Received: 23 September 2022 | Revised: 9 August 2023 | Accepted: 17 August 2023
DOI: 10.1111/joss.12879

ORIGINAL ARTICLE

Journal of Sensory Studies

WILEY

# The visual perception of wetness: The role of stain chroma, size, and hue

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## Abstract

A range of sensory cues contribute to human wetness perception, yet we know little of how visual modalities are involved, specifically if in-situ physical observations differ from ex-situ online observations. We aimed to assess the effect of stain volume, chroma, size, and hue on the wetness perception of static images, with a comparison to previously collected in-situ data. A total of 440 participants completed the online study, including 18 from an analogous in-situ study. Stimuli varied in physical wetness (0, $2.16 \times 10^{-4}$ or $3.45 \times 10^{-4}$ mL mm$^{-2}$), stain chroma (clear saline, light synthetic urine, dark synthetic urine) and stain size (1150 or 5000 mm$^2$). Further stimuli of a fixed wetness ($3.45 \times 10^{-4}$ mL mm$^{-2}$) varied in stain hue (red, orange, yellow, green, blue, violet) and stain size (1150 or 5000 mm$^2$). Participants rated wetness perception using a visual analogue scale (very dry to very wet) and modified yes/no task (dry/wet, gloss/matte, dilute/concentrate). Participants successfully discriminated between all physical wetness levels. Wetness perception shared a positive relationship with stain chroma and size, and varied with hue such that higher wavelengths resulted in greater wetness perception. Finally, online and in-situ wetness perception did not significantly differ.

## Practical Applications

The findings fundamentally contribute to our scientific understanding of wetness perception, giving evidence toward different multisensory integration theories. Further applications lie in industry, such as improving the structure, function, and perception of absorbent hygiene products or informing the design of sportswear with moisture management properties. Additionally, findings may aid the improvement of digital software which uses visual wetness components, for example in augmented and virtual realities.

## 1 | INTRODUCTION

Wetness perception provides critical information about humans and the surrounding environment, forming a fundamental part of daily life. While perception is heavily influenced by haptic cues such thermal and tactile feedback, hygroreceptors which specifically respond to wetness have not yet been found in human skin (Clark & Edholm, 1985). Instead, humans use a multisensory integration mechanism to combine a range of different sensory modalities, combining cues to build the most likely external sensory interaction (Driver & Spence, 2000). However, there is not yet a conclusive model that integrates the senses underpinning wetness perception, with multiple models proposed but each having varying levels of supporting evidence (Merrick & Filingeri, 2019).

While physical aspects of human interactions form the main basis of wetness perception research, studies have also demonstrated that visual stimuli can have a profound influence on perceived wetness levels. This is predominantly in a digital context and focuses on environmental scenes and natural objects, such as visually assessing the wetness levels of soil or differentiating between wet and dry materials including stone and wood. In these cases, increases in both chroma and gloss levels resulted in increased wetness perception (Sawayama et al., 2017; To et al., 2008). Similarly, Iwasa et al. used images of dough that varied in water content to show that physical wetness and resulting image luminance shared a strong positive relationship with perceived wetness (Iwasa et al., 2020). The identification of changes in wetness has also been successful using side-by-side photographic comparisons, in which individuals have been able to identify wetness changes in organic materials, fabrics, and metals (Yoonessi & Zaidi, 2010).

The hue of an image can also affect perception. It has already been shown that thermal perception can be influenced by hue, such as reds and oranges denoting warmth and blues and green being associated with cold (Ho et al., 2014). This could stem from a crossmodal correspondence in nature, such as skin becoming redder when hot and having a blue tint when cold (Changizi et al., 2006). As cold thermal inputs are a primary factor in wetness perception, it may therefore be possible for this association to extend to wetness perception.

Furthermore, wetness perception can be influenced by chroma, with higher intensities indicating higher wetness levels. This occurs in objects with a thin film of water at the surface, which allows total internal reflection and hence reduces external light reflections and makes the wet area appear darker (Lekner & Dorf, 1988). Another visual aspect that has been modeled is the relative sharpening of wet areas within an image. The spectral distribution of a wet surface region is narrower than that of a corresponding dry region at any given wavelength, due to greater levels of multiple scattering and light absorption at the wet interface (Shimano et al., 2017).

While there are several studies presenting photographs of stimuli, these often focus on gloss (Iwasa et al., 2020), with studies involving further visual parameters typically centered around data modeling (Sawayama et al., 2017). The aim was therefore to establish the effect of physical stain volume, chroma, size, and hue on ex-situ wetness perception using an online perceptual assessment platform. A second aim was to compare the ex-situ outcomes with their in-situ counterparts, giving an insight into the multisensory integration mechanisms underpinning wetness perception.

Based on the results from pilot studies, it could be hypothesized that higher chromas and larger stain sizes are likely to result in increased wetness perception. It was also predicted that wetness perception will increase at hues which the retina is most sensitive to, centered around green. Finally, it can be expected that ex-situ wetness perception may be more conservative than their in-situ counterparts, owing to the reduced quality and available perspectives of each stimulus. The outcomes will provide further evidence into an integratory model, and will also be used to inform the design of absorbent hygiene products. Furthermore, digital softwares which use visual wetness components may be improved, for example in augmented and virtual realities.

## 2 | METHODS

### 2.1 | Participants

A total of 440 participants (373 female: 34.9 ± 8.5 years; 67 male: 35.6 ± 9.1 years) were recruited for the online study, of whom 18 had also completed the analogous in-situ study (see Part I). The minimum required sample size of 114 was established using a sample size calculation with an $\alpha$ value of 0.05, a $\beta$ value of 0.20, and an effect size ($f$) of 0.28 based on data from pilot studies (G*Power 3.1.9.2 software; Heinrich Heine Universität, Düsseldorf, Germany). Participants were subject to an inclusion criterion, such that all were healthy non-smoking individuals between the ages of 18 and 60 years with a no visual impairments. The study was distributed internally through the university and externally via social media. Participants who had completed the in-situ study were instructed to complete the online component between one and 2 weeks after finishing their physical session, with reminders sent where necessary. The study design was approved by the Loughborough University Ethics Committee and testing procedures were in accordance with the tenets of the Declaration of Helsinki. All participants were informed of the test procedures and given the opportunity to ask questions. All participants gave their informed consent before participation.

