark stimuli (*hard*/*rough*/*dry*/*uneven*/*not slippery*/*heavy*/*thick*/*sharp*). Error bars indicate ± 1 SE; ∗ = significant at 0.01 level; ∗∗ = significant at 0.001 level. See text (Section 2.2.2.3.) for further details.

assuming random matching. Chips of other hues are less likely to be matched to *dislike*. Remaining panels in Fig. 3 show equivalent data for trials involving the eight haptic/tactile terms of interest. There are obvious similarities between the patterns of matching to dislike and the eight haptic/tactile terms.

Data from each trial was analyzed with Wilcoxon one-sample signed rank tests (critical p-value $= 0.01$). Significant results (min. sig. $z = 2.7$, $p = 0.007$, $r = 0.38$) are indicated in Fig. 3. For *dislike*, matches were significantly less likely to be made to dark chips from regions containing PR/R, BG/B and PB/P hues. More important, matches were significantly more likely to be made using dark chips of YR/R hue. Five of the eight haptic/tactile terms (*rough*, *dry*, *uneven*, *not slippery and heavy*) were also matched to YR/Y hues significantly more often than expected, indicating similarity between matching to these terms and to *dislike*.

Finally, we assessed whether participants who preferentially match dark RY/Y hues to *dislike* are also more likely to match RY/Y hues to the eight haptic/tactile terms under consideration. Participants were divided into two groups. One group consisted of 21 participants who matched dark chips of RY/Y hue to *dislike* relatively more frequently than to chips from any of the other four hue areas. The second group consisted of 28 participants showing no such preference (see Note 4). For each participant, the proportion of matches made using YR/R hues was calculated twice, first combining matches to all eight haptic/tactile terms under consideration and again considering those five terms (*rough*, *dry*, *uneven*, *no slippery* and *heavy*) which the previous analysis showed to be significantly associated with YR/R hues (see Fig. 3).

Data from the two groups was compared using Mann–Whitney U tests. When data from all eight haptic/tactile terms is considered, participants who preferentially match chips of RY/Y hue to *dislike* (mean proportion $= 0.46$, median rank $= 30.9$) were also significantly more likely to match similar chips to the eight haptic/tactile terms than were other participants (mean $= 0.31$, median rank $= 20.6$), $U = 171.0$, $p < 0.025$, $r = 0.36$. For data from just the five terms significantly associated with YR/R hues, the results were similar (mean proportion: gp. $1 = 0.54$, gp. $2 = 0.35$; median rank: gp. $1 = 31.6$, gp. $2 = 20.0$), though with a larger effect size, $U = 154.5$, $p < 0.005$, $r = 0.40$.

3. Discussion

This study investigated cross-modal associations between color and touch, using a task in which colors on the surface of the Munsell color solid were matched to opposing haptic/tactile term pairs. Two sets of analyses were conducted. One assessed matching patterns on trials involving different term pairs, the other explored the possible involvement of valence. Results of the first analysis (see Fig. 2 and Table 5) suggest three different kinds of response patterns across trials; no consistency in matching (*sticky*/*non-sticky*), matching clearly influenced by hue and/or saturation (*warm*/*cool* and *wet*/*dry*) and matching based primarily on lightness (remaining term pairs, listed below).

3.1. Role of Lightness in Matching

On most trials, those involving term pairs; *soft*/*hard*, *smooth*/*rough*, *flat*/*uneven*, *slippery*/*not slippery*, *light*/*heavy*, *thick*/*thin* and *round*/*sharp*, a similar pattern of matching emerges. There are no significant associations involving colors of medium lightness levels. Rather, one term in a pair is associated with light colors and the other with dark colors, a result that replicates the findings of previous studies (see Table 1). This suggests, given differences in methods across studies, that associations involving lightness are robust and bidirectional — matching either colors to terms or the reverse appears to have little influence on matching performance.

