Exploring For Gloss: The Role of Active Exploration in Visual Material Perception

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Abstract

Image motion has been found to contribute to the perception of visual material properties, and motion signals are generated while actively exploring objects. Yet, little is known about the specific visual cues produced through exploration and how exploration, in turn, impacts visual material perception. Using virtual reality and real-time hand tracking, we investigated the influence of material on exploratory hand motion and vice versa. Participants either observed or actively explored objects varying in gloss or in lightness while performing a matching task. We compared the perceptual judgments of actively exploring and observing participants and analysed their manual exploration patterns during the two material judgment tasks in the interactive condition. Results showed systematic variation in exploration patterns based on visual task and material property: participants spent more time exploring objects when judging gloss than when judging lightness, and glossier objects were explored longer. This increased exploration during gloss judgments could suggest a strategic prioritisation of relevant cues for gloss judgments, with observers actively generating highlight movements through larger movements and object rotation to facilitate their gloss judgements. Our study demonstrates that visual material properties impact how individuals interact with objects, and that active exploration influences the perception of visual material properties.

Keywords: Material perception, Gloss perception, Lightness perception, Active exploration

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In everyday activities, we come across a wide range of materials. Every object and surface we see or touch is made of some material, each possessing distinct characteristics such as wetness, roughness, glossiness and softness that can be perceived and inferred through our senses. The perception of material properties is integral to our daily lives, as the material properties of objects are essential in determining how we interact with them or use them. For instance, differentiating between materials such as cream, shaving foam, plastic, metal, oak, and marble helps us discern their attributes such as edibility, durability and aesthetic appeal. Our visual estimations of material qualities enable us to anticipate and adapt our actions accordingly. For example, we might choose a sturdy metal railing over a plastic one for support, adjust our grip force based on fragility or object weight to prevent breakage, or visually inspect whether the ground is slippery and to seek support to prevent slipping (Buckingham, Cant & Goodale, 2009; Buckingham, Ranger & Goodale, 2011; Paulun, Gegenfurtner, Goodale & Fleming, 2016). Hence, the ability to perceive and recognise material properties of objects not only facilitates our immediate decisions but also shapes our actions.

Humans can readily recognise most objects' material properties and almost instantaneously infer functional properties just by looking at them (Adelson, 2001; Fleming, 2014; Sharan, Rosenholtz & Adelson, 2009; Wiebel, Valsecchi & Gegenfurtner, 2013). Prior studies on visual perception of materials have examined and identified several physical factors and visual cues that influence our perception of optical material properties, such as gloss, translucency, and lightness in static scenes (for a review, see Anderson, 2011; Gigilashvili, Thomas & Hardeberg, 2021; Chadwick & Kentridge, 2015; Murray, 2021). For instance, research on gloss perception has found that object shape and surface geometry (Vangorp, Laurojssen & Dutré, 2007; Ho, Landy & Maloney, 2008; Marlow, Kim & Anderson, 2012; Marlow & Anderson, 2013), illumination conditions (Fleming, Dror & Adelson, 2003; Doerschner, Boyaci & Maloney, 2010 a,b; Motoyoshi & Mataba, 2012; Olkkonen & Brainard, 2010), and specular highlights properties like their shape, intensity, location and the orientation between highlights and shading have an impact on perceived gloss (Berzhanskaya, Swaminathan, Beck & Mingolla, 2005; Beck & Prazdny, 1981; Kim, Marlow & Anderson, 2011). In dynamic scenes, researchers have also demonstrated the importance of motion cues in perceiving optical material qualities (e.g. Doerschner et al., 2011; Wendt, Faul, Ekroll & Mausfeld, 2010; Sakano & Ando, 2010; Lichtenauer, Schuetz & Zolliker, 2013). Similarly, lightness perception has been found to be influenced by factors such as direction and intensity

of illumination (Kobayashi & Morikawa, 2019; Gilchrist et al., 1999; Toscani , Zdravković & Gegenfurtner, 2016), contextual information like contrast with surrounding elements and background (Hess & Pretori, 1970; Allred & Brainard, 2013), as well as surface reflectance, orientation, texture, and shape (Toscani, Valsecchi & Gegenfurtner, 2017; Schmid & Anderson, 2014; Boyaci, Maloney & Hersh, 2003; Knill & Kersten, 1991; Pessoa, Mingolla & Arend, 1996). These examples highlight the visual system's reliance on different *visual cues*, including intrinsic factors like surface geometry and object size, and extrinsic factors, such as illumination properties and viewpoints, to infer and estimate visual material properties.

Yet, humans are not simply passively using these visual cues. Instead, they actively seek information that is relevant to the task at hand (Rothkopf, Ballard & Hayhoe, 2007). For example, studies examining eye movement patterns have shown that people are selective and strategic with where they look when judging visual material qualities. Toscani, Valsecchi & Gegenfurtner (2013; 2017) showed that observers tend to focus on the brightest part of the surface and base their judgments on those regions when assessing the lightness of matte objects. If observers are forced to focus on a specific area, the lightness of that area will influence their lightness judgments of the entire surface. Interestingly, the selection of the fixation region is also influenced by surface properties: when judging the lightness of glossy surfaces, observers prioritise regions adjacent to the highlights over the brightest parts, as highlights are not diagnostic of surface lightness (Toscani et al., 2013). In another eye-tracking study, Toscani , Yücel & Doerschner(2019) found that participants focused more on gloss-relevant image motion cues (Doerschner et al., 2011) during gloss judgments than during speed judgments.

Taken together, the research on visual cues suggests that visual sampling strategies are optimised for specific tasks and are modulated by materials properties, with observers looking at areas in static and dynamic scenes that contain the most task-relevant information. However, in real-world settings we judge the qualities of materials not only by looking at objects- but also by manually exploring and interacting with them (Figure 1).

Figure 1. **Active exploration of objects and materials.** Active exploration of objects and materials produces visual cues that aid subsequent visual recognition and estimation tasks. Image sources: https://www.recipetineats.com/outrageous-triple-chocolate-cookies/; https://gadzetarnia.pl/pl/p/Kula-antystresowa-z-brokatem-Gniotek-do-sciskania-Scisk-Antystres/36739

This interaction could provide us with the cues that the visual system learns to use for estimating object properties (e.g. Adolph, Eppler & Gibson, 1993, Metta & Fitzpatrick, 2003, Smith, Jayaraman, Clerkin & Yu, 2015). This is not only true for mechanical material properties as those illustrated in Figure 1, but also the perception of optical material properties can potentially benefit from interaction. For example, Gigilashvili and colleagues (2018, 2019, 2021) qualitatively observed, that, if unconstrained, participants would move real 3D objects and try to look through them when assessing an object's translucency and move their head to judge glossiness. Previous work points to the idea, that motion signals, generated through such interactions, indeed play an important role in determining material appearance (e.g. specular flow or highlight motion for glossiness, see e.g. Doerschner et al., 2011; Wendt et al., 2010; Sakano & Ando, 2010). This raises the question, to what extent are human exploratory hand movements tuned to the visual perceptual task when estimating optical material properties.

To answer this, one has to consider the potential information to be gained through interaction. For example, if the task is to judge the glossiness of a smooth bumpy object, much is to be gained by rotating the object with respect to the light source, because that would generate the type of highlight motion that has been shown to aid in assessing the glossiness of a surface. Figure 2A illustrates this. Suppose the glossy object rotates around the vertical axis a small amount, e.g. 10 degrees. Measuring the change in pixel intensity between two frames, where the object has an angular difference of 10 degrees, (Figure 2C) we see that quite a few pixels change their intensity (brighter colors, denote larger pixel differences). Suppose now that the task is to judge the lightness of a similar, but matte object, as the one shown in Figure 2B. A rotation by the same amount (10 degrees) around the vertical axis would lead to much

less change in pixel intensity (Figure 2D). Consequently, less information would be gained from a rotation of the object in ones' hand.

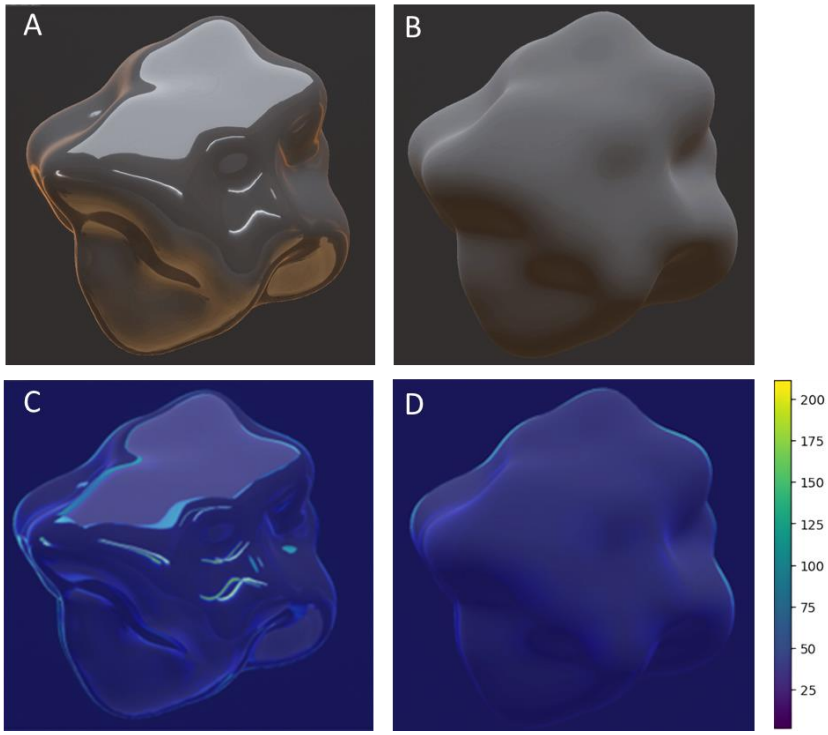

Figure 2. **Absolute pixel intensity difference across frames.** Example of absolute pixel intensity difference across frames. Panel A shows a rotating high-gloss object, and Panel B shows a rotating matte object. Panels C and D display the average absolute pixel intensity difference between two consecutive frames, where the objects differ by a 10-degree rotation. See text for details.

Would we find differential exploration behaviour as a function of perceptual task and material in an experiment? Here we use an active exploration paradigm in virtual reality coupled with real-time hand tracking to investigate whether observers explore objects differently when judging gloss or lightness. During the experiment, participants were tasked with matching the gloss or lightness of an object to a set of seven comparison objects. They could either interact with an object or observe the object while forming their judgments. We expected that if interactions would generate useful information for judging visual gloss, then participants would make more rotational movements while interacting with the object when judging gloss than when making lightness judgments (Doerschner et al., 2011; Toscani et al., 2019), and would also judge objects as more glossy during the interactive condition. The role of image motion in lightness judgments is less clear, and object motion can even compromise lightness constancy (Wendt et al., 2010). Therefore, when judging lightness, participants may instead selectively focus on certain areas, e.g. the brightest part of the object, that provide the most informative cues for their judgments (Toscani et al., 2013; 2017). Since the location of the brightest part of a matte object will not change substantially when moving the object in

hand, we expected fewer overall movements during lightness judgements. We also expected no changes in perceived lightness between interactive and observation conditions.