### 2.2 | Experimental design

The study was conducted as a single blind psychophysical experiment, such that participants were unaware of any information that may bias results. Each participant completed a single online session in which a series of stimuli were presented for perceptual assessment. All stimuli were prepared using 80 mL of 0.9% saline solution (9.0 ± 0.02 g NaCl; 1000 ± 10 mL $H_2O$). The first set of stimuli varied in physical wetness (0, $2.16 \times 10^{-4}$ or $3.45 \times 10^{-4}$ mL mm$^{-2}$), chroma (clear saline, light synthetic urine, dark synthetic urine) and stain size (1150 or 5000 mm$^2$), with the exception of clear saline which was only presented at a 1150 mm$^2$ stain size. The second set had a fixed wetness level of $3.45 \times 10^{-4}$ mL mm$^{-2}$ and varied in stain hue (red, orange, yellow, green, blue, violet) and stain size (1150 or 5000 mm$^2$). This gave a total of 27 stimuli (Table 1), each of which was presented once in a randomized order via Alchemer online survey software (Alchemer, Louisville, CO, USA). Stimuli were perceptually rated using both a 100 mm visual analogue scale (very dry to very wet) and a series of dichotomous response pairings depending on sensory condition (dry/wet, gloss/matte, dilute/concentrate).

### 2.3 | Experimental protocol

Stimuli preparation began with the formation of a stock 0.9% saline solution (9.0 ± 0.02 g NaCl; 991 ± 10 mL $H_2O$) which is analogous to

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**TABLE 1** A total of 27 stimuli combinations with the first set (a) arising from different chromas of synthetic urine, sizes, and wetness combinations and the second set (b) being formed of different color hues, sizes, and wetness combinations.

| (a) | First set | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Chroma | Clear saline | | | Light synthetic urine | | | | | | Dark synthetic urine | | | | | |
| Size | Small | | | Small | | | Large | | | Small | | | Small | | |
| Wetness | Dry | Low | High | Dry | Low | High | Dry | Low | High | Dry | Low | High | Dry | Low | High |

| (b) | Second set | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hue | Red | | Orange | | Yellow | | Green | | Blue | | Violet | |
| Size | Small | Large | Small | Large | Small | Large | Small | Large | Small | Large | Small | Large |
| Wetness | High | High | High | High | High | High | High | High | High | High | High | High |

**TABLE 2** The quantities of each of three dyes required to produce different stimulus hues when mixed with 1 L of 0.9% saline solution.

| | Tartrazine $C_{16}H_9N_4Na_3O_9S_2$ >99% purity | | Allura red AC $C_{18}H_{14}N_2Na_2O_8S_2$ >99% purity | | Brilliant blue FCF $C_{37}H_{34}N_2Na_2O_9S_3$ >65% purity | |
|---|---|---|---|---|---|---|
| | mg | ±mg | mg | ±mg | mg | ±mg |
| Light synthetic urine | 3 | 0.05 | 0.3 | 0.05 | | |
| Dark synthetic urine | 6 | 0.05 | 0.6 | 0.05 | | |
| Red | | | 4.32 | 0.05 | | |
| Orange | 3.04 | 0.05 | 2.16 | 0.05 | | |
| Yellow | 6.07 | 0.05 | | | | |
| Green | 3.04 | 0.05 | | | 40.1 | 0.05 |
| Blue | | | | | 80.2 | 0.05 |
| Violet | | | 2.16 | 0.05 | 40.1 | 0.05 |

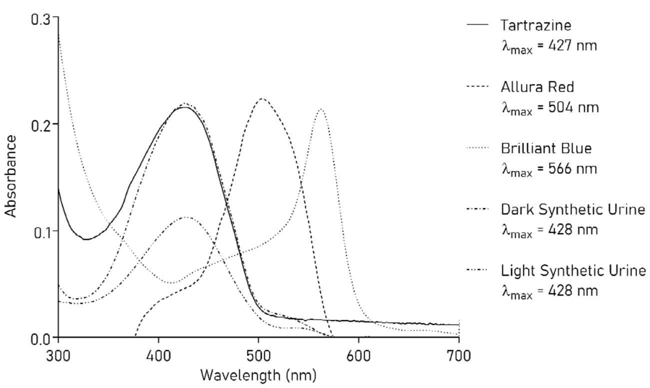


**FIGURE 1** The absorbance values generated for each stimulus hue such that all share the same chroma with the exception of light synthetic urine.

the ionic composition of urine and therefore is optimally absorbed by the substrate. This was then dyed using combinations of Tartrazine, Allura Red AC, and Brilliant Blue FCF colorants to produce two hues of synthetic urine and six further color hues (Table 2). Concentrations were determined by assessing absorbance values with UV–Vis spectroscopy (BioSpectrometer Kinetic 4.3.1.0, Eppendorf, Hamburg, Germany), and back calculating the relevant concentrations to ensure equal absorbance values across all dyes (Figure 1).

The stimuli consisted of the central section of a diaper, which was cut from the elasticated chassis such that it was able to lay flat as opposed to conforming to the shape of the body as intended. Cuts were made ensuring the absorbent core remained intact such that no internal material was lost and no leakages would occur following the application of solution. This process resulted in a 115 × 325 mm rectangular sample to which 80 mL of the solution was applied. The sample was allowed to rest for either 48 h, 10 min, or 1 min, referred to as the dwell time. This resulted in wetness levels in the topsheet of 0, $2.16 \times 10^{-4}$, and $3.45 \times 10^{-4}$ mL $mm^{-2}$ respectively, herein also referred to as dry, low wetness, and high wetness. Including a dwell time allowed the applied solution to be absorbed through the acquisition layers and wicked away from application area to ensure a uniform distribution throughout the absorbent core.

Solutions were applied to the substrate using a custom-made acquisition plate comprising a rectangular plastic frame and foam stage upon which the sample would be placed. Above the sample a flat plate with an aperture tube would be positioned, aligned directly above the center of the diaper when fitted between markers. The size of the aperture tube varied in diameter to produce different areas (⌀ 38 mm, 1150 $mm^2$; ⌀ 80 mm, 5000 $mm^2$) through which liquid would be absorbed. Once all liquid was absorbed, the aperture tube was replaced with a rigid plastic sheet with the same size of aperture.

An additional 1.4 mL of synthetic urine at double the concentration of the associated 80 mL volume was sprayed from directly above at a distance of 150 mm using a natural-type spray pump positioned using a clamp stand. This setup was formed to give an even coverage of spray for both stain sizes while maintaining applied volume as a dependent variable. Stain sizes were verified using digital imaging software

(Photoshop 2017.0.0, Adobe, San Jose, USA) (Merrick et al., 2021). Concentration of spray was established in pilot studies investigating the differential threshold between chromas (Appendix A).