Further, in this study the average saturation of light (4.6) and dark (6.7) chips was lower than the average saturation of medium lightness chips (10.2). If colorfulness (i.e., properties other than lightness) plays a dominant role in matching, then participants would be expected to make matches involving chips that are of higher saturation, that is to chips of medium lightness. This not being the case, for most of the term pairs assessed, suggests patterns of association are driven by lightness.

It is also noteworthy that the term *light* is consistently matched to light colors across studies using different language groups. Unlike English, both Turkish (this study) and Arabic (Jraissati *et al*., 2016) languages use different terms to denote visual lightness and light weight. This suggests the mechanism underlying the association is unlikely to be linguistic, though whether statistical, structural or some combination of the two is uncertain.

For other terms matched to light or dark colors the mechanisms responsible are also unclear. They may be based on statistical correspondences, though it is doubtful that there would be a natural association between visual lightness and haptic/tactile properties in the world — not all lightweight, or smooth or soft objects are of light color. Structural mechanisms may be involved. For example, since both the visual lightness/darkness dimension and haptic/tactile dimensions are prothetic, changes in magnitude along these dimensions may be coded using similar brain mechanisms, such as changes in neural firing rate (Stevens 1957) or in similar brain locations (Walsh, 2003), thereby giving rise to the associations. Finally, emulating properties such as heaviness, hardness and roughness (all matched to dark colors) involves increasing resistance to haptic exploration. Consequently, changes in magnitude on these dimensions lead to variations in effort. One avenue for future research might therefore involve exploring whether effortful haptic exploration may explain why some haptic terms are associated with light and dark colors.

3.2. Role of Hue and Saturation in Matching

Clear evidence of associations involving hue and/or saturation was found on trials using pairs *warm*/*cool* and *wet*/*dry*. The association of color and temperature is well known (e.g., Ho *et al.*, 2014a; Mogensen and English, 1926). Previous evidence (Morgan *et al.*, 1975) indicating young children do not associate specific colors with temperatures, suggests the associations are learned. Whilst finding the expected pattern of matching to the term *warm*, this study only provides evidence for the *cool* term being matched to dark achromatic chips, rather than to blue and green colors. This implies either that associations between warmth and color are stronger than those involving coolness and color or, given participants were Turkish speakers, that cultural and/or linguistic factors exert some influence on associations.

On the *dry*/*wet* trial, participants matched the term *wet* to the highest saturation (medium lightness) examples of blue and purple–blue colors. *Wet* differs from other terms in being closely associated with a particular substance, water, associated with blueness (see Jraissati *et al.*, 2016). Other term pairs are unlikely to be as strongly associated to specific objects or substances. This suggests that matches involving the term *wet* may be statistical in nature.

For other term pairs, the absence of any significant matches involving chips of high saturation implies that hue and saturation exert less influence on matching performance than lightness. Nevertheless, for the term pairs under consideration the analysis of hue (Analysis 2) shows that one term in each pair (*warm*, *soft*, *rough*, *wet*, *flat*, *not slippery* and *round*) is matched to chips of one or more hue intervals significantly more often than expected by chance. This suggests that on trials involving these term pairs, hue and/or saturation influence matching. However, the specific contribution each of these two dimensions makes to matching is unclear, for reasons discussed in Section 3.2.1.

One possible structural account that may help explain how chromatic properties could influence associations of the kind under consideration relates to research indicating that contour and shape detection mechanisms are color sensitive (Gheorghiu and Kingdom, 2007a). This implies a possible role of color in object shape representation. Gheorghiu and Kingdom (2007b) have also shown that the straight part (cord) and curved part (sag) of a sinusoid are coded separately, suggesting that local curvatures (i.e., the shape of contour segments that have a constant sign of curvature) are basic functions in shape representation. This supports the idea that specialized mechanisms detect and encode local curvatures. It is therefore possible that different shaped contour segments (cord or sag) are represented separately and may therefore feature different patterns of color association. Indeed, only sag is selective along the hue–lightness dimension, whilst cord is selective either to hue, or to lightness (Gheorghiu and Kingdom 2007b). This implies that hue is relevant information for sag-like contour detection in more situations than it is for cord-like contour detection.