Methods

Participants

Twenty-three participants (8 males) between 22 to 33 years of age, M_{age} = 26.8 years, SD_{age} = 3.0. years) were recruited from Giessen University. This sample size was comparable to those reported in previous studies that used virtual reality to investigate gloss perception (e.g., Chen et al., 2023; Wendt & Faul, 2018). Twenty participants were right-handed, two were left-handed, and one was ambidextrous based on self-report. All participants had normal to corrected-to-normal vision and had no history of motor impairments. All participants provided informed consent and received compensation of (8€/h) for their participation. This study was approved by the ethics committee at Giessen University (LEK FB06) and conducted in accordance with the declaration of Helsinki (2013) except for preregistration. Three participants were excluded from the analysis due to technique failure with equipment during data collection and were unable to complete all four conditions, and one participant was excluded due to non-compliance with the instructions.

Stimuli

The stimuli consisted of 3D virtual objects rendered with varying levels of smoothness and albedo. Before the main study, a pilot study was conducted to determine the suitable interval between stimulus levels. Based on feedback from 60% of pilot participants (N = 5) who found it difficult to distinguish between stimuli with smaller differences in levels (gloss & lightness), we decided to use perceptually distinct levels of smoothness and albedo instead of uniform increments in gloss and albedo levels.

Shapes. Two novel 3D shapes (‘Glaven objects’; Philips et al., 2009; 2016) were used as the target and comparison objects (Figure 3).

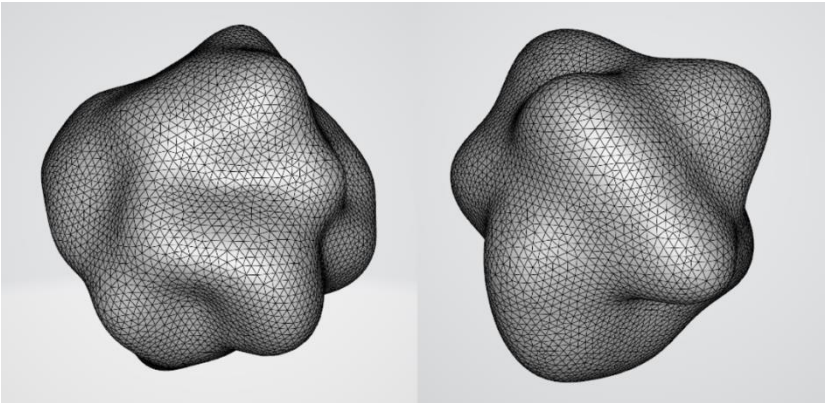

Figure 3. **3D shapes used in the experiment.** Left: target shape, right: comparison shape.

Material. To generate the material for our stimulus sets, we utilised the Unity HDRP built-in Lit shader. We kept the surface index of refraction (IOR) constant at 1.46, similar to the IOR of plastic (Pixel and Poly, 2022). While we could adjust various properties using the Lit shader, we focused on changing only the albedo and smoothness. In Unity, the Albedo property determines a material's base colour (RGB), and the smoothness scale controls the degree of blur in specular reflections. The RGB channel values range from 0 to 1, with greyscale colour resulting when the R(red), G (green), and B(blue) channel values are equal. For instance, black is represented as [0 0 0] and white as [1 1 1]. The smoothness scale operates from 0 to 1, where 0 represents a completely matte surface, and 1 signifies a flawlessly smooth surface that reflects light like a mirror.

Gloss. For the stimuli in the gloss conditions, we chose two sets of dark and light colour RGB values: [0.208 0.004 0.047] for dark stimuli and [0.341 0.243 0.263] for light stimuli. We used two base colours because gloss appearance changes as a function of contrast (e.g. contrast gloss, Hunter (1975)), and the distinctiveness of a highlight might modulate the amount of interaction. For the target objects, we created five levels of gloss by adjusting the smoothness values: 0.10, 0.35, 0.55, 0.70, and 0.85, ranging from least glossy to most glossy. Similarly, we set the smoothness values for the comparison objects to 0.05, 0.25, 0.50, 0.65, 0.75, 0.85, and 0.95 to generate seven distinct gloss levels, from least glossy to most glossy. (See Figure 4).

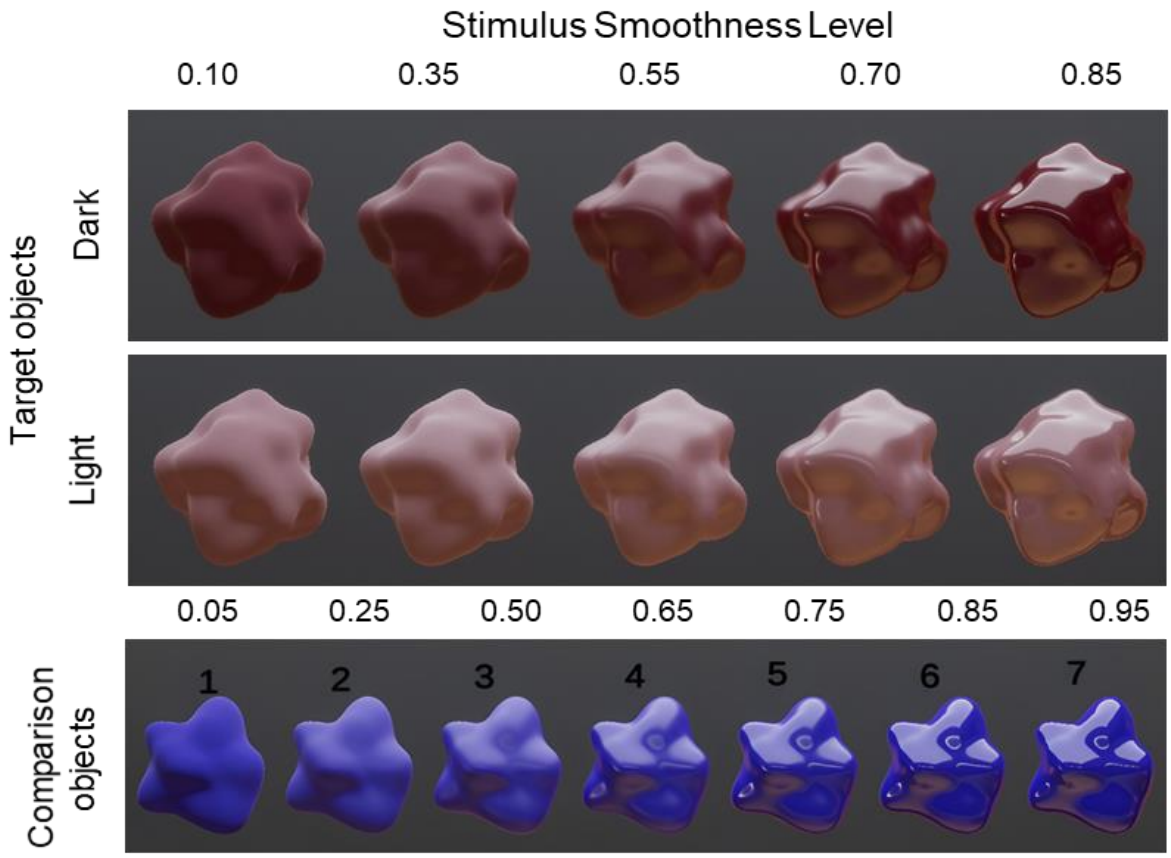

Figure 4. **Target and comparison objects used in the gloss conditions.** Note, that the highest target gloss level 5 corresponds to gloss level 6 of the comparison stimulus. The lowest gloss level of the target is somewhere between level 1 and 2 of the comparison stimulus.

Lightness. For the stimuli in the lightness conditions, the smoothness of all objects was set as 0.5 (somewhat glossy, but no distinct highlights, allowing for comparisons across lightness and gloss tasks) and RGB values were equal for each lightness level (e.g., 0.5: [R = 0.5, G = 0.5, B = 0.5]). Specifically, the RGB values were set for the target objects: 0.50, 0.35, 0.25, 0.15, and 0.01 for the five lightness levels, arranged from the lightest to the darkest. Whereas for the comparison objects, the RGB values were set as 0.60, 0.50, 0.40, 0.30, 0.20, 0.09, and 0.01 for the seven lightness levels, again organised from the lightest to the darkest (see Figure 5).

Apparatus & software

Participants wore a VIVE Pro Eyes head-mounted display (HMD) that displayed a stereoscopic image of the virtual environment with a resolution of 1440 x 1600 pixels per eye (2880 x 1600 pixels combined) and a frame rate of 90Hz. The participant's head movements were tracked, updating their perspective as they explored the virtual environment by turning their head. The

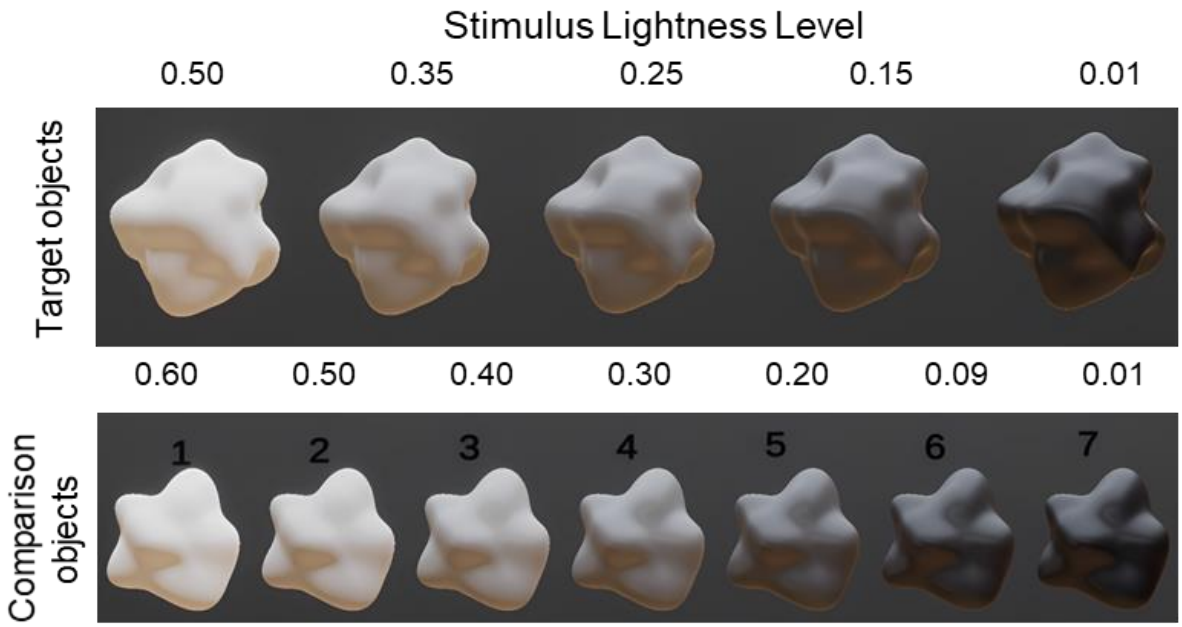

Figure 5. **Target and comparison objects used in the lightness conditions**. Note that the darkest target lightness level 5 corresponds to level 7 of the comparison stimulus. The lightest color of the target (level 1) corresponds to level 2 of the comparison stimulus.

position of participants' arms and hands was tracked using an Ultraleap Leap motion controller mounted on the front of the HMD using a custom 3D-printed mount. The Leap Motion controller consisted of two near-infrared cameras that track the user's hand movement with a resolution of 640 x 240 pixels per camera and a framerate of 60 frames per second. The movement and position of the participant's tracked hands were mapped onto the virtual hand in real-time so that the movement of the virtual hand was congruent with the movement of the participant's actual hand. The avatar hands utilised were sourced from the Ultraleap Gemini (V5.2) SDK's hands module (see Figure 6).