Once a solution had been applied using the relevant methods and the dwell time had elapsed, the sample was immediately photographed (Figure 2). This was performed using an upright stand (CS9, Canon Inc., Ōta, Japan) which allowed a camera to face directly downwards at a sample (D5100, Nikon, Minato, Japan). Homogenous lighting was achieved using a softbox diffuser setup (RFi Softbox 1.3*2, Profoto, Stockholm, Sweden).

Photographic color was calibrated using a color passport (ColorChecker Passport Photo 2, Grand Rapids, MI, USA). Digital imaging software (Photoshop 2017.0.0, Adobe, San Jose, CA, USA) was used to verify chroma using the LCH color mode and to crop and align samples (Figure 3).

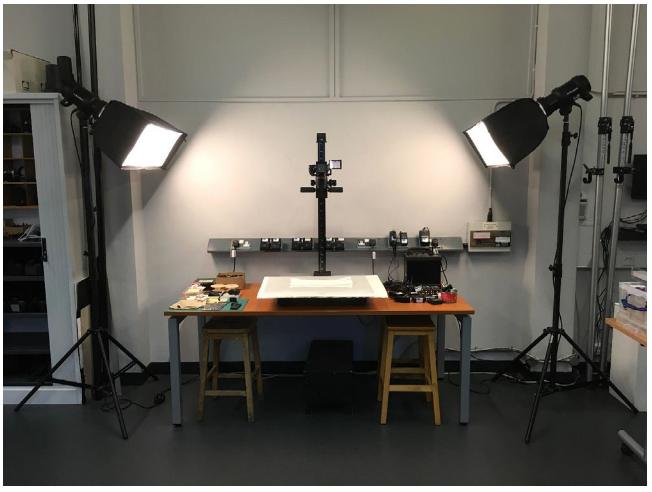

FIGURE 2 Setup for photographing samples, including upright stand, facedown camera, and softbox diffusers.

Prior to assessing the experimental stimuli, participants were shown a series of familiarization stimuli to ensure their understanding of psychometric scales. The familiarization protocol consisted of four stimuli combinations; $3.45 \times 10^{-4}$ mL mm$^{-2}$ light synthetic urine, $3.45 \times 10^{-4}$ mL mm$^{-2}$ dark synthetic urine, 0 mL mm$^{-2}$ light synthetic urine, and 0 mL mm$^{-2}$ dark synthetic urine. Note that while the latter stimuli are dry, they retain hues from the original application of moisture. Photographs of each were presented independently, with the corresponding response on psychometric scales indicated. This provided a frame of reference for the stimuli in addition to acquainting participants with the online study format.

Following familiarization, participants were presented with experimental stimuli and completed a digital perceptual form on the same webpage. Both a 100 mm visual analogue scale (very dry to very wet) and a dichotomous response method were employed (dry/wet, gloss/matte, dilute/concentrate). The dichotomous response paradigm used a binary scoring system for subsequent analyses, with the first response of each pairing designated as 0 and a the second as 1. Once all perceptual responses for the stimulus was completed, participants could advance to the following stimuli page by clicking "next." Participants were shown their relative progress throughout the study, as indicated by a linear progress bar, as such gauges are associated with lower survey dropout rates (Böhme, 2003).

## 2.4 | Statistical analyses

In this study, the independent variables were the stain volume (0, $2.16 \times 10^{-4}$, $3.45 \times 10^{-4}$ mL mm$^{-2}$), stain chroma (clear saline,

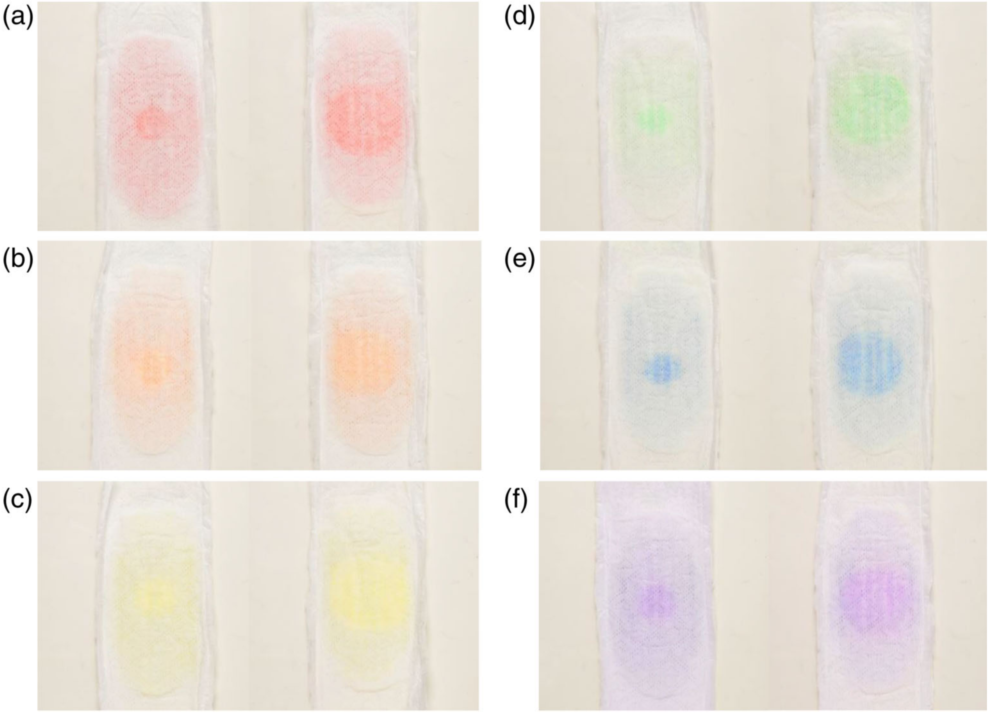


FIGURE 3 A sample of the photographs taken for the online study, including red (a), orange (b), yellow (c), green (d), blue (e), and violet (f) hues. Within each pairing small stains are on the left and large stains are on the right.

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light synthetic urine, dark synthetic urine), stain size (1150 or 5000 mm$^2$) and stain hue (red, orange, yellow, green, blue, violet). The dependent variable was wetness perception (mm). All data were tested for normality of distribution and homogeneity of variances using Shapiro–Wilk and Levene's tests respectively. In cases where the assumptions of these tests were violated, parametric means-based tests were nonetheless applied as they best fit the required analyses of the datasets.