The present study provides evidence of cross-modal correspondences involving chromatic properties and the term *round*, though not *sharp*. One possibility therefore, is that the term *round* is more likely to be associated with color than the term *sharp*, because all contour segments of round objects are curved. Sharp objects, on the other hand, feature straight contour segments. However, the results of Ludwig and Simner (2013) cannot be explained within this framework. They found pointed stimuli were matched to red and black, whilst round stimuli are not matched to chromatic properties. In their study, participants explored three-dimensional volumes with the palm of one hand. It is therefore unclear what part of the experience they associated to color (shape, contour, volume, or pleasantness, intensity of the sensation, etc), which may explain the discrepancy.

3.2.1. Difficulties in Assessing the Influence of Hue and Saturation in Associations

Whilst previous studies investigating color and tactile/haptic association imply hue and saturation influence matching performance, the evidence is inconsistent. The inconsistencies may relate to the differences in populations assessed, or methods used. For example, both Ludwig and Simner (2013) and Slobodenyuk *et al*. (2015) involved matching color to haptic/tactile *sensations* of varying intensities, whilst (Jraissati *et al*., 2016) involved matching haptic/tactile *terms* to color. Some, though not all, the inconsistencies may therefore be explained by assuming quantitative, rather than qualitative, aspects of haptic sensations influence matching (see e.g., Lewkowicz and Turkewitz, 1981) because saturation, unlike hue, varies in intensity.

However in all studies saturation acts as a confound. This study used colors taken from the surface of the Munsell color solid. These colors represent the most saturated examples available at each hue and lightness level, making them a logical choice given the research aims. However, such stimuli vary in saturation, as shown in Table 3. Whilst color stimuli in other studies have not been confined to the outer surface of color space, a similar problem exists because, regardless of system used to specify colors, maximum attainable saturation varies. Such variations probably do not seriously affect the conclusion that lightness plays a dominant role in matching. This is partly because all studies provide similar results in terms of lightness effects and partly because variations in saturation as hue changes at specific lightness levels are less pronounced than such variations at specific hue intervals. Nevertheless, variations in saturation make it difficult to establish the independent effects of hue and saturation on matching.

For example, Ludwig and Simner's (2013) finding that children match softer sensations to higher saturation and to categories labeled *yellow* and *pink* is somewhat ambiguous. Softer sensations may indeed be matched to more saturated stimuli. But they might alternatively be matched on the basis of hue. If hues associated with softer stimuli are available at higher saturation than hues associated with harder stimuli, a spurious effect of saturation may arise. The preference for matching softer sensations to *yellow* and *pink* categorized colors may also be explained in the opposite terms. *Yellow* categorized stimuli are available at higher saturation levels than stimuli of equivalent lightness but different hue. So what appears to be a preference for *yellow* might be explained as a preference for colors that are both light and highly saturated. That these happen to be *yellow* may be a consequence of the structure of color space.

Variations in saturation have another effect, relating specifically to the Munsell system. In both this study and Jraissati *et al.* (2016), stimuli at different lightness level were separated from their neighbors by a fixed number of hue units. Since saturation is relatively higher for stimuli of intermediate lightness levels, such stimuli are further from the achromatic axis than relatively lighter or darker stimuli. Consequently, perceptual separations between adjacent stimuli of the same lightness level vary depending on lightness. Adjacent stimuli of intermediate lightness separated by a fixed number of Munsell hue units therefore appear less similar than adjacent stimuli of higher (or lower) lightness separated by the same number of hue units. Analogously, a twentieth of the distance around a globe is a larger absolute distance at the equator than at higher latitudes. This may have consequences for matching. On any given trial, if a participant selects a dark chip for a match, they are relatively more likely to also choose an adjacent dark chip, since such chips appear relatively more similar to the already selected chip. If, on the other hand, a participant selects a medium lightness chip, there is a relatively lower probability of selecting an adjacent medium lightness chip, because it appears relatively less similar to the already selected chip. A likely consequence is a preponderance of matches involving light and dark stimuli relative to medium lightness stimuli. This implies that the results reported here somewhat overestimate the role of lightness in matching relative to hue and saturation.