The experiment programme and environment were created by us using the Unity 3D Gaming Engine (version 2021.3.9f1) High Definition Render Pipeline (HDRP) with the Ultraleap plugin. The default HRDI sky was used for the virtual environment, and an additional area light (measuring 3.86m x 2.58m with white colour and an intensity of 1721 lumens) was placed above the experimental area, approximately 1.35m from the virtual table. The virtual environment featured a room with a table set against a grey wall. A 3D camera set at eye level was positioned in front of the table. Participants were seated during the experiment in front of a black dot (2cm in diameter) on the table, which served as a reference point for their egocentric location.

In all conditions, the target objects were presented at the same location across trials, approximately 35.5cm from the reference point. However, the orientations of objects were randomised to prevent participants from fixating on specific object regions during exploration or observation. The comparison objects were arranged in a linear formation, positioned 35.5 cm from the reference point, and aligned in a row. In the interactive condition, the comparison objects rotated around the vertical axis at a rate of 1 degree per frame. In the observation condition, the comparison objects remained in the same position but were static.

Design and procedure

In a single session, participants engaged in four experimental conditions: Interactive Gloss, Interactive Lightness, Observation Gloss, and Observation Lightness, the order of which was counterbalanced across participants. Each condition consisted of 50 trials, with each of the five stimulus levels presented ten times in randomised order. The initial perspective of the target object was varied across ten possible orientations involving rotations along either the x or y-axis by 45°, 90°, 135°, 180° or 225°, each appearing five times in randomised order. The session's duration averaged around 1 to 1.5 hours.

After providing their informed consent, participants were asked to sit facing the table, where they were given instructions (Figure 6) for the experiment and encouraged to ask any questions. Participants were told to make matching judgments about either gloss or lightness: they will be presented with a target object, which they would interact with or observe for as long as they needed to, and their task was to select the comparison object that best matches that target object in terms of the specified visual material. Once participants understood the task, they donned the VR headset, and the experiment began. Prior to the start of each condition, corresponding instructions were displayed again within the virtual environment.

On a given trial, participants were first presented with a target object of five varying levels of gloss or lightness in randomised order and were instructed to explore (interactive condition) or observe (observation condition) it at their own pace. They were instructed to notify the experimenter once they felt ready to proceed with their judgments. Afterwards, they were presented with seven comparison objects, each varying in terms of their gloss or lightness. Their task was to select the object that best matched the target object in relation to the specified material (i.e., gloss or lightness). The comparison objects were numbered, and participants conveyed their selections by naming the corresponding number aloud to the experimenter.

Once the experimenter had recorded their responses, the comparison objects disappeared, and the experimenter pressed the enter key to start the next trial.

The general procedure remained consistent for both material judgments (gloss/lightness). The procedure for the exploration conditions (interactive/observation) differed slightly and is outlined next:

Observation conditions. The procedure of this exploration condition was as outlined above, and participants were instructed to maintain minimal body and head movements throughout this exploration condition.

Interactive conditions. In this exploration condition, participants were provided with a virtual hand that was only visible when they were positioning their hand on the starting position (i.e., only at the start of a trial). Participants were first presented with a chrome sphere in front of them, and they were instructed to place their virtual right hand on the sphere as if they were preparing to grasp it (Figure 6). This step was implemented to establish uniform hand positioning before the onset of their explorations. Once their hand was properly positioned, a target object appeared and simultaneously, the virtual hand became invisible and the virtual object became attached to the palm of the now invisible virtual hand. The participant was then able to move and rotate the virtual object by moving and rotating their physical hand. They could freely interact with the object as if they were manipulating it with their physical hand, with both rotational and translational movements possible. Additionally, their hand movements during explorations were captured by the Ultraleap Leap motion controller. This design was aimed to maintain participants' focus on the stimulus they were exploring rather than their virtual hand, as well as to avoid the intersections between the hand and object mesh upon contact. After completing their matching judgement, the comparison objects disappeared

after the experimenter recorded their response, and both the chrome sphere and their virtual hand reappeared, signalling the start of the next trial.

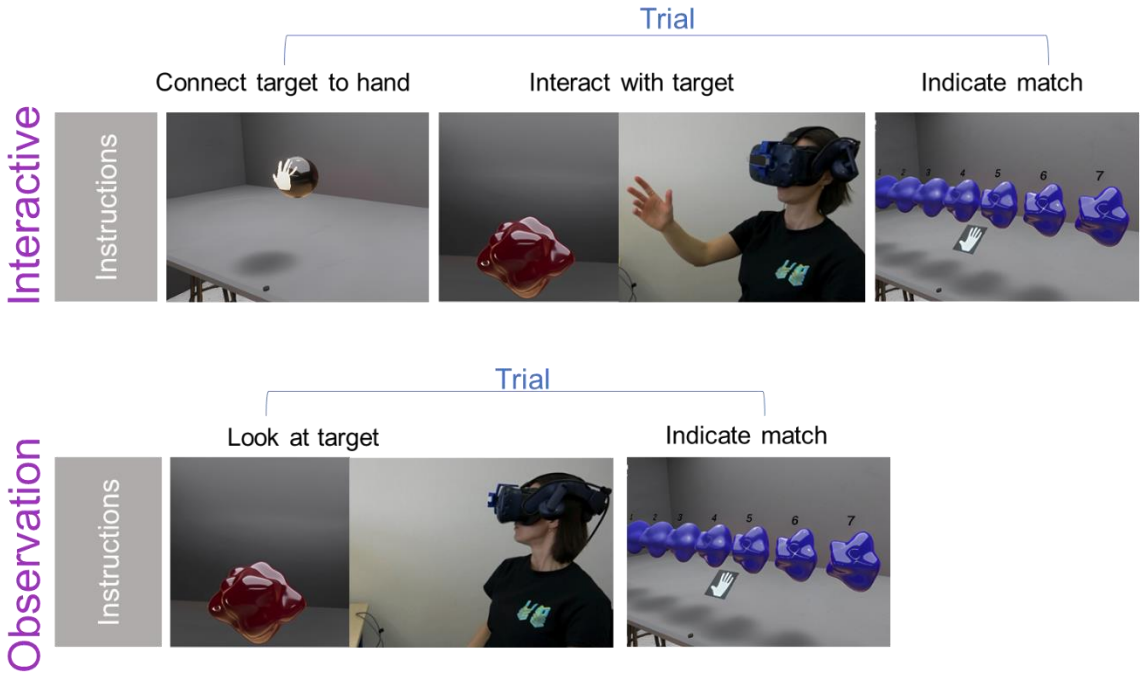

Figure 6. **Trial sequences for interactive and observation conditions**. Interactive: A chrome sphere indicates the starting hand position before the onset of exploration, and the virtual hand participants used to interact with the virtual object in the interactive condition. The participant could freely explore the object that was now yoked to the participant's hand. Once exploration was completed, comparison objects would appear, and the participant indicated their match verbally. The response would be logged in by the experimenter, after which the next trial would start. Observation conditions: Same as the interactive conditions, except for the object-hand yoking procedure.

Measurements

Overall, we recorded several hand movement parameters to assess potential differences in exploration between the gloss and lightness judgements conditions. We also assessed looking time during the observation condition.

Looking/Exploration time. We measured the time duration during which participants observed or explored the target stimulus before making their judgments. For the observation conditions, we measured the looking time, which refers to the duration (in seconds) between the onset of the target stimulus and the onset of the comparison objects. Whereas in the interactive conditions, we measured their exploration time, which is the time elapsed (in seconds) between the onset of the target stimulus (i.e., the start of exploration) and the onset of the comparison objects (i.e., the end of exploration). These measurements allow us to assess how long participant observed/explored the stimulus before forming their judgements.

Palm Distance. We measured the extent of hand movement made by participants during active exploration. To do this, we used the 'palm position' attribute recorded by the Leap Motion controller, which contains the 3-dimensional coordinates of the palm centre point (x, y, z). We calculated the distance travelled by the palm during exploration by quantifying the distance between each set of coordinates in successive frames (*i*,*i+1*) using the following formula: $d = \sqrt{(x_{i+1} - x_i)^2 + \left(y_{i+1} - y_i\right)^2 + (z_{i+1} - z_i)^2}$. Following this, the palm distance value is computed as the sum of distances between all consecutive frames within a trial. This measurement enables us to evaluate the extent of translational movements made by participants during exploration.

Palm Rotation. This measurement is determined using the 'palm normal' attribute captured by the Leap Motion controller. This attribute comprises the 3-dimensional coordinates of a unit vector (X,Y,Z) perpendicular to the plane formed by the palm of the hand. For instance, if the palm is flat and facing upwards, the vector points upwards (see Figure 7). We use this to determine the rotation of the palm as it rotates during interaction with the stimulus. Similar to the cumulative palm movement, we first quantified the distance between each set of coordinates in successive frames using the formula: $D = \sqrt{(X_{i+1} - X_i)^2 + (Y_{i+1} - Y_i)^2 + (Z_{i+1} - Z_i)^2}$ .Then, we sum these distances across all consecutive frames, and finally convert this sum to cumulative rotational angle by multiplying it by$180/\pi$. Using the measurement, we can gauge the extent to which participants rotate their hand during exploration.

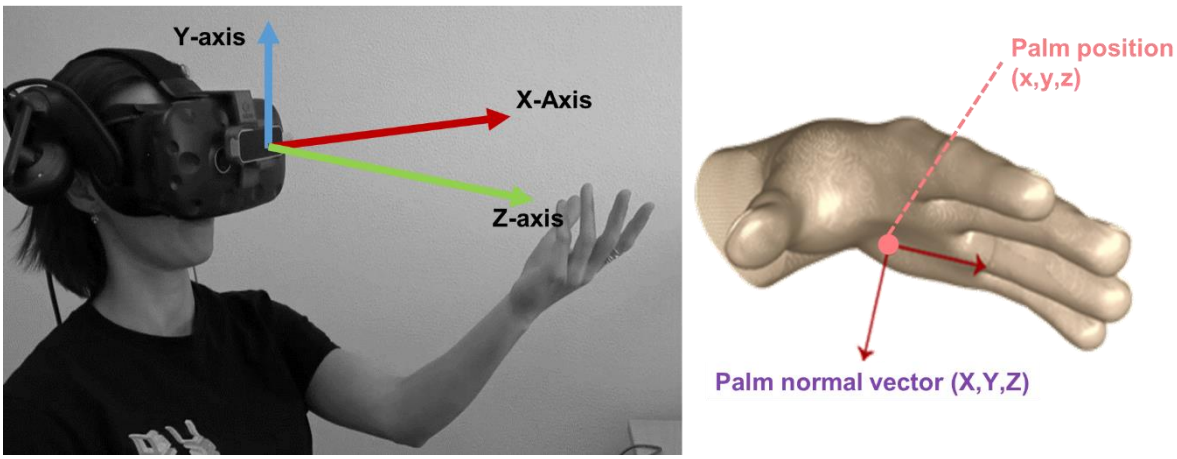

Figure 7. **Leap motion coordinate system and hand movement parameters.** Depiction of the Leap Motion coordinate system, illustrating the palm centre position and palm normal vector.