All statistical data reported in text are means ($\bar{x}$) ± standard deviation (SD), with means and 95% confidence intervals (95% CIs) given in figures unless otherwise stated; $\alpha = 0.05$. All statistical analyses were conducted using SPSS (Statistical Package for Social Sciences, Version 24.0.0.2, IBM, Chicago, IL, USA) and graphical representations of data produced using GraphPad Prism (GraphPad Prism, Version 8.3.0, GraphPad Software, La Jolla, CA, USA).

Magnitude estimation data were used to assess the influence of stain volume, stain chroma, stain size, and stain hue on wetness perception. These were processed using a four-way repeat measures ANOVA in conjunction with linear regression and post hoc Tukey tests. Dichotomous data were assessed using Chi Square frequency tests with post hoc multiple regression based residual analyses (Beasley & Schumacher, 1995). Comparisons between in-situ and ex-situ data sets were made using multiple regression analyses.

## 3 | RESULTS

The effects of stain volume, stain chroma and stain size were apparent in magnitude estimation data (Appendix B). Stain volume shared a significant positive relationship with wetness perception ($F_{2,878} = 10.6$, $p < .001$), but only accounted for 1.12% of total variance. Stimuli were differentiable at all magnitudes of wetness (Figure 4), with dry and high wetness having the greatest difference ($\Delta\bar{x} = 10.11$ mm, CIs = 8.88–11.35, $p < .001$), followed by dry and low wetness ($\Delta\bar{x} = 7.11$ mm, CIs = 5.57–8.65, $p < .001$) and finally low wetness and high wetness ($\Delta\bar{x} = 3.00$ mm, CIs = 1.77–4.24, $p < .001$).

Stain chroma also shared a significant positive relationship with wetness perception, such that more intense chromas were associated with greater wetness perception ($F_{2,878} = 1116.2$, $p < .001$). Overall, chroma accounted for 6.26% of variance in wetness perception. All levels of chroma were differentiable from each other (Figure 5), with clear saline and dark synthetic urine having the greatest average difference in wetness perception ($\Delta\bar{x} = 41.99$ mm, CIs = 40.47–43.51, $p < .001$), followed by light synthetic urine and dark synthetic urine ($\Delta\bar{x} = 31.36$ mm, CIs = 29.64–33.08, $p < .001$) and finally clear saline and light synthetic urine ($\Delta\bar{x} = 10.63$ mm, CIs = 9.48–11.78, $p < .001$.

Small and large stain sizes were also differentiable ($\Delta\bar{x} = 11.08$ mm, CIs = 7.63–14.50) (Figure 6), with larger stain sizes associated with greater wetness perception ($F_{1,439} = 47.25$, $p < .001$). This accounted for 0.25% of overall variance in the model.

The hue of liquid applied to the stimuli resulted in significantly different wetness perception ($F_{5,2195} = 307.7$, $p < .001$) and accounted for 9.96% of total variance in wetness perception. Typically, higher wavelength colors approaching red resulted in higher wetness perception, and lower wavelength colors approaching violet resulted in lower wetness perception (Figure 7). All hues were differentiable from each other with the exception of the yellow and orange pairing.

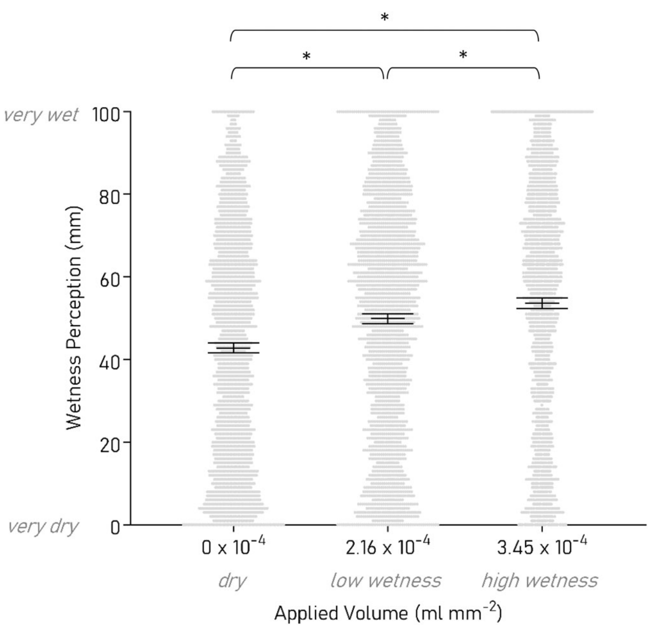


**FIGURE 4** $\bar{x}$ ± 95% CIs ($n = 440$) wetness perception (mm) at three different wetness levels (mL mm$^{-2}$) with significantly different pairings indicated (*).

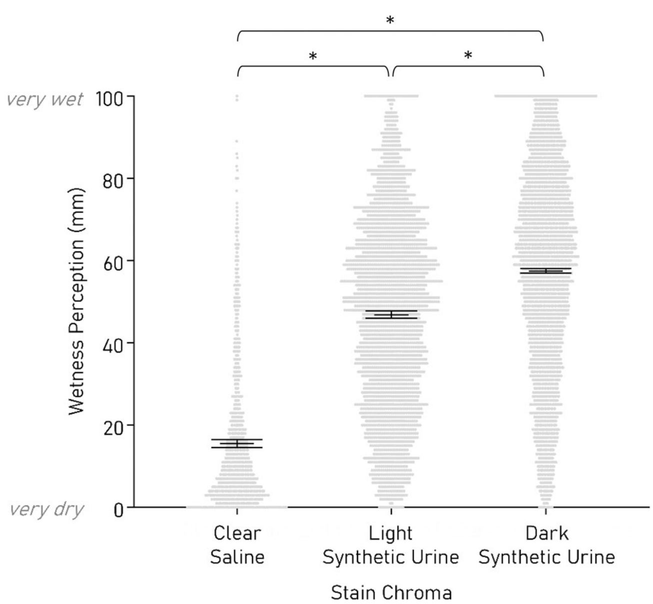


**FIGURE 5** $\bar{x}$ ± 95% CIs ($n = 440$) wetness perception (mm) at three different stain chromas with significantly different pairings indicated (*).

A dichotomous choice method allowed the assessment of stimulus characteristics (Appendix C). Akin to magnitude estimations of wetness perception, dichotomous wet responses significantly increased in frequency as physical wetness increased, indicating that physical wetness resulted in increased wetness perception. The percentage of wet and dry responses were significantly different across each wetness level ($\chi^2_2 = 5370.3$, $p < .001$; Figure 8).