Given the above, results of the second analysis (hue) in this study should be treated with caution. In strict terms, the results indicate associations between terms and latitudes on the surface of the Munsell solid that are of constant hue, but vary in saturation. Excluding associations involving terms *warm* and *wet* discussed previously, results suggest the term *soft* is associated with RP hues, *rough* with Y hues, *uneven* with YR and Y hues, *not slippery* with Y hues and *round* with BG hues. In contrast to the analysis of lightness, which revealed that many opposing terms are matched to either light or dark colors, scant evidence of an equivalent pattern emerged from the analysis of hue. Although hue, unlike lightness, is a circular rather than a prothetic dimension, an analogous finding would have been if opposing terms were matched to opposing hues. The only trial on which something approaching this pattern emerged was that involving terms *flat*/*uneven*, with matches to *flat* concentrated in the light blue region of the array and those to *uneven* in the dark yellow region (see Fig. 2). Thus unlike Jraissati *et al*. (2016), who found evidence opposing haptic/tactile terms are matched to opposing hues, this study provides little evidence supporting this idea. Rather, in all cases, where one term in a given pair is associated with chips of specific hue, the other term is not associated with any hue. If effects of the kind noted by Jraissati *et al*. are present, they may be masked by the dominant influence of lightness on matching.

3.3. Role of Valence

The second set of analyses examined the relationship between color matching to haptic/tactile terms and to the term *dislike*. Performance on the *like*/*dislike* trial agrees with results of previous research into color preference, particularly the association between dark yellow–red and yellow hues and the term *dislike* (see e.g., Palmer and Schloss, 2010). Results of the first analysis, summarized in Fig. 3, suggest similarities in matching patterns involving dark chips to *dislike* and eight haptic/tactile terms (*hard*, *rough*, *dry*, *uneven*, *not slippery*, *heavy*, *thick* and *sharp*) also significantly associated with matches to dark chips. For all eight terms, matches were relatively more likely to be made using dark chips of YR/Y hue than from the other four hue regions. For five of these terms (*rough*, *dry*, *uneven*, *not slippery* and *heavy*), this matching bias is significant.

This does not provide direct evidence that participants' matching is mediated by emotion. It may be that the salience of dark stimuli differs in each of the five hue regions assessed. Dark stimuli of RY/Y hues are of lower average saturation (mean = 4.5) than are equivalently dark stimuli from other hue regions (min. = 5.5, max = 9). Matching may therefore be driven by stimulus saturation, or rather the lack of it. Further analyses compared matching of two groups of participants: those who preferentially matched chips of YR/R hues to the term *dislike*, and those showing no such preference. The results indicated that participants in the first group were also more likely to match YR/R chips to haptic/tactile terms than those in the other group. Although these analyses still fail to provide direct evidence, they provide further support for the idea that participants assign a negative valence to some terms, and then match to colors with similar valence. Such an emotional mediation has been put forward in the case of the association of music to color (Palmer *et al*., 2013).

3.4. Summary

This study makes several contributions to research addressing associations between touch and color. First, the method used differs from that of previous studies, thereby providing a means of assessing the validity and generalizability of previous findings. Second, the results are consistent with previous studies with regards to the role of lightness: across all studies the pattern of association to lightness is generally similar, with one term of an antonym pair, or one extreme of the haptic sensations, associated to lighter stimuli and the other to darker stimuli. Third, on many trials there was a tendency to match one of the haptic/tactile terms used to dark chips in the yellow to yellow–red range. Because the same pattern of significance emerges in the matches to the term *dislike*, the results provide some evidence implying an additional factor, valence, influences cross-modal associations between color and touch. Future research should address this issue.