Data analysis

Perceptual Judgments. Before analysing exploration behaviour we assessed whether participants performed the perceptual tasks reasonably. To this end, we measured the mean perceived gloss level as a function of exploration condition, stimulus colour and gloss level across all repetitions. A repeated measure ANOVA was conducted to determine the significance of these effects and their interactions. In case of a significant main effect, we used Bonferroni post-hoc pairwise comparisons to identify specific differences between the condition, colour, and stimulus level. Similarly, for lightness judgements, we measured mean perceived lightness level as a function of exploration condition and lightness level across all repetitions. We used a repeated measures ANOVA and Bonferroni post-hoc pairwise comparisons to examine the significance of these effects and their interactions. Whenever the sphericity assumption was violated, we applied the Greenhouse-Geisser correction.

Exploration behaviours/ parameters. In our initial exploratory analysis of the gloss data, we observed no significant main effects of colour (p = .527 -.835). This suggests that colour had minimal to no impact on how participants interacted with the stimulus. Consequently, we decided to collapse the data across colours for all subsequent analyses involving the gloss data.

The data (averaged for each participant for each perceptual task, level and repetition) for each exploration parameter (exploration time, looking time, palm distance and palm rotation) were analysed separately with a repeated measure ANOVA. Bonferroni post-hoc pairwise comparisons were used to identify specific differences between main effects levels. Greenhouse-Geisser correction is applied whenever the sphericity assumption is violated.

Interobserver reliability. To evaluate the consistency of perceptual judgments made by participants in each condition, we also calculated Pearson's correlation coefficients between all possible pairs of participants for each stimulus level and repetition. Similarly, for exploration data, we computed Pearson's correlation coefficients between all possible pairs of participants for each stimulus level and repetition to assess their interobserver agreement in each exploration parameter. These parameters include exploration time, palm distance, and palm rotation, for interactive conditions and looking time for observation conditions.

Results

Before we assessed whether exploration parameters varied between perceptual tasks, we first verified that participants performed gloss and lightness judgments reasonably in the virtual reality experiments.

Gloss Perception

Observers performed this perceptual task sensibly: Figure 8 and our results demonstrate that participants consistently rated stimuli with higher gloss levels as glossier and darker stimuli were perceived as glossier compared to lighter ones. We also found that stimuli were perceived as glossier when the participants actively interacted with them, as opposed to merely viewing them passively, though this difference was very small. The 3-way ANOVA revealed significant main effects of gloss level, $F(1.832, 32.977) = 602.011$, $p < .001$, $\eta p^2 = .971$, colour, $F(1,18) = 12.304$, $p = .003$, $\eta p^2 = .406$, and exploration condition, $F(1,18) = 5.164$, $p = .036$, $\eta p^2 = .223$. There was no main effect of repetition in extra analyses (see Figure S.1-2 in the Supplementary). Dark objects were perceived on average to be glossier ($M = 3.653$, $SE = .060$) than light objects ($M = 3.441$, $SE = .057$, $p = .003$), and so were stimuli in the interactive condition ($M = 3.589$, $SE = .055$) compared to those in the observation condition ($M = 3.504$, $SE = .053$, $p = .036$). We also found a significant interaction between colour and gloss level, $F(2.039,36.694) = 29.976$, $p <.001$, $\eta p^2 =.480$. Bonferroni post-hoc pairwise comparisons showed that at the lowest gloss level (1), dark stimuli ($M = 1.268$, $SE = .064$) were perceived to be less glossy than light stimuli ($M = 1.700$, $SE = .078$, $p <.001$). At level 2, there was no difference in perceived gloss between dark and light stimuli ($p = .456$). At levels 3 to 5, dark stimuli ($M = 3.737$, $SE = 3.347$; $M = 4.816$, $SE = .123$; $M = 6.132$, $SE = .096$, respectively) were perceived to be glossier than light stimuli, $M = 3.347$, $SE = .084$, $p <.001$; $M = 4.363$, $SE = .099$, $p = .002$; $M = 5.568$, $SE = .160$, $p<.001$, respectively (See Figure 8). There were no further significant interactions, condition × colour, $p = .90$; condition × stimulus level; $p = .423$, condition × colour × stimulus level, $p = .197$.

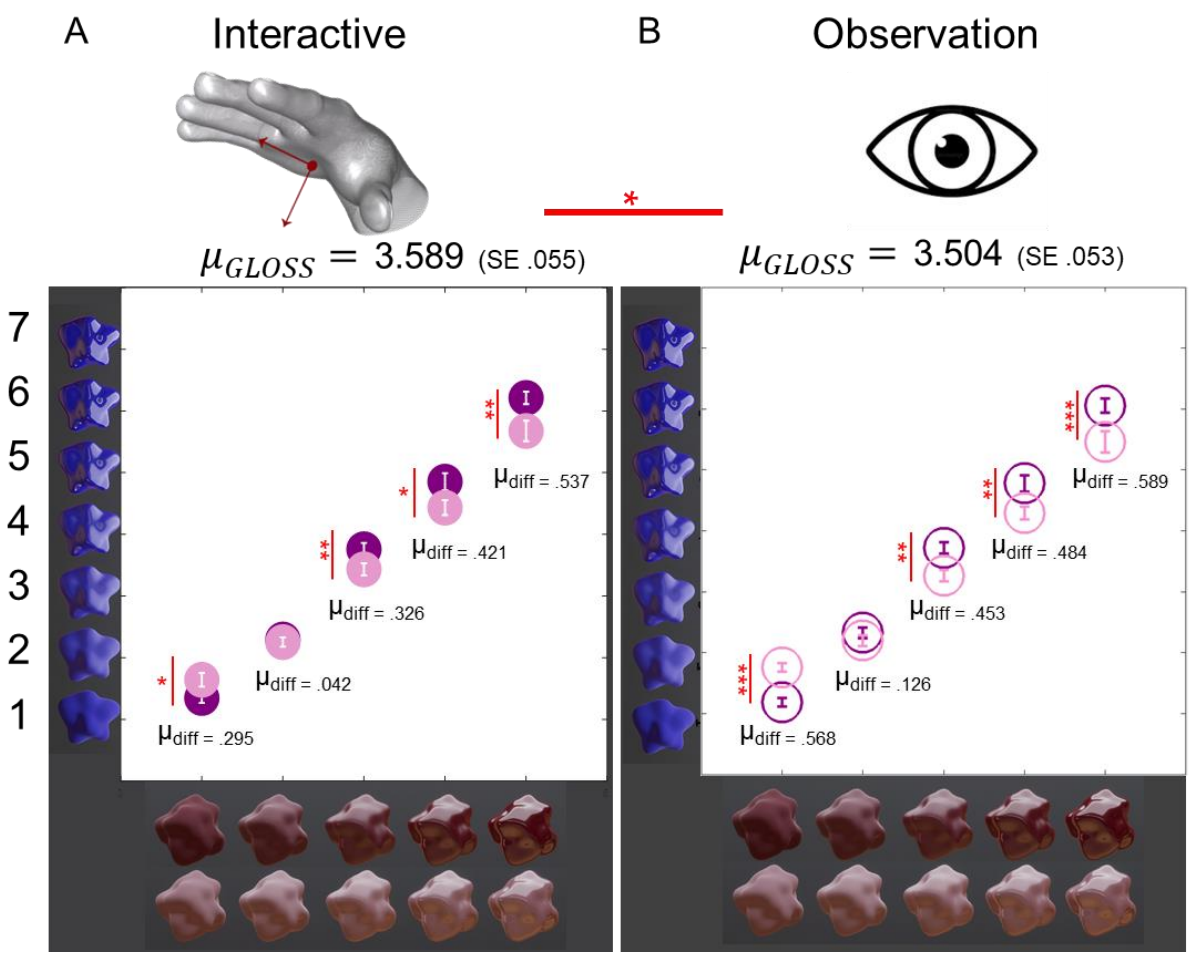

Figure 8. **Gloss perception results**. Panel A: Mean perceived gloss level plotted as a function of stimulus colour for the interactive condition; Panel B: Mean perceived gloss level plotted as a function of stimulus colour for the observation condition. Error bars represent 1 ± SE. With asterisks to indicate significant differences in perceived gloss levels between stimulus colours. Bonferroni post-hoc pairwise comparison showed that all levels (ranging from level 1, representing the least glossy object, to level 5, signifying the glossiest) were found to be significantly different from each other ($p < .001$). Specifically, participants' mean perceived gloss ratings and their respective standard errors (SE) were as follows: Level 1: $M = 1.484$, $SE = .054$; Level 2: $M = 2.268$, $SE = .055$; Level 3: $M = 3.542$, $SE = .070$; Level 4: $M = 4.589$, $SE = .092$; Level 5: $M = 5.850$, $SE = .118$.

Lightness Perception

Also, the lightness task was performed sensibly by participants in the VR experiment (Figure 9). As expected, participants rated stimuli that were darker as darker compared to the lighter ones. Interestingly, we also find some perceptual differences between interactive and observation conditions: participants tended to perceive stimuli at mid-levels of lightness (level 3 and 4), as being darker when they simply observed them, as opposed to interacting with them.

The 3 way repeated-measure ANOVA revealed a significant main effect of stimulus lightness level ($F(4,72) = 1746.346$, $p = <.001$, $\eta p^2 = .990$), and – surprisingly - of exploration condition, $F(1,18) = 8.908$, $p = .008$, $\eta p^2 = .331$, in which stimuli in the interactive condition ($M = 4.217$, $SE = .043$) were perceived to be lighter than stimuli in the observation condition ($M = 4.315$, $SE = .053$, $p = .008$). There was no main effect of repetition in extra analyses (see Figure S.3 in the Supplementary). The significant interaction between lightness level and exploration condition $F(4,72) = 4.547$, $p = .002$ and post hoc analyses revealed that stimuli with lightness levels 3 and 4 were perceived to be significantly darker in the observation condition ($M = 4.532$, $SE = .076$; $M = 5.563$, $SE = .092$, respectively) compared to the interactive condition ($M = 4.305$, $SE = .060$, $p = .002$; $M = 5.342$, SE = .063, $p = .008$, respectively, see Figure 9.