The frequency of gloss over matte responses also increased at greater physical wetness levels such that wetter samples were perceived as being glossier and vice versa. The percentage of gloss and matte responses significantly differed at each of the three wetness levels ($\chi^2_2 = 1384.7$, $p < .001$; Figure 9).

Finally, the frequency of concentrate responses as opposed to dilute shared a significant positive association with wetness perception ($\chi^2_2 = 3842.4$, $p < .001$) such that darker more concentrated samples were typically perceived as wetter (Figure 10).

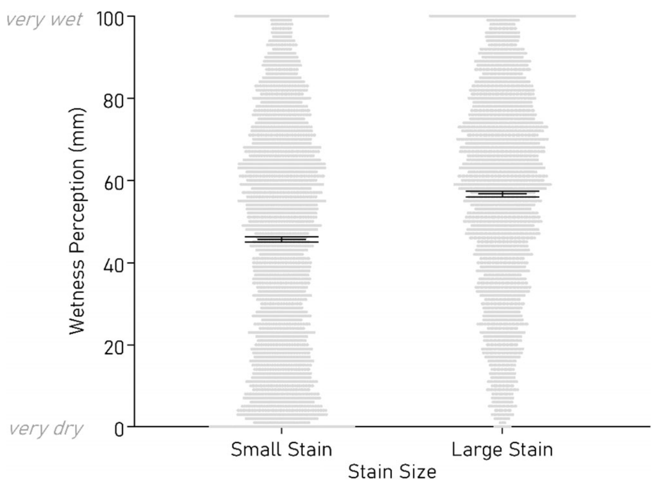


**FIGURE 6** $\bar{x}$ ± 95% CIs ($n = 440$) wetness perception (mm) pooled across all stain chromas and hues at two different stain sizes.

For the participants who completed both in-situ perceptual assessments and the present online study, wetness perception data for synthetic urines could be directly compared (Figure 11). The in-situ and online visual only perception were not significantly different from each other. However, both were significantly different from wetness perception experienced in a visuotactile condition. In each case, visual only assessments over estimated wetness at lower physical wetness levels and underestimated wetness at higher physical wetness levels in comparison to the visuotactile condition.

## 4 | DISCUSSION

In online perceptual studies, there is no possibility of tactile interactions and only a 2D digital image to be viewed, such that the ability to accurately perceive wetness becomes much harder. Despite the limited number of sensory cues involved in the assessments of stimuli, participants were able to successfully differentiate between different physical wetness levels and correctly assign higher magnitudes of perception with higher physical wetness levels.

This shows that while physical aspects have been hailed as the main sensory drivers behind wetness perception (Filingeri et al., 2014), visual cues must also have considerable influence, which may be attributed to different aspects of vision. For example, despite being the same physical wetness levels, larger stains were perceived as wetter than their smaller equivalents. This may be due to an association between larger stains and the likelihood of material saturation, as larger areas typically result from greater liquid loads as opposed to a large distribution of small liquid quantities (Mao, 2000).

The relative distribution or concentration of a stain is also linked to its perceived chroma. The study found a positive relationship between moisture chroma and wetness perception such that more intense areas are indicative of wetness. Again, this may be a learned behavior, such as from the regular handling of damp fabrics which reflect less light at wet interfaces (Lekner & Dorf, 1988). Alternatively

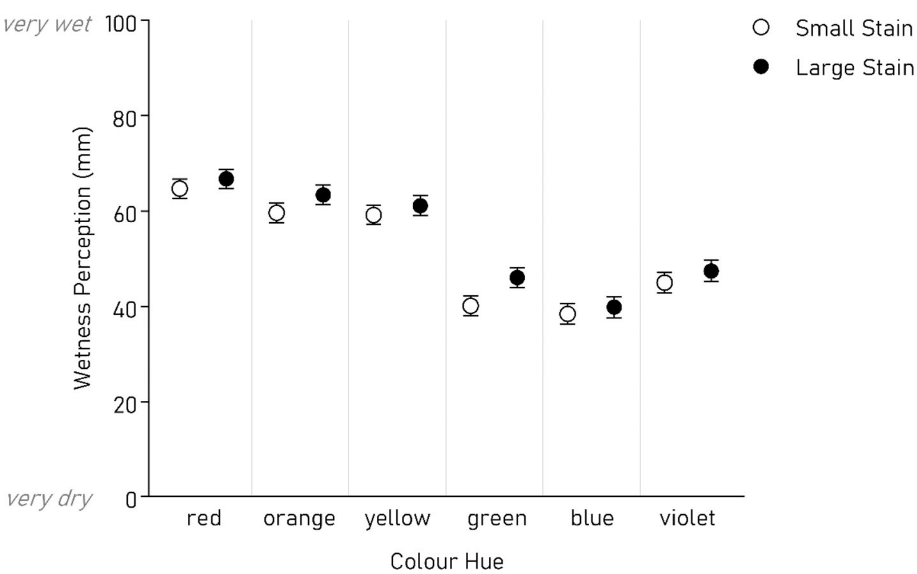


**FIGURE 7** $\bar{x}$ ± 95% CIs ($n = 440$) wetness perception (mm) at six different stain hues. All pairings significantly differ with the exception of yellow and orange.

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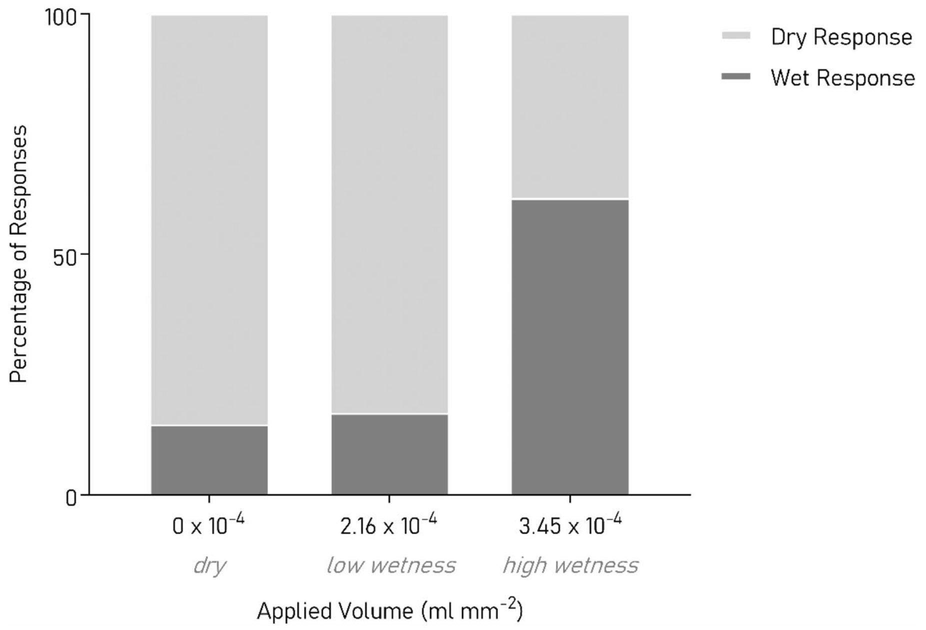


**FIGURE 8** The frequency of dry and wet dichotomous responses at three wetness levels (mL $mm^{-2}$) during online stimuli observations ($n = 440$).