At present, any assessment of the mechanisms underlying the associations is likely to be somewhat speculative. The reasons stem partly from insufficient research investigating patterns of color–touch associations across different language, age and culture groups. Similarly, the influences of hue and saturation on such associations are, at present, poorly understood, in part because the structure of color space makes them difficult to assess. Resolving the latter issue requires using carefully controlled sets of color stimuli. One approach would be to use stimuli sets in which two of color's dimensions are kept constant, whilst varying the third. Research that more precisely specifies the role hue and saturation play in associations between touch and color would likely assist understanding the mechanisms involved in the associations, which can in turn contribute to understanding processes related to multisensory integration.

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Notes

1. The Munsell color system defines color using dimensions of hue, value (referred to as lightness in text) and chroma (saturation). The Munsell color solid is an irregularly shaped globe, with achromatic stimuli located on an axis running between the two poles. Differences in lightness, corresponding to differences in latitude, are indicated using a 10-point numerical scale, with higher numbers indicating lighter colors. Differences in saturation, also indicated using a numerical scale, relate to distances

from the achromatic axis, with less saturated colors nearer the axis. Hue is a circular dimension, corresponding to differences in longitude and is divided into 10 regions signified using letter codes (R, YR, Y, GY, G, BG, B, PB, P, RP). In general, R hues appear reddish, YR hues orange, Y hues yellow and so on. Each of the 10 regions can be further subdivided, usually into four sub-steps indicated numerically (2.5, 5, 7.5 and 10).

2. The set of stimuli used were of almost identical Munsell notations to those used by Jraissati *et al*. (2016), the only differences being in notations of lightest (value 9.5 vs. 10) and darkest (value 1.5 vs. 0) achromatic chips.

3. Grouping the chips into five hues regions (each containing four chips), rather than 10 regions (each containing two chips), increases the power of the analysis, though at the expense of precision.

4. Included in this group were 11 participants who made no matches using dark chips to *dislike*, 11 participants who matched RY/Y hue chips most frequently to *dislike* but who also matched chips from one or more other hue areas to *dislike* with equal frequency, and six participants who most frequently matched chips from some other hue area (not YR/R) to *dislike*.

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Appendix A

Turkish term pairs used in the study were derived from a list of English terms. The English list contained all the term pairs shown in Table 1, with the exception of the *sticky/not stick*y and *slippery/not slippery* terms pairs. In place of these two terms pairs the pair *sticky/slippery* were used. The list was given to eight bilingual (Turkish/English) speakers recruited from the academic English teaching unit at Bahçeşehir University. They were asked to translate each word individually, giving as many translations as possible for each, together with antonyms. For most terms translation was unproblematic, with respondents showing high levels of agreement. Respondents also showed a high level of agreement in translating the term pair *sticky*/*slippery*. However, they did not appear to be directly opposed. Most participants translated the term *slippery* as '*kaygan*', offering '*kaymayan*' (*not slippery*) as the antonym. For the term *sticky*, most participants used the term '*yapiskan*' and offered '*yapismayan*' (*not sticky*) as the antonym. We therefore used two separate term pairs ('*kaygan*/*kaymayan*' and '*yapiskan*/*yapismayan*') to represent the concept expressed using *sticky*/*slippery* in English.

Appendix B: Task Instructions Presented to Participants (Translated From Turkish)

'This research investigates how people match colors to words that describe *tactile qualities* (*touch*) and *preference*.

There are 64 color patches on the table and two words: *warm* and *cool*. Choose colors that seem *warm* and put them next to the word *warm*. Choose colors that seem '*cool*' and put them next to the word '*cool*'.

There is no limit to the number of colors you can choose for each word.

You must choose at least one color for each word. If you do not think any colors match a word, then choose a single color at random and place it next to the word.

You cannot choose the same color for both words.

There are no correct or incorrect answers. When you do the task, just make selections that seem right to you.'