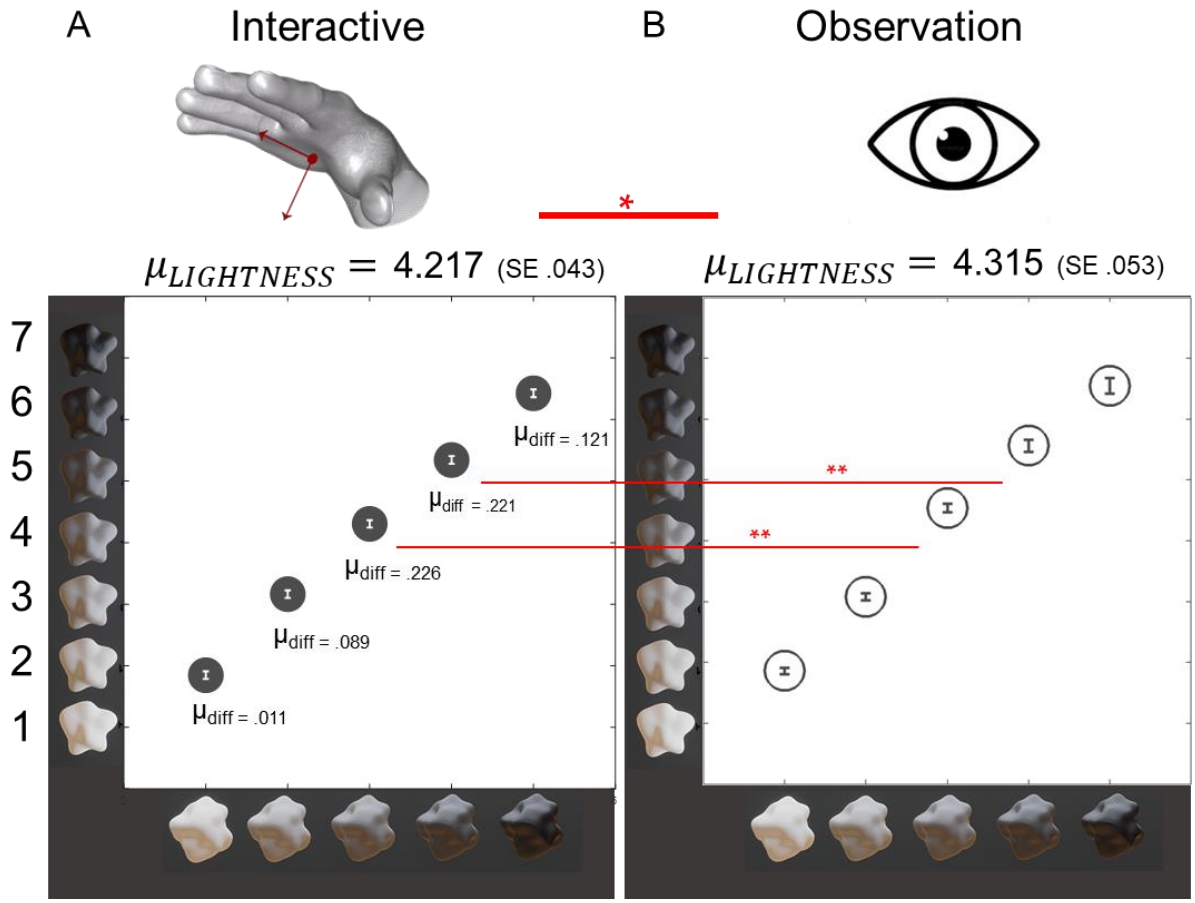

Figure 9. **Lightness perception results**. Mean perceived lightness level plotted as a function of exploration condition. With asterisks to indicate significant difference in perceived lightness levels between exploration conditions. Error bars represent 1 ± SE. Bonferroni post-hoc pairwise comparisons revealed that all lightness levels (ranging from level 1, representing the lightest stimulus, to level 5, representing the darkest stimulus) were found to be significantly different from each other ($p < .001$). Specifically, participants' mean perceived lightness ratings and their respective standard errors (SE) were as follows: Level 1: $M = 1.853$, $SE = .051$; Level 2: $M = 3.118$, $SE = .059$; Level 3: $M = 4.418$, $SE = .061$; Level 4: $M = 5.453$, $SE = .070$; Level 5: $M = 6.487$, $SE = .059$

Exploration Behaviours

The main goal of this study was to investigate whether observers adapt their interaction to the perceptual task demands. To this end, we measured several exploration parameters and assessed how they varied between experimental conditions. Figure 10 shows an overview of the results. Overall, we found that, participants spent longer exploring objects in the gloss condition as compared to the lightness condition.

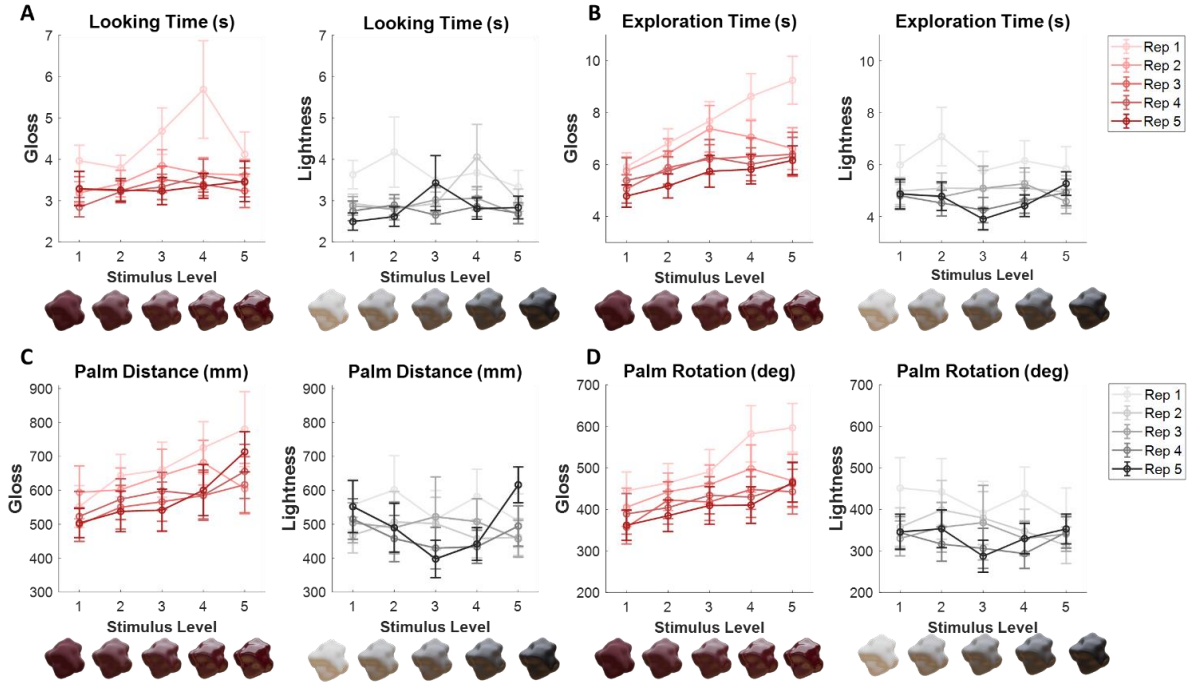

Figure 10. **Results exploration parameters.** A) Mean looking time, B) Mean exploration time, C) Mean palm distance, and D) Mean palm rotation across perceptual tasks plotted as a function of stimulus level and repetition. Error bars represent 1 ± SE.

Interactive conditions parameters

Exploration time. refers to the duration (in seconds) between the presentation of the target stimulus and the appearance of the comparison objects in the interactive conditions. Overall, we found that participants spent longer time actively exploring the stimulus in the gloss condition (M_{gloss} = 6.353, SE = .539) than in the lightness condition ($M_{lightness}$ = 5.076, SE = .522, p = .030, Figure 10B). A repeated-measure 3-way ANOVA revealed significant main effects of perceptual task, $F(1,18) = 5.524$, $p = .030$, $\eta p^2 = .235$, stimulus level, $F(4,72) = 4.338$, $p = .003$, $\eta p^2 = .194$; and repetition, F (1.913, 34.431) = 27.848, p <.001, $\eta p^2 = .607$. There was also a significant interaction between perceptual task and stimulus level, $F(4,72) = 8.112$, $p < .001$, $\eta p^2 = .311$. We found that participants spent significantly longer time exploring in the gloss condition compared to the lightness condition at stimulus level 3 (M_{gloss} = 6.661, SE =

.594; $M_{lightness}$ = 4.815, *SE* = .557, *p* = .006), level 4 (M_{gloss} = 6.765, *SE* = .607; $M_{lightness}$ = 5.105, *SE* = .534, *p* = .014), and level 5 (M_{gloss} = 6.947, *SE* = .679; $M_{lightness}$ = 5.113, *SE* = .515, *p* = .008). Moreover, participants spent a longer time exploring the stimulus at the first repetition (*M* = 6.911, *SE* = .465) than during all subsequent repetitions (i.e, repetition 2 to 5): repetition 2: *M* = 5.843, *SE* = .478, *p* <.001; repetition 3: *M* = 5.443, *SE* = .471, *p* <.001; repetition 4: *M* = 5.285, *SE* = .508, *p* <.001; repetition 5: *M* = 5.091, *SE* = .508, *p* <.001. No other significant main effects or interactions were found, *p* = .080 - .493.

Palm Distance. refers to the cumulative distance covered by the palm as participants interact with the stimulus. Overall, we found that participants move their hand to a greater extent in the gloss condition compared to the lightness condition (M_{gloss} = 605.508, *SE* = 52.507 vs $M_{lightness}$ = 498.844, *SE* = 58.572, Figure 10C). A repeated-measure 3-way ANOVA revealed a significant main effects of perceptual task, *F*(1,18) = 4.930, *p* = .039, ηp^2 = .215, and repetition, *F*(1.685,30.332) = 3.692, *p* = .044, as well as a significant interaction between perceptual task and stimulus level, *F*(2.663, 47.942) = 3.809, *p* = .019. In particular, participants exhibited increased palm movement (Figure 10C) in the gloss condition compared to the lightness condition at stimulus level 3 (M_{gloss} = 603.052, *SE* = 53.716; $M_{lightness}$ = 473.242, *SE* = 69.224, *p* = .033), level 4 (M_{gloss} = 635.517, *SE* = 63.469; $M_{lightness}$ = 484.461, *SE* = 54.509, *p* = .005), and level 5 (M_{gloss} = 674.268, *SE* = 68.479; $M_{lightness}$ = 508.031, *SE* = 53.165, *p* = .017). No other significant main effects or interactions were observed, *p* = .070- .615.

Palm Rotation. refers to the total angle rotated by the palm normal during interaction with the stimulus. Overall, participants rotated their hand more (Figure 10D) during the gloss judgement task condition than during the lightness task (M_{gloss} = 443.575, *SE* = 36.605, $M_{lightness}$ = 355.976, *SE* = 46.938, *p* = .027). A repeated-measure 3 way ANOVA found significant main effects of perceptual task, *F*(1,18) = 5.782, *p* = .027, ηp^2 = .243), and repetition, *F*(1.395, 25.107) = 9.231, *p* = .003, ηp^2 = .339. In particular, participants made significantly more rotational movements in the first repetition (*M* = 468.074, *SE* = 47.711), than in subsequent repetitions (repetition 2-4): repetition 2: *M* = 407.042, *SE* = 42.901, p = .038; repetition 3: *M* = 381.376, *SE* = 40.170, *p* = .008; repetition 4: *M* = 372.270, *SE* = 36.993, *p* = .046. Furthermore, we observed an interaction between perceptual task and stimulus level, *F*(4,72) = 5.085, *p* = .001. In particular, participants exhibited increased rotational movements in the gloss condition compared to the lightness condition at stimulus level 3 (M_{gloss} = 442.355, *SE* = 40.448; $M_{lightness}$ = 346.439, *SE* = 57.127, *p* = .046), level 4 (M_{gloss} = 473.620, *SE* = 45.985; $M_{lightness}$ = 347.655, *SE* = 42.699, *p* = .002), and level 5 (M_{gloss} = 486.720, *SE* = 50.604; $M_{lightness}$ = 346.419, *SE* =

40.822, p = .005).No other significant main effects or interactions were observed, p = .318 - .756.