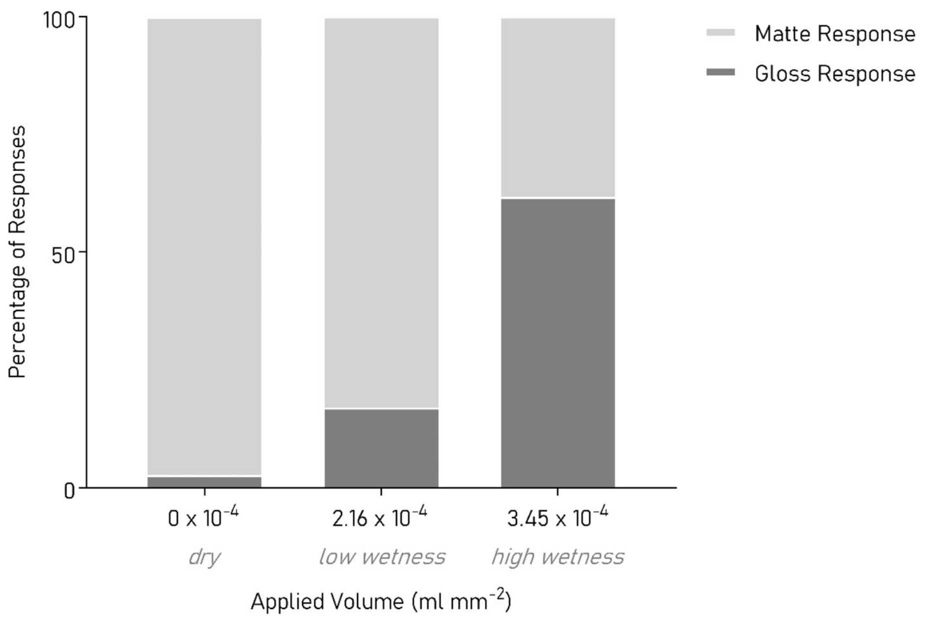


**FIGURE 9** The frequency of matte and gloss dichotomous responses at three wetness levels (mL $mm^{-2}$) during online stimuli observations ($n = 440$).

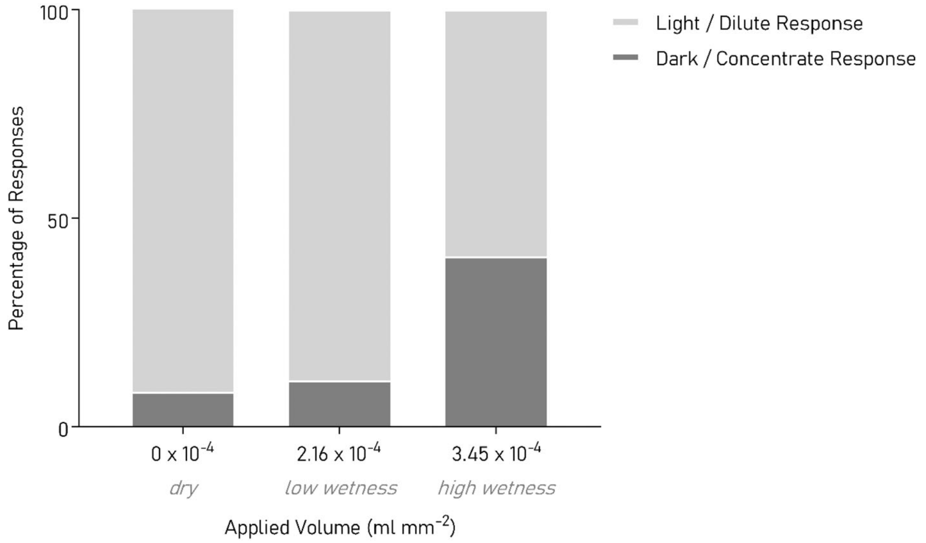


**FIGURE 10** The frequency of light/dilute and dark/concentrate responses at three wetness levels (mL $mm^{-2}$) during online stimuli observations ($n = 440$).

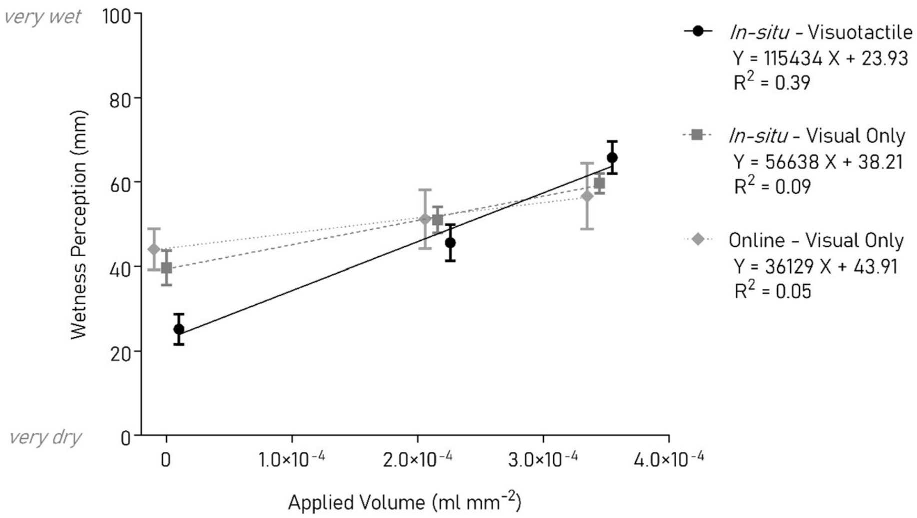


**FIGURE 11** $\bar{x} \pm 95\%$ CIs ($n = 18$) perceived wetness at varying physical wetness levels (mL mm$^{-2}$), comparing data from a set of participants who completed both in-situ visuotactile and visual only studies in addition to the current visual only online study. Corresponding linear regression equations shown.

this could relate more to an evolutionary component such as the association of darker colors with higher volumes of water, such as comparing a deep lake with a shallow bay, which occurs due to the attenuation of light by water and hence makes deeper areas appear darker (Geyman & Maloof, 2019). Interestingly, the magnitude of difference between wetness perception associated with each chroma was considerably larger in the online study compared to the in-situ visual only study. This implies that in certain scenarios specific cues will begin to dominate perception.