Observation condition

Looking time. refers to the duration (in seconds) between the presentation of the target stimulus and the appearance of the comparison objects in the observation conditions. Overall, participants spent longer observing the stimulus (darker colours in Figure 10A) before making their judgements in the gloss condition than in the lightness condition (M_{gloss} = 3.587, SE = .296, $M_{lightness}$ = 3.061, SE = .248). A 3-way repeated-measure ANOVA found significant main effects of perceptual task, $F(1,18) = 4.892$, $p = .040$, $\eta p^2 = .214$, stimulus level $F(4,72) = 3.312$, $p = .015$, $\eta p^2 = .155$ (post-hoc pairwise comparisons were however not significant), and repetition, $F(1.513,27.231) = 17.019$, $p < .001$, $\eta p^2 = .486$. Figure 11 A illustrates participants spend more time looking during the first repetition (M = 4.056, SE = .307) than during subsequent repetitions (repetition 2: M = 3.347, SE = .264, p = <.001; repetition 3: M = 3.109, SE = .221, p = <.001; repetition 4: M = 3.030, SE = .240, p = <.001; repetition 5: M = 3.079, SE = .273, p = .006). There were no other significant main effects or interactions, p =.094-.632.

A task or a material effect on exploration behaviour?

To determine whether the increased exploration and observation in the gloss condition was influenced solely by the presence of high-gloss stimuli or, conversely by the absence of high-gloss stimuli in the lightness condition, we conducted further analyses. We did not use the same stimuli in lightness and gloss judgement tasks, however, since stimuli were not fully matte in the lightness condition we had – at least at the low gloss end – approximately comparable stimuli across the two tasks. Figure 11 shows these stimuli: gloss & lightness equivalent pairs were the dark gloss objects at stimulus level 2 and lightness objects at stimulus level 4, and light gloss objects at stimulus level 2 and lightness object at stimulus level 2.

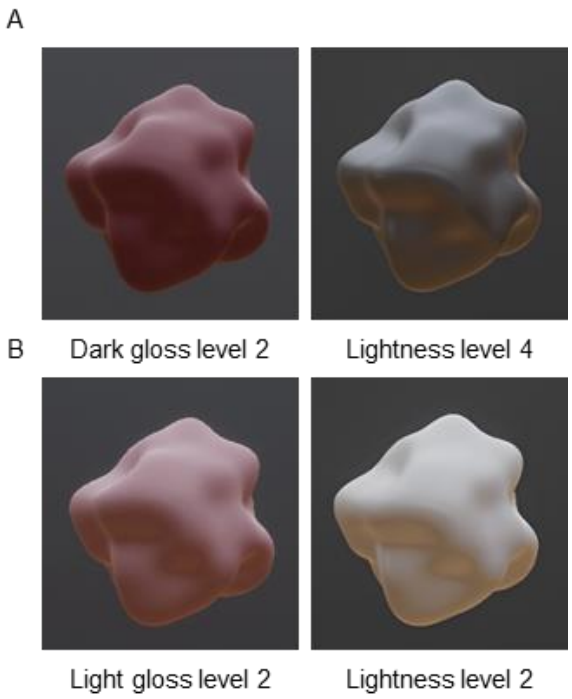

Figure 11. **Illustration of the two equivalent stimulus pairs used in the analysis.** Panel A: Dark gloss stimulus level 2 and lightness stimulus level; Panel B: light gloss stimulus level 2 and lightness stimulus level 2.

For each pair, we performed a 1-way repeated measure ANOVAs for all exploration parameters at the first repetition with the perceptual task as the independent variable and the corresponding parameter as the dependent variable. We chose to examine only the first repetition because previous analyses and plots indicated that differences in exploration patterns significantly diminished after the initial repetition. Including all subsequent repetitions could potentially obscure any differences in exploration patterns that were present in the first repetition; therefore, focusing on the first repetition allows us to capture the potential differences in exploratory patterns.

Overall, we did not find an effect of the perceptual task on exploration parameters (exploration time, observation time, palm distance and palm rotation) for these stimulus pairs. See Supplementary page 3 for details on specific statistical values. Figure 12 shows the overall means of exploration parameters for each of the two equivalent stimulus pairs.

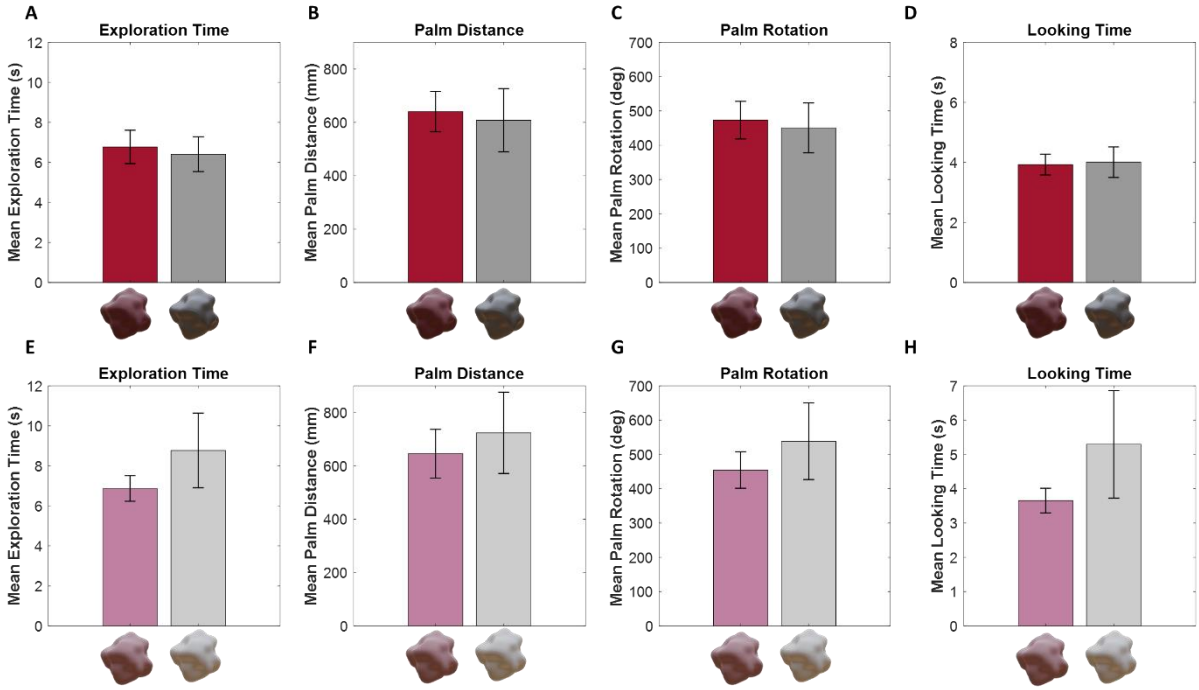

Figure 12. **Comparison of exploration parameters between the two equivalent stimulus pairs at the first repetition.** Bar plots comparing various exploration parameters between different stimulus conditions at the first repetition. Panels A-D showed comparisons between dark gloss stimulus level 2 and lightness stimulus level 4: (A) Mean exploration time, (B) Mean palm distance, (C) Mean palm rotation, and (D) Mean looking time. Panels E-H show comparisons between light gloss stimulus level 2 and lightness stimulus level 2: (E) Mean exploration time, (F) Mean palm distance, (G) Mean palm rotation, and (H) Mean looking time. Error bars represent ±1 SE.

Interparticipant correlations and individual differences

We were interested to what extent participants agree in their perceptual judgements and exploration behaviours. Figures 13 and 14 show Pearson's correlation coefficients between all possible pairs of participants for each *perceptual task*, across all stimulus levels at the first repetition for the interactive and observation conditions, respectively. We have omitted participants' perceptual judgments and exploration patterns after the first repetition to avoid obscuring meaningful differences evident in the initial repetition. However, further analysis of the interobserver correlations of perceptual ratings and exploration parameters for all participants across all stimulus levels and repetitions can be found in Figure S.4-5 in the Supplementary.

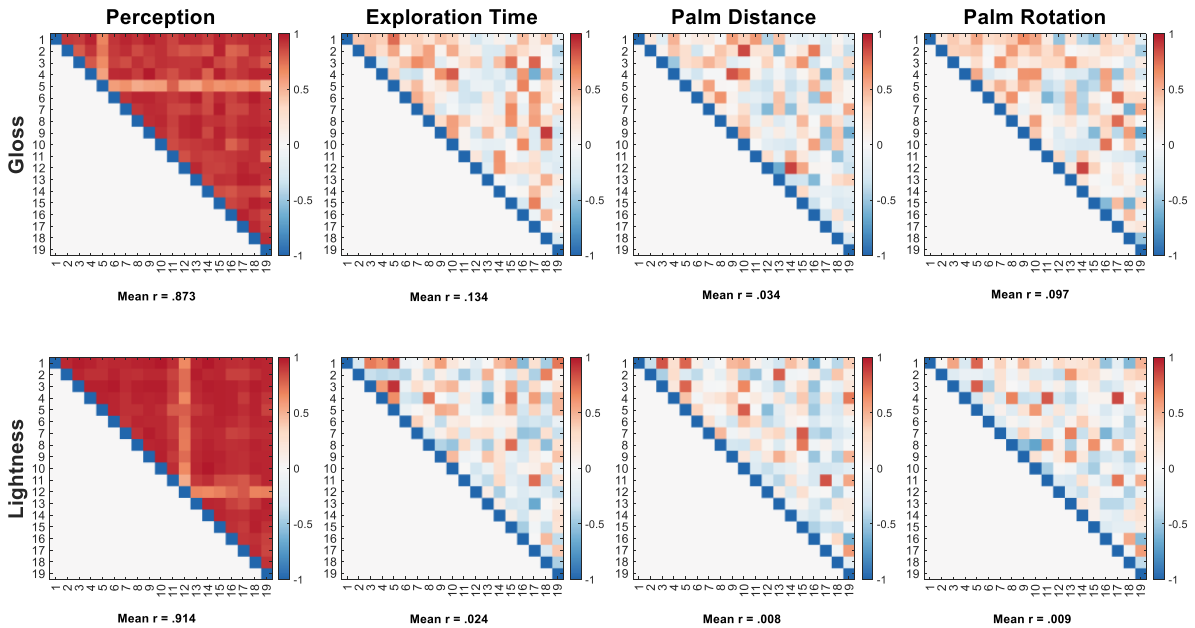

Figure 13. **Interobserver correlations in the interactive condition.** Shown are correlations between each pair of participants, for all stimulus level at the first repetition. Perceptual agreement was much higher for perceptual judgments than of exploration parameters.

Overall and on average, perceptual ratings were highly consistent across participants for all conditions with correlation coefficients ranging between .873 and .924. In contrast, interparticipant correlation was much lower for the exploration parameters assessed in our experiment, ranging on average between -.007 and .134. Interestingly, a similar low correlation between participants was also found for looking time Figure 14 (-0.007 to - 0).

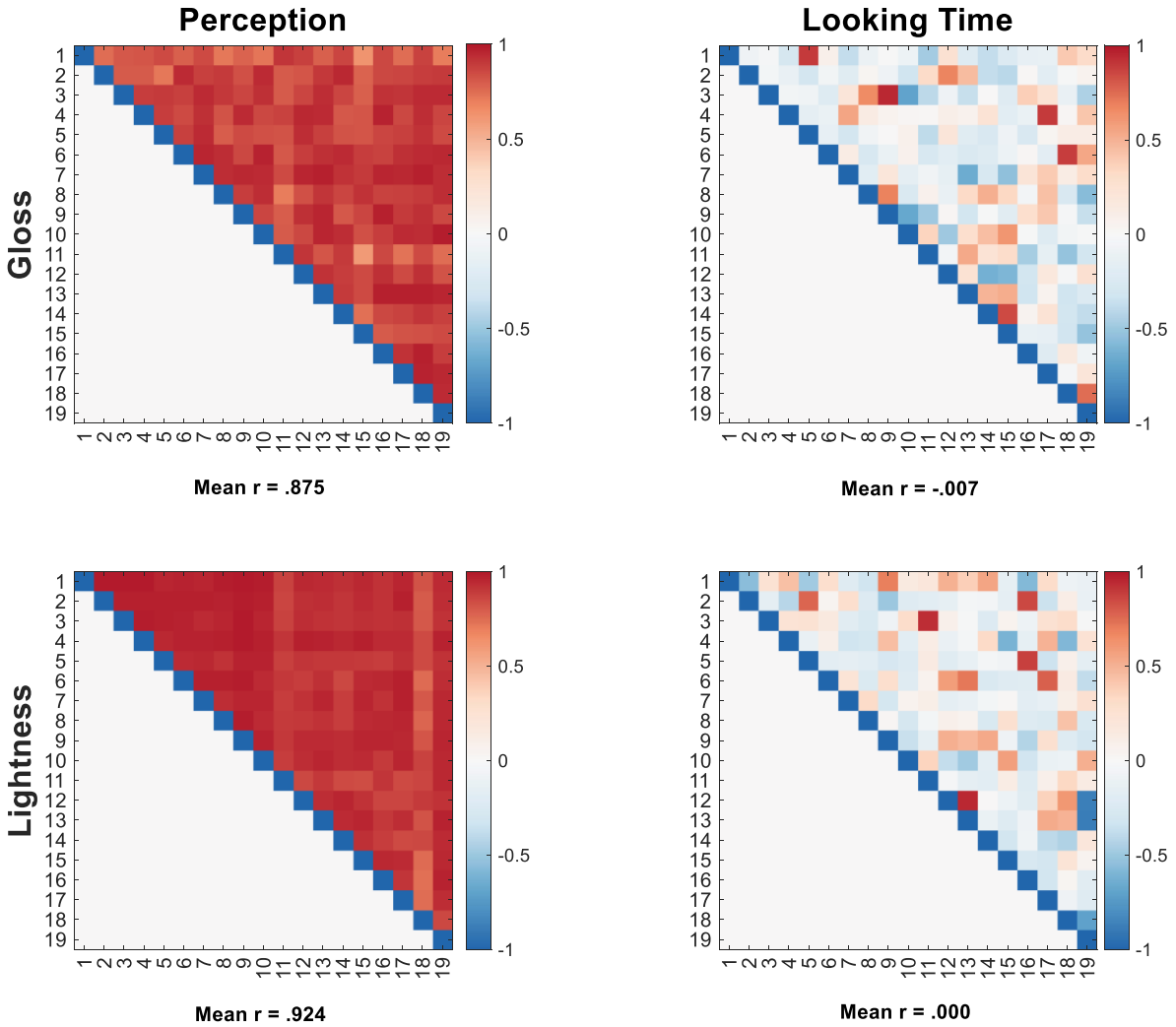

Figure 14. **Interobserver correlations in the observation condition**. Shown are the interobserver correlations of perceptual ratings and looking time for all participants across all stimulus levels at the first repetition.

These patterns could suggest that exploration behaviours vary differently across stimulus levels and tasks differently between participants, and that observers had used idiosyncratic behaviours to actively generate information when judging gloss and lightness (Doerschner et al., 2022). They could, however, also imply that potential systematic differences in exploration behaviour between different stimuli were relatively small as compared to the unsystematic noise. When visualising the participants' movement trajectories during exploration (Figure 15), the influence of perceptual task and repetition on the extent and

duration of stimulus exploration becomes quite evident, i.e. more rotation, and longer exploration in the gloss conditions. Yet, one can also observe considerable individual variations in participants' exploration approaches, as illustrated in Figure 15. For instance, in Figure 15, the palm rotational trajectories of two participants (participants 7 and 14) were depicted. Despite both participants dedicating more time to exploring stimuli and rotating them more extensively in the gloss condition compared to the lightness condition during the first repetition, their palm rotational trajectories exhibited substantial differences. Therefore, given the consistently low inter-participant correlation in participants' exploration behaviours, it is possible that different exploration patterns may yield similar perceptual cues that are being used by the visual system to make judgements about different visual material properties. The palm rotation trajectories for all participants are visualised in Figures S.6-10 in the Supplementary.

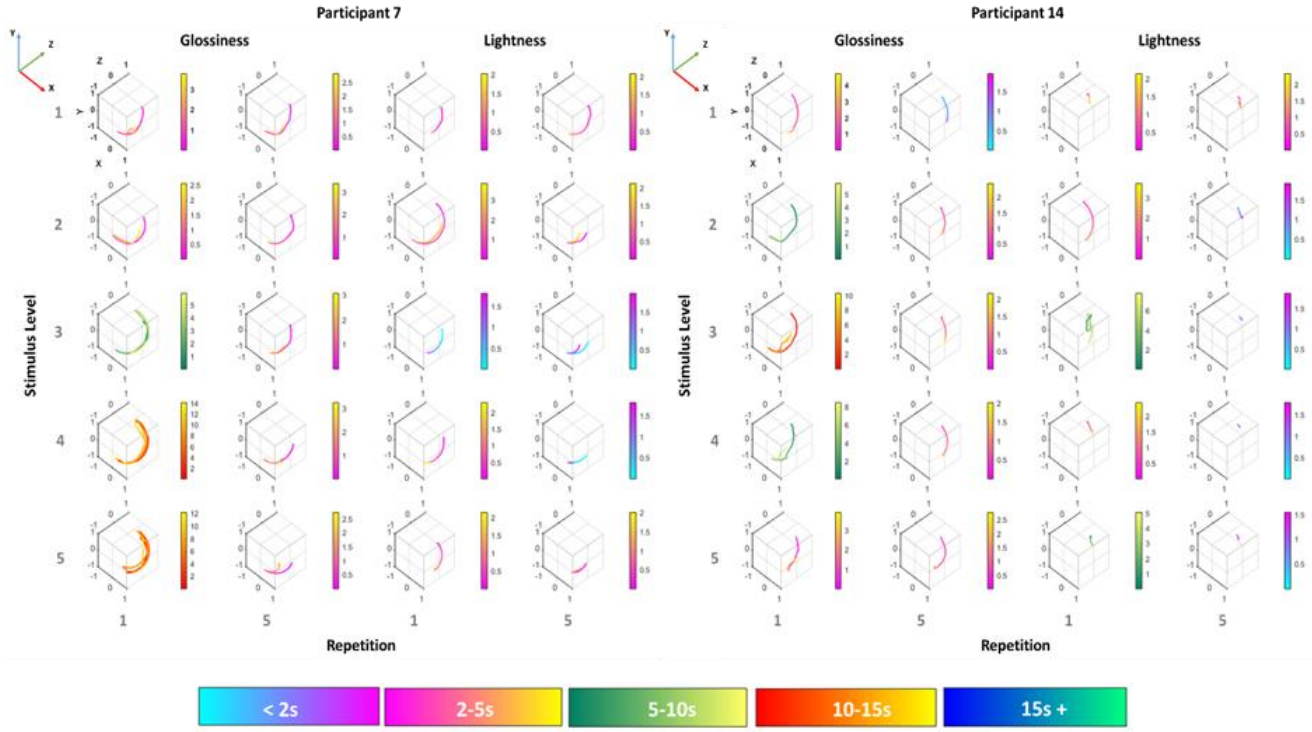

Figure 15 . **Visualisation of palm rotation trajectories during explorations**. The figure displays the palm rotation trajectories of two participants (Participants 7 and 14) during exploration. As illustrated, both participants spent more time exploring objects during the gloss task compared to the lightness task. However, their actual palm rotation trajectories showed marked differences.

Discussion

How the process of exploration modulated influences the perception of visual material properties and vice versa is poorly understood. We conducted a VR experiment to examine whether exploration behaviour is modulated by an object's material and the perceptual task, and whether exploration influences the perception of visual material properties. Participants were asked to make matching judgements about the gloss or lightness of objects after interacting with -, or just looking at an object. We assessed observers' exploration patterns and perceptual judgments. We expected that observers would engage more with the stimulus during gloss judgement tasks since more potential information could be gained by rotating a glossy object, e.g. by generating highlight movement across the objects surface.

1. The perceptual task and material properties modulate exploration behaviour

There were two perceptual tasks in our experiment, and importantly, stimuli in the two tasks differed: in the gloss judgement task, stimuli differed in gloss level, in the lightness task stimuli's' gloss level was fixed to a low value (.3) and they differed in lightness. Thus, to some extent, task and material difference covaried. However, we might be able to tease the relative contributions of each of these factors to exploration behaviour apart. We will first discuss the combined effects of material and task and then potential individual contributions.

Overall task/material effects. Overall, participants spent more time exploring objects and made more translational and rotational hand movements during gloss judgments than during lightness judgments. These differences in movement patterns could suggest a strategic prioritisation of relevant cues for the different tasks: It is possible, for example, that observers are attuned to visual cues such as highlight motion, and they actively generate these cues through larger movements and object rotation to facilitate their judgements of perceived gloss. In an ongoing research project, we incorporate eye tracking to explore whether observers use material-specific cues to judge various visual material qualities (Doerschner et al., 2011) during active explorations. This will also allow us to assess how observers' visual sampling behaviours vary based on the task and how visual exploration is coordinated with hand movement patterns during interaction. In contrast, lightness judgments may rely more on global, overall brightness perception, necessitating less extensive exploration (Toscani et al., 2013 & 2017). While this may be true, we found that, surprisingly, active exploration modulated lightness judgments slightly, but significantly.

While taken together, these findings may indicate a systematic variation in participants' exploration patterns depending on the visual task they were performing (Hayhoe & Ballard, 2014). It is also possible that these modulations were due to differences in material properties between the stimuli in the two different tasks: one set varying in gloss with lightness levels fixed, one set varying in lightness with gloss level fixed. Can the material alone explain the differences in exploration time and amount?