The association between naturally occurring color hues and thermal inputs have already been highlighted (te Kulve et al., 2016), but similar principles have not transferred to wetness in this case. For example, green forests and blue oceans are typically associated with cool sensations, whereas amber deserts and red fires are more associated with heat (Ho et al., 2014). Therefore, it could be expected that blue and green hues resulted in higher wetness perception. Additionally, the human eye is most sensitive to green light, and so even at equal physical chromas green stimuli may have generated higher wetness perception (Saunders et al., 2008).

However, the contrary was found in this study, with higher wavelength colors resulting in greater wetness perception. While chroma was quantitatively established to ensure all stimuli were the same molecular concentration, there is potential for the use of a diaper as a stimulus to have influenced results. For example, color association predominantly occurs through nature (te Kulve et al., 2016), whereas diapers are manmade items which users may be more likely to associate with higher wavelength hues representing urine. Additionally, colors such as red will have a greater contrast when applied to the white substrate compared with a more similar color such as yellow or green.

For the participants who completed both in-situ perceptual assessments and the online study, wetness perception data could be directly compared. Overall, visual only assessments overestimated wetness at lower physical wetness levels and underestimated wetness at higher physical wetness levels in comparison to the visuotactile condition. This shows that visual only perception is more conservative than those which also include tactile cues, with online data showing the lowest mean deviation in magnitude values between each wetness level.

However, as the in-situ and online visual only wetness perception were not significantly different from each other, overall wetness perception must rely on similar cues that were present in both in-situ and online assessments. Despite this, there were some small changes in variables contributing to wetness perception, such as size being a significant factor in the online study but not in-situ. This implies that different factors are weighted and integrated into a feasible scenario as opposed to one aspect overriding others. While in-situ and online visual perception deviated from each other minimally, both were significantly different from visuotactile perception. This again highlights the importance of haptic cues and gives further evidence toward visual cues being an influencing but not dominating factor.

As hypothesized, the study highlights a positive relationship between physical wetness, stain chromas, stain sizes and wetness perception. The relationship between stain hue and wetness was inverse to expected, which may be attributed to learned color associations as opposed to physical parameters. This shows that visual components of wetness perception are analogous whether stimuli are presented online or in person, and while there are several visual aspects that influence wetness perception, it is still predominantly influenced by haptic cues. It is therefore likely that the multisensory integration behind wetness does not rely on visual dominance, and instead uses a weighted balance of cues based on their relative quality and likelihood. This research is relevant in the further assessment of multisensory integration, both in the context of wetness sensation and across wider cognitive pathways. In addition to academic significance, there are also a range of industrial applications. For example, improving the structure, function, and perception of absorbent hygiene products such as diapers, sanitary towels, and incontinence pads, or informing the design of sportswear with moisture management properties. Additionally, findings may aid the improvement of digital software which uses visual wetness components, for example in augmented and virtual realities.

## 5 | CONCLUSIONS

The study highlighted significant relationships between wetness perception and visual characteristics including stain chroma, size and hue using digital photos on an online platform. Wetness perception was positively associated with physical wetness such that higher levels of wetness resulted in greater wetness perception. Wetness perception also shared a positive relationship with chroma, such that clear, light, and dark stains were all significantly different. Similarly, increased stain size resulted in greater wetness perception with small and large stains being differentiable. Stain hues with higher wavelengths were associated with higher wetness perception compared to lower wavelengths.

Finally, visual wetness perception experienced online was not significantly different to in-situ visual counterparts, with participants overestimating low wetness levels and underestimating high wetness levels in both visual only conditions compared to visuotactile conditions. While this shows conservative estimates of visual wetness perception, this may highlight the importance of both quality and quantity of information surrounding a stimulus and how their relative states effect potential modes of integration. This information contributes to the overall multisensory integration model surrounding wetness, and shows how it may vary in different sensory conditions. Applications of these findings include aiding the design of products with moisture management properties and improving digital software with visual wetness components.

## AUTHOR CONTRIBUTIONS

Charlotte Merrick, Rodrigo Rosati, and Davide Filingeri conception and design of research. Charlotte Merrick performed experiments. Charlotte Merrick analyzed data. Charlotte Merrick and Davide Filingeri interpreted results of experiments. Charlotte Merrick prepared figures. Charlotte Merrick drafted manuscript. Charlotte Merrick, Rodrigo Rosati, and Davide Filingeri edited and revised manuscript. Charlotte Merrick, Rodrigo Rosati, and Davide Filingeri approved final manuscript.

## ACKNOWLEDGMENTS

The authors would like to thank Professor Sue Hignett and Dr Ashleigh Filtness for their guidance, and Sam Swift for developing the script used to produce interactive visual analogue scales.

## FUNDING INFORMATION

The present research was conducted in the context of an industry co-funded PhD at Loughborough University, with financial support from The Engineering and Physical Sciences Research Council and Procter and Gamble Service GmbH.

## CONFLICT OF INTEREST STATEMENT

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

## DATA AVAILABILITY STATEMENT

Research data are not shared.

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**How to cite this article:** Merrick, C., Rosati, R., & Filingeri, D. (2023). The visual perception of wetness: The role of stain chroma, size, and hue. *Journal of Sensory Studies*, e12879. https://doi.org/10.1111/joss.12879

## APPENDIX A

### A.1 | A Table Showing The Mean Responses of Participants Attempting To Differentiate Between Two Presented Stimuli ($n = 5$).

| Concentration multiplier | Participant 1 mean | Participant 2 mean | Participant 3 mean | Participant 4 mean | Participant 5 mean | Modal value |
|---|---|---|---|---|---|---|
| 1 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 1.25 | 0.17 | 0.00 | 0.17 | 0.00 | 0.00 | 0.00 |
| 1.5 | 0.17 | 0.33 | 0.33 | 0.17 | 0.00 | 0.17 |
| 1.75 | 0.33 | 0.33 | 0.50 | 0.33 | 0.17 | 0.33 |
| 2 | 0.50 | 0.50 | 0.50 | 0.33 | 0.50 | 0.50 |
| 2.25 | 0.50 | 0.67 | 0.67 | 0.50 | 0.50 | 0.50 |
| 2.5 | 0.50 | 0.67 | 0.67 | 0.50 | 0.67 | 0.67 |
| 2.75 | 0.67 | 0.83 | 0.83 | 0.67 | 0.67 | 0.67 |
| 3 | 0.83 | 0.83 | 0.83 | 0.83 | 0.83 | 0.83 |
| 4 | 1.00 | 1.00 | 1.00 | 0.83 | 1.00 | 1.00 |
| 5 | 0.83 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| 10 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |

*Note*: In each case, one stimulus was prepared at a single concentration and another at a different concentration multiplier. A value of 0 indicated they were not differentiable, while 1 indicated that participants could correctly differentiate between them. Therefore, a mean value of 0.5 indicates the differential threshold. Light gray shading indicates the first concentration a participant's mean met this 0.5 value. Dark grey shading indicates the first modal value to meet the 0.5 threshold and its corresponding concentration multiplier.