To answer this question, let's consider at gloss judgments only. Here, we found a modulatory effect of stimulus level on participants' exploration patterns: participants explored high-gloss objects longer (cumulative time) and to a greater extent (cumulative distance) than those with low gloss. In contrast, for lightness judgments, we see no such dependence of exploration on stimulus level. One might therefore argue, that the increase in exploration in the gloss condition might solely be driven by the high-gloss stimuli or conversely, by the absence of high-gloss stimuli in the lightness condition. To test this possibility, we compared exploration parameters between approximately equivalent stimuli across both tasks (Figures 11 & 12). Yet, this analysis yielded no significant differences. This suggests that the increased exploration observed during gloss judgements might be driven by the material properties of the stimuli rather than the task demands (judging gloss vs. judging lightness). However, in order to fully resolve the task vs material issue we would need to conduct a similar analysis for high gloss stimuli for both tasks. We plan to address this in future experiments, where we will use identical stimuli for lightness- and gloss judgements.

Nevertheless, the overall more pronounced differences in exploration of glossy objects at high levels (3-5) might be explained by the distinct presence of highlights (Figure 4). If we return to our introductory toy example of information gained through object rotation in Figure 2, we can see that a decrease in distinctiveness of specular highlight covaries with a decrease in average pixel differences across any two frames of a rotating object (Figure 16). This is especially so for darker glossy objects. Conversely, average pixel difference across frames does not show any systematic trend in the lightness condition. Given this, there simply might be more information to gain by rotating moderate to high glossy objects, than matter ones. One may ask whether then we should mainly see more movement for the dark as compared to the light coloured high gloss objects, because for these the changes by rotation are particularly large. However, exploratory strategies can sometimes be heuristic rather than fine-tuned – at least in haptic perception (Kaim & Drewing, 2011), and more movement might be a

heuristically appropriate strategy for exploring higher gloss objects – even if there is no benefit in every single case.

Alternatively, the increased exploration of high gloss objects might reflect the participants' effort to gather sufficient and reliable perceptual information, despite the inherent or increased instability of the signal. This instability is evidenced by the greater variability in pixel differences across frames for high gloss objects. For haptic perception, extended exploration has been shown to improve perceptual reliability, and that participants tune their movements in order to reach good perceptual levels of performance (Kaim & Drewing, 2011; Metzger, Lezkan & Drewing, 2018; Zoeller & Drewing, 2020). Likewise, the participants' extended movements with higher gloss levels might compensate for higher variability of the perceptual information.

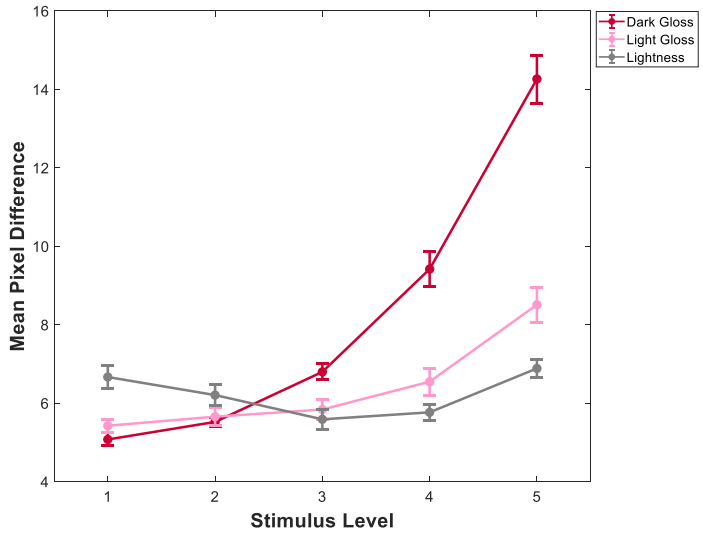

Figure 16. **Average pixel difference across frames for various stimulus levels.** Average pixel difference across 11 frames for each stimulus level, with the object rotating by 5 degrees per frame. Each line corresponds to different types of stimuli: dark glossy, light glossy, and lightness objects. Error bars represent 95% CI. It can be seen that the variability of differences as reflected in the CIs gets larger with higher gloss levels, but stays constant for different lightness levels.

Interestingly, the increase in exploration with gloss level contrasts with the results reported by Lichtenauer et al. (2013). In their experiment, participants were given control to rotate a rendered patch (by moving a computer mouse). They found that overall, observers did not make excessive use of the to-be-gained motion information and, in fact, even moved matte patches more than glossy ones (e.g. Lichtenauer et al. 2013, their Figure 10 & Table 5). This discrepancy between their and our study could be attributed to several things. For example, they used planar rough surfaces coated with different lacquers, whereas we used smooth curvy objects. Mesoscale rough surfaces (and planar objects) yield quite different highlight

appearances across changes in object orientation compared to smooth surfaces. Additionally, participants were limited to horizontal or vertical moving the virtual rendering via mouse control. This limitation may have prompted them to use larger movements when interacting with low-gloss objects to glean more information about surface texture and properties. Whereas in the current experiment, participants could freely move around and interact with objects using a virtual hand in a virtual environment, this increased freedom of movement may have influenced their exploration patterns differently. Finally, the range of gloss levels was different from ours, making direct comparisons between studies challenging.

Cognitive factors modulating exploration. While we offer a possible explanation for the observed increase exploration behaviour for high gloss stimuli in our study, based on the to-be-gained visual information (Figure 2), it is also possible that cognitive aspects modulate the extent of exploration. For example, aesthetic preferences might influence exploration, as participants may find high-gloss objects more attractive and appealing than those with low gloss (Silvia et al., 2018). The heightened exploration of high-gloss objects may stem from participants' motivation to engage with visually captivating and reflective surfaces thoroughly. The overall significant increase in observation time for gloss judgements would support this (even though the increase is not as systematic across stimulus levels as, for example, manual exploration time). However, this remains speculative, and it would be interesting for future research to investigate whether aesthetic preferences contribute to individuals' exploration patterns alongside the imperative to gather information for perceptual judgments.

Exploration decreases with repetition. Overall, and unsurprisingly, we found that independent of task and condition, participants engage in more extensive exploration during the first repetitions than in all subsequent repetitions. This can likely be attributed to perceptual learning, where participants became more sensitive to task-relevant features and visual cues (Dosher & Lu, 2017; Paffen et al., 2008). During the first repetition, participants invest more time and exploration in locating and identifying sensory cues crucial for tasks like making gloss or lightness judgments. Once these task-relevant cues are identified, they streamline their attention to these particular features in subsequent repetitions, thus reducing exploration duration and extent. An alternative explanation could involve habituation and/or memory interference. Participants may become accustomed to specific gloss or lightness levels with repeated exposure and interaction. However, we did our best to have sufficient stimulus variation in the experiment to prevent simple memorization. Nevertheless, familiarity could

lead to a decreased need for extensive exploration and observation as individuals adapt to the perceived qualities, potentially diminishing engagement over subsequent repetitions.

2. Exploration behaviour modulates material appearance

Gloss. We expected that participants would judge objects as more glossy during the interactive condition, because previous research has shown that moving stimuli are perceived to be more glossy (e.g. Doerschner et al., 2011; Wendt et al., 2010; Sakano & Ando, 2008, Marlow & Anderson, 2016). While overall, stimuli in the interactive condition were perceived as significantly more glossy, the difference in perceived gloss between interactive and observation condition was very small. We think this might be attributable to a ceiling effect. Glossy stimuli in the observation condition were embedded in complex scenes with a natural light field, potentially yielding the most glossy appearance for each stimulus possible (Fleming et al. 2003). Moreover, participants were able to move their heads, which might have also generated small highlight movements. Under these conditions, highlight motion from in-hand object rotations might have had a relatively small effect on glossy appearance.

Lightness. Since the location of brightest part of a matte object (Toscani et al 2013) will not change substantially when moving a matte object in the hand, we expected no changes in perceived lightness between interactive and observation condition to occur. In contrast to our expectation, we found that interactions made objects appear slightly lighter, particularly for darker lightness levels (starting from lightness level 3 onwards). What might be the reason for this surprising outcome? Overall, participants spent more time with the object during the interactive exploration condition (about 2s). Therefore, they might simply have had more time to look at the bright regions on the object (Toscani et al. 2013), and we know that temporal aspects affect lightness judgements (e.g. Toscani et al. 2016). However, the asymmetry of the effect remains a puzzle, i.e. that only medium-dark objects appeared lighter? Perhaps also this has to do with how participants sample visual information across the object as the object moves and the intensity changes of surface patches between directly and obliquely lit positions. Figure 17 illustrates some interesting differences between lighter and darker objects in our study: The pixel brightness between directly lit and shaded regions appear to be more pronounced for dark surfaces than for lighter ones. Perhaps, as the difference between lighter and darker regions on the object becomes greater participants tend to look more at the brighter parts of the object, whereas when this difference is smaller, participants tend to look at both, brighter and darker

regions on the object. To understand whether such stimulus differences modulate the sampling of visual information conditions we need to measure eye movements during the exploration process. We currently pursue this in an ongoing project.

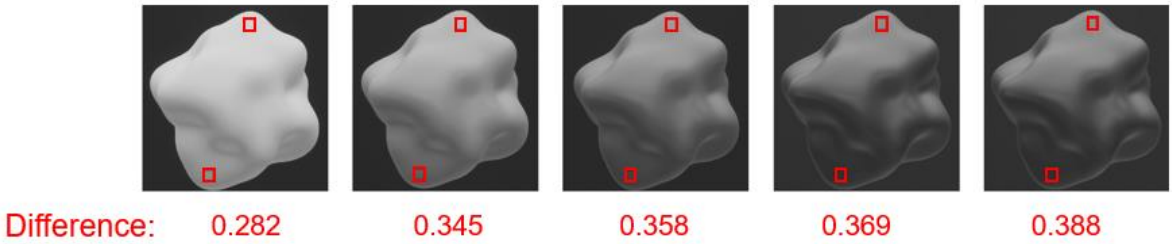

Figure 17. **Lit-shaded region pixel brightness differences.** Red squares denote the lit and shaded regions on each stimulus in the lightness judgement experiment. The red value below is the difference in pixel intensity between these two regions. This difference is larger for darker stimuli, which tended to be judged as lighter.

Individual differences

Despite high agreements in their perceptual judgements across conditions, participants exhibited considerable individual differences in their exploratory patterns. This suggests that while the ultimate perceptual judgments may align, the underlying exploratory behaviours leading to these judgments can diverge. Attentional bias may contribute to this variability, with participants exploring and attending to distinct yet relevant features of the stimuli during their exploration. Different exploratory approaches or patterns may yield similar perceptual information that forms the basis of their perception of visual materials. Given the intrinsic link between attention and gaze (Hoffman & Subramaniam, 1995; Kowler et al., 1995), exploring observers' gaze behaviours in the same paradigm could reveal insights into individual differences in eye movement activities during active exploration/information gathering for visual material perception, shedding light on attentional allocation and visual sampling strategies during object exploration.

Conclusion

Taken together, the current experiment demonstrated visual material and maybe task and material properties influence how individuals interact with an object and that, in turn, active exploration could influence the perception of visual material properties. We have also illustrated that individuals utilise a variety of exploratory behaviours to generate information

when assessing gloss and lightness, suggesting that different exploration pat terns may produce similar perceptual cues crucial for perceiving visual material qualities. Overall, our findings demonstrated the impact of visual material and task in guiding and modulating human interactions with objects.

Acknowledgement

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