## APPENDIX B

### B.1 | Magnitudes of Wetness Perception (mm) ($\bar{x}$ ± SD) Associated With Two Sets of Stimuli ($n = 440$).

| (a) | | First set | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Chroma | | Clear saline | | | Light synthetic urine | | | | | | Dark synthetic urine | | | | | |
| Size | | Small | | | Small | | | Large | | | Small | | | Large | | |
| Wetness | | Dry | Low | High | Dry | Low | High | Dry | Low | High | Dry | Low | High | Dry | Low | High |
| Wetness perception (mm) | $\bar{x}$ | 13.6 | 17.5 | 15.5 | 40.8 | 43.4 | 49.6 | 39.5 | 51.9 | 56.3 | 58.0 | 66.3 | 72.0 | 62.1 | 70.6 | 74.9 |
| | SD | 17.2 | 18.9 | 17.6 | 23.6 | 22.7 | 22.7 | 23.5 | 21.6 | 21.4 | 23.5 | 20.8 | 20.5 | 23.1 | 20.9 | 20.1 |

| (b) | | Second set | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hue | | Red | | Orange | | Yellow | | Green | | Blue | | Violet | |
| Size | | Small | Large | Small | Large | Small | Large | Small | Large | Small | Large | Small | Large |
| Wetness | | High | High | High | High | High | High | High | High | High | High | High | High |
| Wetness perception (mm) | $\bar{x}$ | 64.7 | 66.8 | 59.6 | 63.4 | 59.2 | 61.1 | 40.1 | 46.0 | 38.4 | 39.8 | 45.0 | 47.4 |
| | SD | 21.6 | 21.5 | 21.7 | 22.1 | 21.4 | 22.5 | 22.3 | 21.7 | 22.9 | 23.8 | 22.9 | 23.6 |

*Note*: The first set (a) arise from different chromas of synthetic urine, sizes, and wetness combinations and the second set (b) is formed of different color hues, sizes, and wetness combinations.

## APPENDIX C

### C.1 | Relative Percentages of Dichotomous Responses (x̄ ± SD) Associated With Two Sets of Stimuli ($n = 440$).

| (a) | | First set | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Chroma | | Clear saline | | | Light synthetic urine | | | | | | Dark synthetic urine | | | | | |
| Size | | Small | | | Small | | | Large | | | Small | | | Large | | |
| Wetness | | Dry | Low | High | Dry | Low | High | Dry | Low | High | Dry | Low | High | Dry | Low | High |
| Wet responses (%) | x̄ | 15.5 | 25.0 | 22.3 | 60.5 | 70.5 | 78.4 | 62.7 | 82.7 | 87.7 | 81.8 | 93.0 | 95.2 | 88.4 | 95.5 | 95.7 |
| | SD | 36.2 | 43.4 | 41.7 | 49.0 | 45.7 | 41.2 | 48.4 | 37.9 | 32.8 | 38.6 | 25.6 | 21.3 | 32.0 | 20.9 | 20.3 |
| Gloss responses (%) | x̄ | 8.86 | 7.50 | 6.36 | 9.55 | 13.9 | 16.1 | 6.14 | 15.7 | 18.2 | 12.3 | 23.0 | 24.1 | 18.2 | 27.7 | 27.7 |
| | SD | 28.5 | 26.4 | 24.4 | 29.4 | 34.6 | 36.8 | 24.0 | 36.4 | 38.6 | 32.8 | 42.1 | 42.8 | 38.6 | 44.8 | 44.8 |
| Concentrate responses (%) | x̄ | 1.82 | 1.82 | 2.05 | 20.7 | 24.1 | 33.6 | 23.6 | 55.5 | 64.1 | 61.1 | 77.0 | 83.0 | 74.8 | 79.5 | 84.5 |
| | SD | 13.4 | 13.4 | 14.2 | 40.5 | 42.8 | 47.3 | 42.5 | 49.8 | 48 | 48.8 | 42.1 | 37.6 | 43.5 | 40.4 | 36.2 |

| (b) | | Second set | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hue | | Red | | Orange | | Yellow | | Green | | Blue | | Violet | |
| Size | | Small | Large | Small | Large | Small | Large | Small | Large | Small | Large | Small | Large |
| Wetness | | High | High | High | High | High | High | High | High | High | High | High | High |
| Wet responses (%) | x̄ | 90.7 | 92.5 | 86.4 | 89.5 | 88.4 | 90.0 | 64.3 | 77 | 63.1 | 66.6 | 69.1 | 73.2 |
| | SD | 29.1 | 26.4 | 34.4 | 30.6 | 32.0 | 30.0 | 48.0 | 42.1 | 48.3 | 47.2 | 46.3 | 44.4 |
| Gloss responses (%) | x̄ | 21.1 | 26.1 | 19.1 | 23.6 | 23.4 | 19.8 | 15.0 | 19.3 | 15.9 | 15.0 | 13.6 | 13 |
| | SD | 40.9 | 44.0 | 39.3 | 42.5 | 42.4 | 39.9 | 35.7 | 39.5 | 36.6 | 35.7 | 34.4 | 33.6 |
| Concentrate responses (%) | x̄ | 77.5 | 83.0 | 74.1 | 79.3 | 43.6 | 43.9 | 18.4 | 41.8 | 24.8 | 29.3 | 47.3 | 55.9 |
| | SD | 41.8 | 37.6 | 43.9 | 40.5 | 49.6 | 49.7 | 38.8 | 49.4 | 43.2 | 45.6 | 50.0 | 49.7 |

*Note*: The first set (a) arise from different chromas of synthetic urine, sizes, and wetness combinations and the second set (b) is formed of different color hues, sizes, and wetness combinations.